INNOVATIONS IN NEUROPSYCHOLOGY ASSESSMENT METHODS USING IMMERSIVE VIRTUAL REALITY

Khawla AJANA

Thèse présentée en vue de l'obtention du grade de Docteure en sciences psychologiques et de l'éducation

Septembre 2023

Innovations in neuropsychology assessment methods using immersive virtual reality

Khawla AJANA

Thèse présentée en vue de
l'obtention du grade de Docteur
en sciences psychologiques et
de l'éducation

Promoteur

Martin Gareth EDWARDS (UCLouvain)
Thierry Lejeune (UCLouvain)

Comité d'encadrement

Prof. Michael ANDRES (UCLouvain)
Prof. Gaëtan STOQUART (UCLouvain)

UCL PRESSES UNIVERSITAIRES DE LOUVAIN

Collection de thèses de l'Université catholique de Louvain, 201X

Président

Prof. Michael ANDRES

Comité d'accompagnement et jury

Prof. Nele DEMEYER
Dr. Lars EVALD
Prof. Valérie GOFFAUX
Prof. Gaëtan STOQUART
Prof. Marie VAN REYBROECK

Dépôt légal : D/201x/9964/xx
ISBN : 978-2-87588-xxx-x
Imprimé en Belgique

Couverture : Marie-Hélène Grégoire

Diffusion : www.i6doc.com, l'édition universitaire en ligne
Sur commande en librairie ou à
Diffusion universitaire CIACO
Grand-Rue, 2/14
1348 Louvain-la-Neuve, Belgique
Tél. 32 10 47 33 78
Fax 32 10 45 73 50
duc@ciaco.com

Acknowledgments

I started my PhD shortly before the outbreak of the Covid-19 pandemic, a period characterized by various challenges and marked by numerous uncertainties. Nevertheless, I have managed to come this far. This would not have been possible without the support of exceptional individuals whom I feel tremendously grateful to have encountered along this journey, and who continue to be a part of my life today.

Firstly, I would like to express my gratitude to my PhD promoters. **Professor Thierry Lejeune**, for generously sharing his extensive academic knowledge and clinical experience, and for his guidance throughout the entire process. To **Professor Martin Gareth Edwards**, for his unwavering support, his compassionate and patient tutelage, and invaluable guidance: I am truly grateful for your mentorship, thank you for leading with kindness, thank you for believing in me when it was difficult to do so myself, and thank you for your dedication to my academic and personal growth. You inspire me to be a better researcher than I could ever have aspired to be!

I would like to extend my sincere thanks to the members of the jury, **to Professor Nele Demeyer**, **Doctor Lars Evald**, **Professor Valérie Goffaux**, and **Professor Marie Van Reybroeck** for their insightful comments and thought-provoking questions. To **Professors Michael Andres and Gaëtan Stoquart** for their assistance through my doctoral studies and valuable feedback. Your suggestions have enhanced greatly the quality of this work.

I would like to offer my special thanks to **Région Wallonne**, The **SPW-Economie-Emploi-Recherche** and the **Win2Wal program** for funding this doctoral project.

Furthermore, my PhD project is the culmination of a collaborative effort that involved the contributions and assistance of various individuals. My sincere thanks to **Gauthier Everard**, **Stéphane Grade**, **Anthony Garcia**, **Camille Ganci**, **Gregorio Sorrentino** and all the **students** who helped in the development of this project.

A special appreciation goes to all the wonderful colleagues and members of the Institute of Psychological Institute, some of whom I proudly call my friends today: **Silvana Romero Saletti**, **Veena Kamble**, and **Iqra Shahzad**. I extend a heartfelt thanks to **Martine Janssens**, for her support and kind help that made the doctoral school easy to navigate.

I would like to express my appreciation to the clinicians at Cliniques universitaires Saint-Luc: **Mathilde Van Durme** and **Caroline Sencie**. Without their kind assistance and collaboration, participants recruitment would have been a challenging task. Thank you for **Professor Yves Vandermeeren and Eloise Gerardin** for opening their laboratory doors to me. I am excited for future collaborations with you. Additionally, I want to extend my heartfelt thanks to all the participants who took part in my studies. Many thanks for willingly and generously dedicating their time and effort to further the progress of this project.

This PhD journey, could not have been as meaningful without the constant presence of my friends and family. I would like to thank: **Soccorsa, Malek, Sofia, Salma, Kirti, Delphine, Iris, Yasmina**, **Annelies** and **Yasmine**. For patiently enduring my enthusiastic rambling about my research and for graciously listening to my occasional complaints along the way. A special thanks to my flatmate **Safia**, who consistently displayed interest for my work. My deepest thanks to **Simon,** my rock. I have been fortunate to have your unconditional support and faith in my abilities. You have been my source of strength and motivation. Weather by providing a listening ear during the challenging times, or by celebrating the smallest victories. I cannot express enough my gratitude for having you in my life. To my aunties, **Khadija** and **Leila,** for their support. **Bouchra**, **Meriam**, **Zineb** and **Jamila** for their encouragement. To all my extended family and my cousins, who put effort in understanding my research and the specifics of my work. Thank you to my siblings: **Najwa** and **Reda,** for their empathic support and for being a source of inspiration. Lastly, there is not enough words to convey my gratitude to my **mother** and **father**: my pride and joy. For their unconditional love and support, that have been the essence of my determination and resilience, their dedication to my education, for the values and principles that they have instilled in me, and that have shaped the person I am today. This thesis is dedicated to you.

Table of contents

List of abbreviations

Abbreviation	Definition
ANOVA	Analysis of variance
CI	Control individuals
CV	coefficient of variance of speed
Electroencephalography	EEG
HN	Hemineglect
IVR	Immersive virtual reality
MV	Mean velocity
OCS	Oxford Cognitive Screen
RT	Response time
SI	Post-stroke individuals
SI:HN+; SI:HP+HN	Individuals with hemiparesis and with HN
SI:HN-; SI:HP-HN	Individuals with hemiparesis and without HN
SI:HP	Individuals with upper limb hemiparesis
TAP	Test of attentional performance

Abstract - Résumé

Neuropsychological assessment has undergone significant changes in response to criticisms of paper and pencil tests. These criticisms include practice effects and poor ecological validity and have prompted a need for transformative approaches. This urgency becomes more evident in the context of measuring stroke individuals' performance changes during neurorehabilitation programs, where practice improvements can confound treatment outcomes. Moreover, these traditional methods fail to capture the complexity of cognitive functioning, such as hemineglect. New technologies, such as immersive virtual reality have the potential to address these limitations. This thesis aims to contribute to enhancing the quality of neuropsychological assessment, and to bring new insights into understanding post-stroke cognitive impairment. Throughout this thesis, two novel serious games in immersive virtual environments were introduced. Each of these games was designed to assess distinct components of cognitive functioning. Additionally, this thesis investigated the feasibility, validity, and user experience for the two serious games. Finally, the advantages and limitations of our serious games, as well future perspectives are discussed.

L’évaluation neuropsychologique a subi des changements significatifs en réponse aux critiques des tests papier-crayon. Ces critiques, qui portent sur l’effet d’entrainement et une faible validité écologique entre-autres, ont précipité l’adoption de nouvelles approches. Cette urgence est d’autant plus évidente dans le cadre de la prise en charge des troubles cognitifs chez des patients ayant survécu à un accident vasculaire cérébral. Ceci en raison de l’impact que l’évaluation initiale des troubles cognitifs peut avoir sur leur développement. De plus, ces méthodes traditionnelles ne parviennent pas à capturer la complexité du fonctionnement cognitif, comme dans le cas d’une héminégligence. Les nouvelles technologies, telle que la réalité virtuelle immersive, sont une solution potentielle à ces limitations. Cette thèse a pour objectif de contribuer à l’amélioration de la qualité de l’évaluation neuropsychologique, et à la compréhension des troubles cognitifs dû à un accident vasculaire cérébral. Deux nouveaux jeux sérieux en réalité immersive sont présentés dans cette thèse. Chacun de ces jeux a été conçu pour évaluer des composantes distinctes du fonctionnement cognitif. En outre, dans cette thèse la faisabilité, validité, et l’expérience utilisateur des deux jeux sérieux. Enfin, nous discutons les avantages et les limites de ces jeux sérieux, ainsi que les perspectives futures.

Prologue

Neuropsychology is relatively a young discipline, with less than 150 years of activity, which has undergone significant changes over this time course (Bilder & Reise, 2019). These changes have been driven by neuropsychologists who have continuously challenged the methods used for neuropsychological assessment in clinical and research settings (Miller & Barr, 2017; Valladares-Rodríguez et al., 2016). Currently, there is an urgent need for new transformations that are motivated by criticisms that paper and pencil tests lack in reliability (showing practice effects) and show poor ecological validity (Howieson & Lezak, 2008; Plummer et al., 2003), among other criticisms. The issue of test reliability becomes increasingly important for measuring how stroke individuals' performance changes in correspondence to neurorehabilitation programmes, whereby practice improvement effects confound improvements that result from the treatments. Poor ecological validity is where a test might accurately capture an impairment in stroke individuals (e.g., the line bisection test showing impaired spatial hemineglect; Edwards and Humphreys (1999)), but the measure being unrelated to any of the impairments that the patient reports as symptoms. Related to this point, a third criticism is that paper and pencil tests are often unable to detect the complexity of cognitive functioning, for example whereby a stroke individual reports difficulty in making dinner in a kitchen or walking down a street in a shopping area full of people. These difficulties are frequently reported by individuals with hemineglect, and these behaviours involve interactions between several cognitive functions including spatial attention, inhibition, executive function, and memory (etc.).

In this PhD thesis, we focus on hemineglect, which is a syndrome that results from a stroke, and is expressed in different sensorial modalities, in different frames of reference, and in different spaces (Pizzamiglio et al., 1989; Vallar, 1998). It has a high prevalence among stroke survivors, and the functional consequences of hemineglect significantly alter patients' autonomy and every-day life activities (Azouvi, 1996; Husain, 2008). There have been several attempts to explain this condition, but most explanations have only been successful at describing components of impairment (Posner & Petersen, 1990; Takamura et al., 2021), and not how all these components work together (i.e. missing the complexity of the condition). This lack of explanation may be in part due to the tests used to evaluate hemineglect, that lack an integrative cognitive approach. Advances in technology bring new possibilities to tackle the criticisms of paper and pencil tests, with immersive virtual reality (IVR) and serious games allowing for the development of controlled integrative cognitive testing that can mimic realistic interactions, giving new promise to enhance the quality of neuropsychological assessment. We aim to use this new technology to develop tests that investigate complex cognitive behaviour for stroke individuals with hemineglect (and hemiparesis), using a rich three-dimensional ecologically valid environment, with naturalistic responses, experimental rigour and psychometric properties.

In this PhD thesis, I will elaborate on the benefits of IVR and serious games in neuropsychological assessment, focusing on hemineglect. The first chapter, Chapter 1, will provide an overview of the relevant literature pertaining to neuropsychological assessment and associated technological methodologies. I will also provide a brief overview of the current understanding of hemineglect, although it should be noted that the aim of this PhD is not to add to the theoretical understanding of hemineglect (although at a later stage, the tests that we have developed during my PhD thesis may contribute to new understanding). Following Chapter 1, I present four empirical chapters (Chapters 2-5). These chapters are standalone papers intended for submission to international peer-reviewed journals. Chapter 3 is already published (Ajana et al. 2023), Chapter 5 published as a pre-print (Ajana et al., 2023), and Chapters 2 and 4 are submitted and currently undergoing journal peer-review. As each of these Chapters are intended to be journal papers, each contains a detailed literature review, that may cause overlap /

redundancy between Chapters. Furthermore, Chapter 1 is reduced as each of the empirical Chapters 2-5 has a comprehensive introduction. The final chapter, Chapter 6, summarises the research findings of the PhD thesis in relation to the PhD thesis objectives and the current body of literature.

It should be noted that this PhD thesis contains clinical research. It was initiated in November 2019, at the beginning of the COVID-19 pandemic period. Because of the measures taken in Belgium to restrict the spread of COVID-19, we had to adapt the research plan to accommodate the health restrictions, which included an initial inability to test any participants for research, and a much longer restriction for accessing hospital environments for research purposes. As a result, the first part of this doctoral research focused on developing immersive reality serious games. From an analysis of the literature, two virtual reality serious games were identified that would present test novelty and add to furthering the fundamental understanding of hemineglect. These serious games were named the Peach test, presented in Chapter 2, and the REASmash, presented in Chapters 3-5. The two tests were developed in parallel. The health restrictions were lifted during the mid-phase of my PhD, first allowing for the testing of healthy aged participants, where we focused on testing the feasibility of the serious games. Towards the end of the mid-phase of my PhD, clinical testing restrictions were lifted, allowing me to test the validity of the REASmash serious game. We focused on the REASmash because the feasibility analyses showed better results than those for the Peach test (which did not show all the predicted effects with the aged healthy participants). A secondary problem to note was the relatively reduced numbers of individuals having stroke after the COVID-19 pandemic. Together, these issues explain the relatively low numbers of patients recruited for the studies.

Chapter 1

General introduction

In this general introduction, I will perform a detailed review of current neuropsychological assessment and discuss the limitations with these current assessment methods. I will then introduce technology advances that can be applied to neuropsychological assessment, with a focus on virtual reality and serious games. I will then perform a brief review on Stroke, focused on hemineglect, followed by a review of Immersive Virtual Reality (IVR) and Serious Games (SG) for the neuropsychological evaluation of hemineglect. I will end with the PhD thesis objectives and outline of the thesis.

1. A brief introduction to neuropsychological assessment

Neuropsychology is a discipline that uses empirical-scientific methods to investigate correlates of brain, behaviour and cognition (Lezak et al., 2004; Vanderploeg, 2014). Traditionally, the discipline makes correlates between general brain conditions (e.g., dementia) or specific localised dysfunctional brain regions (e.g., inferior parietal damage) and behaviour / cognition (Costa, 1983; Howieson & Lezak, 2008; Vallar & Caputi, 2022). It traces its roots from the late 19th and early 20th centuries (Eling, 2019; Hartlage & DeFilippis, 1983) and includes research from prominent figures such as Paul Broca and Carl Wernicke who made significant contributions to the establishment of the field (Graves, 1997; McRae, 2005). Specifically, they identified distinct brain areas associated to specific language components of production and language comprehension, dispelling the concept of a generalised ‘language area’ of the brain, and instead identifying different areas of the brain for specific cognitive processes that can be used for language (Damasio, 1992; Mohr et al., 1978).

The development of neuroimaging techniques, such as electroencephalography (EEG) and functional magnetic resonance imaging (fMRI) diversified the domain of neuropsychology by providing new methods to investigate correlates between functional brain region activity (in a healthy brain) with cognition and behaviour. These methods also brought new value to traditional neuropsychology by increasing the quality of measures for structural abnormalities of the brain, allowing for greater precision for understanding the neural correlates of cognitive and behavioural dysfunctions that occur during specific tasks (Bigler, 2017; Bilder & Reise, 2019). Neuropsychologists embraced this technical advancement and used it to examine, more comprehensively, the relation between cognitive dysfunction and brain injury (Bigler, 1994; De Zubicaray, 2006).

Advances in neuropsychology assessment have also developed over the last 100+ years. One significant development in the discipline was created by the advent of standardized tests and assessment batteries (Casaletto & Heaton, 2017). This approach, that mainly relies on paper and pencil tests, is considered the common means for neuropsychological assessment (Rabin et al., 2016). It consists of administering a test to a representative sample of normative healthy participants within a population controlling for factors of age, sex, and other demographics (such as socio-economic status) that can influence cognition (confound variables). These data are then used to create norms that define the expected normal profile of performance for the given test. The norm is defined by a confidence interval of variance around the normative mean (for example, two-tail 95%), where upper and lower cut-off boundaries are defined. Individual scores (e.g., from a stroke individual) are then compared to these statistical norms to determine if the performance falls within the "normal" distribution, or outside of the cut-off boundaries, and indicating a statistically significant performance impairment.

Using documented and clinically relevant interpretation of scores, the abnormal scores are subject to further investigation, often across combined with other tests measuring related cognitions, to obtain a precise diagnosis (Crawford et al., 2007; Kane, 1991; Shenal et al., 2001). The Wechsler Adult Intelligence Scale (WAIS), and the Luria-Nebraska Neuropsychological Battery are examples of early neuropsychological assessment batteries (Golden & Freshwater, 2001; Wechsler & Kodama, 1949). The strength of the monothetic standardized test-based approach lies on its ability to identify individuals performing significantly below expectations based on objective norms. Furthermore, this approach can be used to monitor the evolution of the performance through a repetitive testing, to track improvements caused by spontaneous recovery or neurorehabilitation (Leposavić et al., 2010) (and compensating for practice effects by understanding the test-retest variability). Although, standardized paper and pencil tests are popular among clinicians, it is essential to recognize their limitations. In the following section, I will review the challenges and criticism that paper and pencil neuropsychological assessment methods have faced.

2. Neuropsychological assessment measures

Although the field of neuropsychology has evolved significantly over time, the main role of neuropsychologists is still related to detecting cognitive impairments and guiding differential diagnosis (Casaletto & Heaton, 2017). These tasks heavily rely on neuropsychology assessment measures that need to be carefully selected (Brooks et al., 2009). The weaknesses and strengths of these neuropsychology assessment measures, mostly related to their psychometric properties, direct the attractivity and practice choices of tests (Brooks et al., 2009; Sherman et al., 2011). The crucial psychometric properties for neuropsychological assessment are validity and reliability (Barr, 2001; Howieson, 2019; Sherman et al., 2011). Validity refers to the capacity of a test to measure the intended behaviour or cognition (Anastasi & Urbina, 1997). It encompasses various aspects of assessment validity, that can be classified into three broad categories: content-related, construct-related, and criterion-related (Anastasi & Urbina, 1997; Sherman et al., 2011). In this thesis, we investigated “concurrent validity”, which is defined as the degree to which results of a newly developed test align with a gold-standard practice accepted measure, and considered as the most important aspect of validity (Sherman et al., 2011). It is usually tested using correlation coefficient (Helmerhorst et al., 2012). Reliability is the extent to which a test is capable of providing stable and consistent results (Anastasi & Urbina, 1997; Sherman et al., 2011). Similarly to validity, reliability of a test is determined through the evaluation of different aspects of reliability, including internal, alternate form, interrater reliability, and test-retest (Anastasi & Urbina, 1997; Sherman et al., 2011). In this thesis, test-retest reliability of the developed test was investigated. It is commonly estimated by calculating the correlation coefficient between scores of a test administered in two times with the same participants (Shou et al., 2022). Concurrent validity and test-retest reliability are considered as major influences in choosing which test to use in practice (Calamia et al., 2013; Dikmen et al., 1999)

In the current clinical practice, most standard assessments of an individual's cognitive functioning is made through conventional paper and pencil neuropsychological tests that are administered one-on-one (patient-clinician) in a clinical or a laboratory setting by a trained psychometrician (Rabin et al., 2016; Strauss et al., 2006; Sullivan & Bowden, 1997). Despite their popularity, standardised assessments have received several criticisms. For example, many of these tests are considered old, and in some cases, the original principles on which they were developed are now outdated (Kessels, 2019; Ratcliff & McKoon, 2022). It has also been suggested that some of these tests are becoming too familiar to the public, since they can be easily found on internet (Howieson, 2019), or their principals have been embedded into popular games (e.g., the card game Uno that uses similar principles to the Wisconsin card sorting test; Berg (1948)). Furthermore, many tests have been developed to assess severe cognitive dysfunction, for example following stroke, making them less sensitive to milder and widespread cognitive impairments (Horowitz et al., 2019; Merten et al., 2007;

Treviño et al., 2021). Indeed, neuropsychological tests have been facing issues of sensitivity and specificity (Parsons, 2011).

In addition to the aforementioned limitations, the ecological validity of paper and pencil neuropsychology tests have been extensively discussed in the scientific literature (Howieson, 2019). Ecological validity refers to the extent to which an individual's performance in neuropsychological assessment corresponds to their performance in real-world activities (Holleman et al., 2020; Schmuckler, 2001). Paper and pencil tests are considered to have limitations of ecological validity that arises from their often simplistic nature, and their controlled assessment deviating from the real-world demands (Howieson, 2019). Moreover, they are frequently administered to test one cognition at a time, and in isolation from other factors or distractors that are outside of the test demands (Sbordone, 2008). These controlled settings allow a standardized administration and scoring, but at the detriment of replicating the complexity of real-world cognitive functioning. Another factor that influences the paper and pencil tests ecological validity is related to the lack of consensus regarding the constructs measured by tests (Chaytor & Schmitter-Edgecombe, 2003; Guilmette et al., 2020). Burgess et al. (2006) noted that traditional neuropsychological tests were designed to assess cognitive "constructs" such as cognitive flexibility, or inhibition response, without considering the capacity to predict real-world activities. Furthermore, disagreement on what the tests actually assess, and the labels applied to the cognitive functions pose problems on their utilization and scoring (Chaytor & Schmitter-Edgecombe, 2004; Spooner & Pachana, 2006).

Another limitation of current neuropsychological assessment tests is that they are largely proposed in only few languages, and contain stimuli that can be specific to particular cultural codes, making them inaccessible to a wider and more diverse populations (Daugherty et al., 2017). The high cost of these tests can further limit their accessibility, specifically in resource-limited settings (e.g., small clinics, regions with limited funding and/or healthcare services) (Fernández & Evans, 2022). This high cost can be associated to the time and resources of administration. Conducting a neuropsychological assessment using paper and pencil tests can be time consuming (Collie & Maruff, 2003). The administration of the tests requires a trained specialized clinician to administer them on a one-to-one basis with the patient, and then score and interpret the data, as well as using a dedicated space and equipment to run the testing sessions (Camara et al., 2000). These costs of personnel time and facilities can pose serious challenges for less well funded health care systems.

To summarize this section, traditional paper and pencil neuropsychological assessment tests have played a crucial role in evaluating the performance of cognitive functions in individuals, bringing benefits of good psychometric properties and statistical comparison to norms. However, these paper and pencil assessment have recently faced substantial criticisms regarding issues of validity (based on current understanding), ecological validity, a lack of sensitivity or complexity in evaluation, cultural specificity, and high resource demands (costs of test, time demands of specialised personnel and use of clinical space). Recent innovative assessment approaches and sophisticated technological advancement have allowed for many of these criticisms to be addressed. In the next section, I will present the literature about how new advancements benefit neuropsychological assessment, and what are some of the technologies that can be applied to the field of neuropsychology.

3. Technological advances applied to neuropsychological assessment

The modern society is immersed in rapid technological advances (Horst, 2020; Livari et al., 2020; Rosenberg et al., 2009). For example, 25 years ago, it was rare that individuals owned a personal computer or a mobile telephone. Today however, individuals are surrounded by new technologies, such as advanced smart phones, tablets, multiple computer technologies, and artificial intelligence, which are undeniably present and used in most daily life activities (Abbasi et al., 2021; Beauvisage, 2009; Zhang & Lu, 2021). This ongoing and rapid technological progress has been enthusiastically embraced by several sectors (Alam, 2021; Mishra et al., 2022). For example, in medicine, many different diagnosis equipment now runs on integrated digital platforms. Moreover, technologies such as virtual and augmented reality are expanding, and have been applied to many different fields such as anatomical and physiological education (Kamphuis et al., 2014; Maramba et al., 2019). Technology advancement has also enhanced neuroscience methods, with advances in brain imaging measurements, which have led to many further innovations, such as the development of brain computer interfaces that can be used to operate wearable or integrative robotic devices (Mudgal et al., 2020).

In neuropsychology, an increasing number of researchers and clinicians have been adopting new technological approaches to neuropsychological assessment. This started with computerised assessment, which brought advances in validity (with tests based on current scientific understanding), reliability (with test stimuli randomised, reducing practice effects) and cost-effectiveness (with less need for official paper score sheets and because computerised tests can self-score and analyse data, reducing the work of the clinician) (Germine et al., 2019; Marques-Costa et al., 2022; Parsey & Schmitter-Edgecombe, 2013). The advantages of using technology in neuropsychological assessment have been demonstrated and discussed in several studies (Bauer et al., 2012; Spreij et al., 2020). Furthermore, the development and use of recent affordable virtual reality methods have added to these advancements, with additional benefits provided by increasing task complexity and improving ecological validity (Neguț et al., 2016; Parsons, 2011; Pieri et al., 2023). In the following section we discuss the use of virtual reality in neuropsychological assessment, and demonstrate its role in addressing the limitations of the traditional paper and pencil neuropsychology assessment tests.

4. Virtual reality

4.1 What is virtual reality?

Virtual reality (VR) refers to a computer-generated immersive experience, that simulates two-dimensional (2D) or three-dimensional (3D) environments (Alqahtani et al., 2017; Wohlgenannt et al., 2020). The virtual environment can be explored using visual presentation (2D stimuli) or a head-mounted display devices (3D stimuli) (Buttussi & Chittaro, 2017; Havig et al., 2011). Interactions can also be generated through audio and haptic feedback, increasing the sense of presence and engagement with the task (Coelho et al., 2006; Mach et al., 2019). Computer-generated environments can replicate real-world settings and interactions, where users can navigate through the space, interact with various objects, and engage in different activities (Dionisio et al., 2013; Zheng et al., 1998).

VR can be categorized into two main types: Immersive VR (IVR) and non-immersive VR (non-IVR) (Suh & Lee, 2005). In IVR, users are fully immersed in the generated-environment. It typically involves wearing head mounted display that contains two slightly offset screens, one for each of the user’s eyes, and blocks any physical surrounding or distractions. The user uses controllers to directly interact with stimuli in the virtual environment (Jennett et al., 2008; Sveistrup, 2004). Users can experience a full immersion and a sense of presence through synchronisation of visually and audibly rich environments (Walsh & Pawlowski, 2002). The difference for non-IVR from IVR, is that the virtual experience is not fully blocked from the physically surrounding, so that users remain aware of their real environment while engaging with the virtual content. Also, non-IVR can only currently use 2D stimuli, whereas IVR can consist of 2D or 3D stimuli (by use of the offset screens). In non-IVR, the virtual content is usually displayed on screen, and the users interact with it through a peripheral keyboard, mouse, or joystick device (Bevilacqua et al., 2019), whereas in IVR, the use can interact with the actual stimuli. In this thesis, we focused on the application of IVR to neuropsychological assessment, driven by several advantages over paper and pencil methods of evaluation. We will elaborate these issues in the next section.

4.2 What does immersive virtual reality bring to neuropsychological assessment?

IVR holds the potential to enhance the quality of neuropsychological assessment and address many of the shortcomings of paper and pencil tests (Diaz-Orueta et al., 2020; Gómez-Cáceres et al., 2022; Khan et al., 2003; Rizzo et al., 2004). It allows the simulation of real-world environments, using objective behavioural measures that can be challenging, yet presented in a safe, ecologically valid context (Bashiri et al., 2017; Rizzo & Buckwalter, 1997). Using IVR, researchers and clinicians can recreate complex and dynamic scenarios that simulate real-world interactions, thereby assessing cognitive functions in complex environments reflecting everyday life cognitive demands, while maintaining experimental control over the stimuli and measures (Pratt et al., 1995; Schultheis & Rizzo, 2001). These controlled stimuli can be presented in several sensorial modalities (e.g., haptic, visual, or auditory) (Parsons & Duffield, 2020).

A growing body of evidence suggest the roles that IVR could play in improving neuropsychological assessment ecological validity (Campbell et al., 2009; Kothgassner & Felnhofer, 2020; Parsons, 2011; Spooner & Pachana, 2006). This is due to the capacity of IVR technology to create situations that more closely resemble real-world interactions, with precise stimuli, and dynamical control modalities, as discussed above (Parsons, 2011, 2015). Additionally, IVR increases motor activation, as users can interact with the surrounding virtual environment and objects (Bohil et al., 2011). These features result in creating “a sense of presence” that has been shown to improve ecological validity (Kothgassner & Felnhofer, 2020; Long et al., 2023).

It is essential to reiterate our ecological validity definition used here in this thesis. In general, we define ecological validity as the extent to which an outcome obtained in a controlled experimental setting corresponds to the outcomes observed in a naturalistic environment (Holleman et al., 2020; Tupper & Cicerone, 1990). Within the neuropsychological assessment context, our definition of ecological validity corresponds to the extent to which performance in a test corresponds to real-world environment performance (Holleman et al., 2020). IVR allows the development of assessment settings for measuring performance replicable of real-world situations (Parsons, 2015). These IVR settings therefore simulate actual real-world environments, such as a supermarket (Grewe et al., 2013; Zygouris et al., 2015), classrooms (Rizzo et al., 2009), kitchens (Allain et al., 2014; Giovannetti et al., 2019), or farms (Eisapour et al., 2020). However, the setting aspect is considered secondary to the tasks performed within the virtual setting, with the similarity between performance responses being the more important factor of ecological validity. Rizzo et al. (2004) argues that the “ecological value” of an IVR-based test comes from its tasks that must require the same performance as in real-world functioning. In this thesis, we developed IVR serious games tests that involve tasks similar to real-world activities (i.e., visual search and responding directly to the target in the REASmash), in environments close to real-world settings (i.e., kitchen and a garden).

IVR devices incorporate various sensors that enable the acquisition of different measures, thereby facilitating more precise and comprehensive behavioural analyses (Pieri et al., 2023; Rizzo et al., 2004; Seo et al., 2017). For instance, the controllers within IVR setup allow direct responses to stimuli, and the tracking of these interactions extends to the measurement of motion data (e.g., head orientation and hand position tracked over time) (Barnard, 2019). Studies demonstrated that movements performed within a virtual environment exhibit kinematic resemblance to those executed in real-world scenarios, thus highlighting the usefulness of IVR for clinical assessment (Arlati et al., 2022; Viau et al., 2004). The potential of IVR to yield kinematic measures represent a significant advancement, as it can provide distinctive “motion signatures” of performance or digital biomarkers (Miller et al., 2020). These biomarkers can be used to identify specific cognitive impairments, thereby augmenting the diagnostic precision and scope of neuropsychological assessment (Cavedoni et al., 2020).

Furthermore, this confluence of IVR and kinematic analysis brings increased test validity to diagnosis evaluations, with for example, hemineglect defined by congruent effects in omissions, response time and performance kinematic variables (Broeren et al., 2007; Montedoro et al., 2018). In this thesis, we measured two kinematic variables: (1) mean velocity (MV) and (2) coefficient of variance of velocity (CV). Mean velocity refers to the average speed at which an action is performed over a specific time interval. It was measured in this thesis by dividing the total distance travelled by the time taken to cover that distance. Coefficient of variance of velocity indicates the relative variability or dispersion of speeds within a set of data. It was calculated in this thesis by dividing the standard deviation of the instantaneous speed values by the mean speed. The coefficient of variance of speed provides insights into the extent of variability in speed values for a given response, and helps to quantify how much the speed deviated from the mean speed (Alt Murphy & Häger, 2015; An, 1984). These kinematic analyses can provide important insights for diagnosing neuropsychological deficits (Garre-Olmo et al., 2017; Scherder et al., 2008). For example, Seo et al. (2017) tested a group of healthy individuals and individuals with mild cognitive impairment on two daily living tasks in a virtual environment, and measured their behavioural kinematic performance (i.e., body movement trajectory, time to completion and speed), and on conventional neuropsychological tests. They demonstrated that the inclusion of kinematic measures significantly enhanced the differentiation between healthy individuals and those with mild cognitive impairment when compared to using only neuropsychology test scores.

Having control over virtual stimuli and the flexibility of the environment can be considered as a major advantage of IVR (Rizzo et al., 2009). Indeed, it allows the researchers or clinicians to customize the measurements and stimuli presentation according to the patients' cognitive abilities and needs (Bohil et al., 2011; Jin et al., 2020). This can be very beneficial, for example by incrementing the difficulty and challenge of the tasks within the virtual assessment tests. This modularity allows the personalization or individualization of tests that match the ability of the individual, while maintaining consistency in diagnosis measures (Neguț et al., 2016; Schultheis & Rizzo, 2001; Schultheis et al., 2002). This allows the same test to be used with acute stroke individuals with major impairments, and later, with the same individuals in the chronic phase, following significant recovery, and perhaps having some minor impairment remaining.

Another big advantage of IVR is that the cost of the equipment is decreasing, and readily available in high street shops (Hamad & Jia, 2022). In this thesis, we used the Oculus Quest 2, running from a tablet (with no computer needed). The equipment costs were approximately 600 euro, and after more than three years of testing, the devices remain fully functional. This places the cost of the technology at a significantly lower level than traditional paper and pencil tests, allowing many clinics and healthcare facilities to purchase this new technology (Weiss & Katz, 2004). Furthermore, as the Oculus Quest 2 and tablet runs off a battery (lasting for at least 4 hours of testing), the clinical tests can be used in the 'field' (outside of clinic), making these tests even possible to use in remote areas such as in central Africa where electricity supply can be variable.

A final advantage of IVR is the potential to enhance the motivation of the users, and their engagement with the evaluation procedures, thereby improving the neuropsychological assessment reliability and validity (Bell et al., 2020). This is made possible through the implementation of video games elements that we discuss in the next section. In the scientific literature, this approach is commonly referred to as “serious games” (Doumas et al., 2021b; Dubbels, 2013; Krath et al., 2021).

4.3 Serious games in immersive virtual environments

Serious games, also described as “gamified tasks”, are defined as interactive computer-based software that has the intention to facilitate “serious” learning, in addition to entertainment (Lumsden et al., 2016; Ritterfeld et al., 2009). They embody elements inherited from entertaining games, such as featuring challenging objectives, presented within fun and enjoyable scenarios, and in an engaging environment. They may additionally incorporate scoring mechanisms to enhance the interactive and motivational experience (Bergeron, 2006; Wattanasoontorn et al., 2013), with better performance leading to increased points / prizes. Importantly, by facilitating the motivation of the user, they encourage user engagement with learning material while the game is played (Jenkins et al., 2009).

Serious games are very popular in several fields, such as education (Zhonggen, 2019), medicine (Graafland et al., 2012; Olgers et al., 2021), and rehabilitation (Doumas et al., 2021b). Their use has recently been expended to neuropsychological assessment (Mezrar & Bendella, 2022; Tong et al., 2016; Valladares-Rodríguez et al., 2016). They are regarded as a means which can prevent dropout and support compliance with the assessment procedures (Shute & Rahimi, 2017). They can be programmed and integrated within different technologies, for example in IVR (Kato & de Klerk, 2017).

4.4 What challenges do serious games in virtual reality encounter?

Notwithstanding the various advances that IVR brings to neuropsychological assessment, there remains several limitations (Jin et al., 2020). These limitations confront reluctance in terms of technology acceptability from neuropsychology clinicians (Schmand, 2019). It has been reported that neuropsychologists are slow to adapt new technology into their practices, and have historically showed a strong preference for conventional paper-and-pencil tests (Miller & Barr, 2017; Parsons, 2011). The technical complexity required to build virtual environments is considered as one main limitation of IVR (Hamad & Jia, 2022; Huang & Alessi, 1998). Indeed, the development of virtual environments rely on skilled computer programmers and complex 3D modelling software, both of which can be regarded as costly (Huang & Alessi, 1998). Additionally, despite the sophistication of the existing software, certain virtual interactions remain constrained, and the graphic realism has not yet been fully realized (Gandhi & Patel, 2018; Pieri et al., 2023; Ruthenbeck & Reynolds, 2015).

Current application of IVR technology into clinical practice lacks standardization, and few guidelines exist (LaRocco, 2020; Timmerer, 2017). This is problematic as developers currently interact with different interfaces with specific functionalities, making transferability of IVR applications between devices technically difficult and time-consuming (Hamad & Jia, 2022; Krauß et al., 2021). This can affect the user experience, insofar as end-users may find it challenging to switch between devices due to the differences in interaction paradigms (Men et al., 2017). Furthermore, the lack of guidelines makes it difficult to troubleshoot bugs and obtain support in case of an issue during the development or usage of IVR applications (Hamad & Jia, 2022).

Another technical issue of IVR to consider is related to the field of view covered by the headset (Kishishita et al., 2014). Field of view is defined by the size of a visual field processed instantly, and it is expressed in degrees (Jang et al., 2016). The current headsets can cover 20 to 180 degrees of horizontal field of view (Ragan et al., 2015). The Oculus Quest 2 that was used in this thesis covers 97 degrees of horizontal and 93 degrees of vertical field of view (Quest, 2023). This may be considered as very narrow when compared to the human visual system that involves a binocular field of view exceeding 210 degrees horizontally and 150 degrees vertically (Strasburger, 2020). Therefore, the IVR headsets do not fully cover the human field of view and only allow the display of information in part of the periphery (Trepkowski et al., 2019). This limited visual field in IVR may have an impact on tests of spatial attention, as exploratory behaviour in hemineglect is known to be modulated by the size of the visual field (Karnath & Niemeier, 2002).

Psychometric rigor is another limitation that neuropsychological tests in IVR face (Borghesi et al., 2022; Morel et al., 2015; Pieri et al., 2023). While it has been demonstrated that IVR-based assessment tests have high construct validity (Armstrong et al., 2013; Borgnis et al., 2022; Ouellet et al., 2018; Plotnik et al., 2017), there are number of other important psychometric issues that are not often addressed. These include reliability (test-retest), accuracy (sensitivity), and user experience (Borgnis et al., 2022). Reliability is an important psychometric component, as clinicians monitor the longitudinal progress of patients (Urbina, 2014; Yen & Lo, 2002). Therefore, it is essential for these tests to yield excellent result consistency on the same sample across different points in time (Guttman, 1945). For example, a systematic review focusing on VR-based tests designed for the evaluation of executive functions (Borgnis et al., 2022), found that among one hundred studies, only one included a test-retest reliability measure (Plotnik et al., 2021).

The second psychometric component is accuracy, relying on sensitivity/specificity indexes (Lezak, 1995; Urbina, 2014). When choosing a neuropsychology test, it is important to consider these indexes to ensure that individuals with a cognitive condition are accurately identified (sensitivity), while those without the condition are not subject to an unnecessary neuropsychological intervention (specificity) (Glaros & Kline, 1988; Lalkhen & McCluskey, 2008). However, a meta-analytic review investigating IVR-based assessment test sensitivity revealed that although tests did display sensitivity, the level of sensitivity was only moderate, and frequently, there was no measure of specificity (Neguț et al., 2016).

The last critical component that presents an additional challenge for IVR-based neuropsychology assessment tests is the user experience (Borghesi et al., 2022). Several studies have highlighted the importance of evaluating user experience when developing IVR-based tests to establish a framework that ensures usability, usefulness, and positive interactions between the user and the IVR interface (Pedroli et al., 2013; Sauer et al., 2020; Spreij et al., 2022; Tuena et al., 2020). However, only few studies include user experience measurements into their protocols (Borgnis et al., 2021; Shen et al., 2020; Voinescu et al., 2019), sustaining the belief that IVR may not be suitable for some participants, most typically aged participants.

4.5 Summary

The use of IVR and serious games bring several advantages compared to paper and pencil tests. They can bring improved ecological validity and reliability, different and sensitive measures, and interactive and simulating environments, improving the clinical and research evaluation methods of neuropsychology. In recent years, a growing number of researchers have begun exploring the application of serious games in IVR for the neuropsychological assessment with individuals having cognitive dysfunctions due to stroke.

5. Stroke: Definition and consequences on cognitive functioning

Stroke has been clinically defined as the sudden emergence of symptoms indicating localized neurological dysfunction that lasts more than twenty-four hours (Coupland et al., 2017; Hankey, 2017). It occurs when the blood supply to the brain is disrupted, either due to a blockage (ischemic stroke), or bleeding (haemorrhagic stroke) (Grysiewicz et al., 2008; Shiber et al., 2010). Several risk factors can increase the likelihood of experiencing a stroke, including non-modifiable risks such as heredity factors, age, or gender, and modifiable risks, such as smoking, physical inactivity, and diabetes (Boehme et al., 2017; Elkind & Sacco, 1998).

According to Feigin et al. (2021), stroke remains the second leading cause of death and disability, and can cause a combination of motor and cognitive impairments (Mansfield et al., 2018; Rimmele & Thomalla, 2022). For example, it has been reported that 24% to 96% of post-stroke individuals can experience cognitive impairments (Douiri et al., 2013; Pérez et al., 2011). Clinical studies have indicated that attention, executive function, and speed processing are the most prevalent cognitive impairments (Aam et al., 2020; Cumming et al., 2013; Nys et al., 2007). Moreover, the disturbance of spatial attention causes a condition known as hemineglect, which can be observed in approximatively 23% of first stroke acute patients (Heilman et al., 1987; Kamtchum Tatuene et al., 2016; Pedersen et al., 1997). Hemineglect can also be associated with a non-spatial (distractor inhibition) deficits (Robertson, 2001; Takamura et al., 2021).

5.1 Hemineglect: A complex condition

Hemineglect, also referred to as hemispatial neglect, neglect, or unilateral spatial neglect, is a neuropsychological disorder following a unilateral brain lesion (Heilman et al., 1987; Vallar, 1998). Individuals who suffer from hemineglect have difficulties attending or responding to stimuli presented in the space opposite or contralateral to their lesion (Buxbaum et al., 2004; Demeyere & Gillebert, 2019; Kerkhoff, 2001). It frequently manifests following a right-hemisphere stroke (though a left-hemisphere stroke can also cause hemineglect) (Husain, 2008).

Hemineglect has been explained by several hypotheses, one of which suggests that hemineglect follows a disturbance in directing spatial attention (Corbetta et al., 2005; Vallar, 1998). Spatial attention is defined as the process that allows the selection of a stimulus on the basis of its spatial location (Vecera & Rizzo, 2003). Individuals suffering from hemineglect may fail to disengage attention from ipsilesional space and shift it contralesionally to the neglected space (Bartolomeo & Chokron, 2002b; Losier & Klein, 2001). Posner and Petersen (1990) explained this phenomenon through a model that suggest that spatial attention can be separated into three steps: (1) alertness, (2) disengagement from the current target, and (3) engagement to a new target. Anecdotally, Posner et al. (1984) studied the influence of peripheral uninformative and central informative cues on the detection of peripheral targets on the left and right side of the visual field in parietal post-stroke individuals. They showed that these individuals were slower to responded to a target in the contralateral compared to ipsilateral side of space when preceded by an ipsilateral cue. This indicated that the parietal post-stroke individuals were unable to disengage their attention from the ipsilateral space (Posner et al., 1984).

An alternative explanation of hemineglect by Kinsbourne (1970) suggests that the attentional bias, with excessive orientation towards the ipsilesional space, is due to an imbalance in the interplay of two opposing mechanisms controlled by the right and left hemispheres. Each of these mechanisms directs attention towards the opposite side of surrounding space (Karnath, 2015; Kinsbourne, 1970; Koch et al., 2008). In hemineglect, where there is an impairment in the activation of one hemisphere, the direction of attention is shifted, causing a focus on the ipsilesional space (Karnath et al., 1998; Kinsbourne, 1970). Complementary to this proposal, Heilman et al. (1994) proposed that each hemisphere has an independent attentional system. The right hemisphere is dominant and guides attention towards both sides of space, whereas the left hemisphere influences attention specifically to the right side of space (Heilman et al., 1993; Heilman et al., 1994). In case of a right hemisphere lesion, left hemineglect occurs. This is due to the left hemisphere's inability to compensate for the difficulty in directing attention towards the left side of space. Conversely, a left lesion is less likely to result in right hemineglect, as the right hemisphere remains functional and capable of orienting attention towards the right side of space (Heilman et al., 1994; Smania et al., 1998).

Independent of the attentional theory of hemineglect, all models have predicted that an increase in attentional load would lead to a performance deterioration among hemineglect individuals (Heilman et al., 1984; Kinsbourne, 1987). Several studies demonstrated the impact of factors such as target saliency (Aglioti et al., 1997; Kaplan et al., 1991; Weintraub & Mesulam, 1988), distractor similarity (Riddoch & Humphreys, 1987) and distractor number (Chatterjee et al., 1999; Neppi-Mòdona et al., 2002) on hemineglect. This combination of spatial and non-spatial deficits appears to be present and common in many individuals with hemineglect (Buxbaum et al., 2004; Chechlacz et al., 2016). The lesion sites underlying hemineglect involve several brain regions including non-spatial networks (Lemée et al., 2018). This is corroborated by rehabilitation studies, which have shown that interventions solely focused on spatial attention in hemineglect do not achieve complete success, whereas programs that addressed the spatial and non-spatial attention processes were more successful at restoring the perceptual bias observed in hemineglect (Manly et al., 2002; Striemer et al., 2013).

Takamura et al. (2021) investigated the pathological structure of hemineglect using multivariate analysis and machine learning algorithms and demonstrated that hemineglect constituted four principal aspects: arousal and attention state, exogenous attention, spatial working memory and attention bias. These different roles have already been explained in the literature by different models of hemineglect. The role of arousal was explored and defined by Heilman et al. (1978), the role of sustained attention was explored and defined by Robertson et al. (1997) and Rengachary et al. (2011), and the role of spatial working memory was explored and defined by Toba et al. (2018). There have also been studies proposing exogenous attention as a component of hemineglect (Behrmann & Moscovitch, 1994; Losier & Klein, 2001). These non-spatial components of hemineglect have been said to explain its persistence and severity (Corbetta & Shulman, 2011; Robertson, 2001).

It is noteworthy to state that the nomenclature of non-spatial attention has extensively been discussed in the scientific literature (Chechlacz et al., 2016; Dale et al., 2008; Husain, 2008). A consensus suggests that non-spatial attention encompasses a set of general mechanisms that regulate the dynamics of cognition and action (Diamond, 2013; Miyake & Friedman, 2012). These include: (1) inhibitory control, (2) working memory, and (3) cognitive flexibility (Diamond, 2013; Miyake & Friedman, 2012). In this thesis, we focused on the inhibitory control process, specifically “distractor inhibition”. We defined this as the ability to control attention, being able to attentionally select the target, and inhibit attention to the irrelevant *(distractor)* stimuli (Posner & DiGirolamo, 1998; Theeuwes, 2010).

To sum up, hemineglect is a complex condition that encompasses heterogenous symptoms, and has a high prevalence rate. The doctoral studies presented here will focus on the expression of spatial attention deficit in hemineglect within the peri- and extra-personal spaces (Chapter 2), as well as the expression of both spatial and non-spatial (distractor inhibition) attention in hemineglect (Chapters 3, 4 and 5).

5.2 Hemineglect: Different domains and frames of reference of a complex condition

Hemineglect is a heterogenous syndrome that can be expressed in different sensory, representational, and motor domains (Vallar, 1998). Sensory hemineglect refers to the difficulty to respond to stimuli presented in the contralateral space to a lesion that does not involve deafferentation or focal cortical sensory damage (DeVore et al., 2017). It can occur in all the sensory modalities (visual, auditory and tactile) (Plummer et al., 2003). Representational hemineglect is defined as a mental imagery deficit, and is thought to be caused by an impairement of the attentional-exploratory process (Bartolomeo et al., 2005; Bartolomeo & Chokron, 2002a; Guariglia et al., 2005). It is uncovered by asking patients to explore and mentally describe a given space (i.e., such as a town square) (Bisiach & Luzzatti, 1978). According to Guariglia et al. (2013), this deficit is more frequent than previously reported. A lack of reliable assessment has contributed to the challenge of promptly identifying representational hemineglect (Guariglia et al., 2013; Salvato et al., 2014).

Motor hemineglect can be characterized by the underuse of the contralateral limb to the brain lesion (Bartolomeo, 2021). The failure to generate a movement is not considered a result of a motor deficit, as when solicited, the patient can move the limb (Rode, Pagliari, et al., 2017). Coulthard et al. (2008) suggested that it could be a consequence of the lateralized inhibition deficit, causing a deficit in the selection of the limb to make the response. Further literature suggests that motor hemineglect can be distinguished into two types of manifestations (Sampanis & Riddoch, 2013). In first type, as described above, motor heminegelct is considered unrelated to deficiencies in strength, reflexes, dexterity, or sensory perception (Laplane & Degos, 1983). It can be characterized by a non- or weak-participation of the contralesional limb in bimanual tasks, by an absence of hand spontaneous gesturing while speaking, an absence of arm swinging while walking, a lag in leg movement while walking, and finally, by the absence of spontaneous placing reaction (Laplane & Degos, 1983; Sampanis & Riddoch, 2013). The second type, known as premotor hemineglect and directional hypokinesia, refers to defected movement of an ipilesional body part to the impaired hemispace (Saevarsson, 2013). It is distinguished by impaired kinematics, such as delayed movement initiation, slowness in movement execution (i.e., movement time, peak velocity), reduced spatial exploration and amplitude, and an inability to sustain action (Saevarsson, 2013; Sampanis & Riddoch, 2013; Siekierka-Kleiser et al., 2006).

Hemineglect can manifest in distinct spatial domains (Pizzamiglio et al., 1989). Most frequently, the hemineglect occurs within the immediate proximity of the patient, in their peri-personal space (Thomas & Sunny, 2017; Vallar, 1998). In this context, hemineglect patients suffer an impaired awareness and inattention in the contra-lesional side of space within reach, resulting in difficulties in tasks requiring interactive responses to the presented stimuli (Caggiano et al., 2014; Varnava et al., 2002). Conversely, hemineglect can also extend outside of the immediate reach of the patients, encompassing what is termed as extra-personal space (Vallar, 1998). This form of hemineglect involves an impaired awareness and inattention to stimuli presented in the contra-lesional side of a more distant space (Bisiach et al., 1986; Vallar, 1998). Patients with extra-personal space hemineglect might face difficulties in activities such as navigation, and exploration of surroundings located in their neglected extra-personal space (Bjoertomt et al., 2002; Husain, 2008; Pizzamiglio et al., 1989).

Hemineglect can also simultaneously or independently disturb different spatial reference frames (Farah et al., 1990; Plummer et al., 2003; Rode, Fourtassi, et al., 2017). Patients with hemineglect can face difficulties perceiving stimuli in their contra-lesional space in reference to their viewpoint (Mozer, 2002a; Vallar, 1998). This viewer-based or egocentric frame of reference is determined by the mid-sagittal plane of the gaze, head orientation, and/or torso (Bisiach et al., 1997; Farah et al., 1990). Hemineglect can also be expressed in relation to objects. In this object-centric or allocentric frame of reference, the frames are coded in respect of the object features (Rorden et al., 2012; Vallar, 1998), with the patient neglecting to perceive the contra-lesional side of each object.

5.4 Hemineglect: The impact of an avatar's presence on a complex condition

The spatial environment is typically coded with respect to an individual's own perspective or point of view (i.e., egocentric reference). However, in situations involving others, individuals tend to favour the perspective of those around them when describing a scene (Mainwaring et al., 2003; Samson et al., 2010). Even without direct communication, the mere presence of another person can lead to a shift in perspective towards the other (Tversky & Hard, 2009).

Research shows that hemineglect can be influenced by these shifts in perspective. Bisiach and Luzzatti (1978) demonstrated that two individuals with hemineglect were unable to recall details from the left side of a familiar environment when asked to remember from memory. However, when these two individuals changed their imagined perspective to the opposite position of where they stood, they were then able to recall and describe the left-sided details that they could not remember initially. In a similar study, Della Sala et al. (2004) showed that individuals with representational hemineglect, who were instructed to recall stimuli from a scene from both their own perspective and from an opposite perspective, struggled to remember stimuli presented on the side of the visual field that was opposite to their chosen perspective (either own or opposite). This indicated that their hemineglect could be related to the spatial positioning of the stimuli relative to their represented perspective. In this thesis, we aimed to investigate this effect using the presence of an avatar, which we predicted would prompt a shift of perspective, impacting the hemineglect (Chapter 2).

5.5 Hemineglect: Neuropsychological assessment of a complex condition

A precise and valid assessment of hemineglect is important, as it orients clinicians towards the most appropriate treatment methods for patients, and has an influence on prevalence estimation, functional outcome estimation and likely neural correlates. Given that hemineglect is a complex heterogenous syndrome, a thorough assessment is needed to define the degree of severity and exhibited sub-types (Azouvi et al., 2002; Evald et al., 2021; Plummer et al., 2003). There is no single gold-standard assessment used for the diagnosis of hemineglect, but instead, at least 60 different measures can be used for diagnosis of the different sub-forms of the condition (Bowen et al., 1999; Menon & Korner-Bitensky, 2004). The most common hemineglect assessment methods used in clinics involve paper and pencil tools. For example, the various forms of the line bisection test requires the estimation and indication of the midpoint of a horizontal line presented on a piece of paper placed in front of the participant (Friedman, 1990). If the participant marks the line biased towards the ipsilateral side from their lesion, they are 'neglecting' the contralateral extent of the line and perceiving the line to be shorter in length.

A second popular method of assessment is cancellation tests. They involve the participant searching for several targets presented among distractors on a piece of paper. They are instructed to mark the targets. There are several versions of these cancellation tests that manipulate the distractor types to modify test difficulty. Most of these tests’ diagnosis egocentric hemineglect. However, some tests can simultaneously diagnose the egocentric (space) and allocentric (object) forms of hemineglect (e.g., the apples test (Bickerton et al., 2011) and the broken hearts test (Demeyere et al., 2015)). For example, in the broken hearts’ test, full heart targets are placed among broken heart distractors, some broken on the left side and some broken on the right side. If a patient has a right lesion and correctly finds the targets on the right side of space, but less so on the left side of space, and they do not mark the distractors, they are diagnosed with egocentric spatial hemineglect. However, if they mark all the targets, and distractor items containing a gap on the left side, they are diagnosed with allocentric (object based) hemineglect. Another common test involves figure drawing or copying, such as clocks, or geometric shapes (Friedman, 1991). Evaluation of the drawings lack sensitivity, reliability and ecological validity (Bailey et al., 2004; Plummer et al., 2003), but they can be used to show egocentric and allocentric forms of hemineglect by qualitative assessment (e.g., with the contralateral side of the drawing or the contralateral side of each object neglected and not copied).

5.6 Summary

In conclusion, stroke is a leading cause of worldwide disability that causes several complex cognitive impairments, including spatial and non-spatial (distractor inhibition) attention deficits associated with the condition of hemineglect. Although there are several clinical tests that are used for diagnosis, these tests are mostly paper and pencil tests, and they suffer from the problems discussed in Section 2 of this introduction. This highlights an urgent need for innovations in neuropsychological assessment methods, using new technology such as IVR to combat the current diagnosis test limitations. In the subsequent section, we highlight studies that have contributed to the development of new assessment methods using IVR serious games.

6. IVR Serious game approaches for hemineglect

Researchers have now recognized the advantages that IVR serious games bring to the assessment of hemineglect within the field of neuropsychology, with the number of studies exponentially increasing on this subject over the past twenty years (Pieri et al., 2023). Valladares-Rodríguez et al. (2016) denoted four approaches to developing serious games in IVR for neuropsychological assessment. The first approach consists of adapting an existing game to neuropsychological measurement. Measures are embedded in the parameters of the existent game that can be used to identify the neuropsychological condition (e.g., hemineglect). For example, Tong et al. (2016) modified the well-known ‘whac-a-mole’ fairground game to measure changes in spatial cognitive responses by implementing a calibration system and measuring response accuracy, response time and motor coordination. According to Valladares-Rodríguez et al. (2016), this approach demands a good recognition of the cognitive processes involved in the existent game features.

The second approach proposes a computerized modification of existing tests, such as a digital translation of a classic paper and pencil test into a computerised virtual environment. For example, Fordell et al. (2011) proposed a VR-test battery composed of digitalized tests for hemineglect (e.g., line bisection, virtual star cancellation, etc.). The third approach consists of developing a scenario based on classic neuropsychological assessment, implement in a fun game. For example, Huygelier and Gillebert (2020) developed an IVR serious game for the evaluation of hemineglect, contrasting contralateral and ipsilateral stimuli (relative to the lesion) and salient informative cues, where users engaged in a challenging and enjoyable scenario. Finally, the fourth approach involves the replication of real-world activities in IVR. Here, cognitive processes are measured in a virtual environment that simulates a familiar everyday activity. For example, Kim (2010) created a 3D IVR task involving street crossing to assess extra-personal hemineglect.

In this thesis, we adopted approaches 1, 2 and 3. The Peach Test of Chapter 3 modified a cancellation test, albeit containing one distractor, and combined the test with gaming features. The REASmash of Chapters 4 and 5 was based on an existing game (the whac-a-mole) and on the Feature Integration Theory for the assessment of distractor inhibition.

7. Outline of the thesis

The main objectives of this PhD thesis are (1) to contribute to the development of improved methods of neuropsychological assessment using interactive 3D IVR that (2) bring new insights of understanding for post-stroke cognitive impairments. This thesis is composed of 6 chapters. Following this Chapter 1 (General Introduction), Chapter 2-5 present standalone empirical papers that I explain below. These 4 chapters are followed by Chapter 6 (General Discussion), where I will discuss the findings of my research, the limitations and perspectives for the future.

In **Chapter 2**, we proposed a new IVR serious game for the assessment of hemineglect, named the Peach test. The serious game consisted of a target search test combining the assessment of contra- versus ipsi-lateral and peri- versus extra-personal spaces, in the presence or absence of avatars. Participants were required to play three randomized conditions of the Peach test (no avatar, friendly avatar, non-friendly avatar), where they had to find a peach among other fruits and vegetables as fast as possible. The target was systematically and randomly presented across a hidden grid, with random distractors placed in the other cells than that of the target. We examined the feasibility and user experience of Peach test with a group of post-stroke individuals with hemiparesis and hemineglect and a group with hemiparesis and without hemineglect, which showed positive results. We also investigated the effect of the presence of an avatar on hemineglect, and whether this presence caused an automatic perspective shift. Unfortunately, these latter results were inconclusive, and we discuss the possible reasons for these null effects.

In **Chapter 3**, we developed another IVR new serious game for the assessment of spatial and non-spatial (distractor inhibition) attention, named the REASmash. The test was based on Feature Integration Theory (Treisman & Gelade, 1980) and contrasted 6 levels of search task. Participants had to find a specific target presented among distractors and directly respond by touching the target with a virtual hammer. Three of the levels promoted parallel search using targets that showed high salient differences between the target and distractors. Each level (1-3) had increasing numbers of distractors (11, 17 and 23). The other three levels promoted serial search, with low salient differences between the target and distractors, again with increasing numbers of distractors for levels 4, 5 and 6. We tested healthy aged control individuals and replicated the Feature Integration Theory, showing that for parallel search, there was no change in performance for distractor number. However, for serial search, the number of distractors significantly reduced performance, demonstrating that the test can be used to evaluate distractor inhibition cognition. In addition, we also demonstrate the use of IVR technology for kinematic measures.

In **Chapters 4 and 5**, we extended Chapter 3. In **Chapter 4**, we investigated the psychometric properties of the REASmash. Firstly, we replicated the findings of Chapter 3 with a new group of control individuals. We then performed a multiple case study with 9 post-stroke individuals diagnosed with hemineglect. We then examined the validity, reliability, and user experience of the REASmash with a group of post-stroke individuals (with and without hemineglect) and a group of healthy controls. The replication and the results of the validity, reliability, and user experience were all positive. Furthermore, the case analyses showed some interesting results, but we were cautious in the interpretation of these results, and instead recommend the collection of more data.

In **Chapter 5**, we used the REASmash to investigate whether post-stroke individuals with hemiparesis, who were not diagnosed with cognitive impairment, could have non-spatial (distractor inhibition) deficits. We tested a group of twenty individuals with hemiparesis (the same group of hemiparesis individuals included in Chapter 4) and twenty control individuals (new participants distinct from the groups reported in Chapters 3 and 4). The results confirmed this prediction, suggesting a need to perform thorough neuropsychological assessments for all stroke survivors, even if they do not display obvious cognitive deficits. We showed evidence of significant distractor inhibition impairments, and based on prior literature, we know that these significant subtle impairments moderate clinical neurorehabilitation success of their hemiparetic limb.

In **Chapter 6**, we discussed the findings of the thesis with reference to our two main objectives presented in this chapter (Chapter 1). We discuss the contribution of this research and the limitations. Finally, we discuss potential future perspectives that can extend the findings of the PhD thesis.

It is noteworthy to mention that all individuals (controls and post-stroke individuals) who participated in these studies, participated voluntarily. To select the controls individuals, we followed a two-stage sampling process. Firstly, a call for participation was sent through the University of Louvain participation panel and social media groups. Secondly, we used a quota inclusion / exclusion criteria sampling technique to select a representative group. To avoid selection bias, the following inclusion criteria were defined across all studies: corrected-to-normal vision, and no reported history of neurological or psychiatric disorders or motor dysfunction. However, depending on specificities of studies and their objectives, other inclusion/exclusion criteria were determined. The control individuals sample reported in each study was unique, and these participants were not included in other studies. For the post-stroke individuals, we followed a convenience sampling method. Participants were pre-selected through their hospital-based neurorehabilitation clinician using pre-defined inclusion criteria. The post-stroke individuals with hemiparesis included in the study reported in Chapter 4 were also included in the study reported in Chapter 2 and 5.

Chapter 2

An immersive virtual reality serious game set in a 3D kitchen environment for the clinical assessment of spatial attention impairment: Effects of avatars on perspective?

Background: Hemineglect (HN) is commonly defined as an impairment in identifying spatial targets from an egocentric frame of reference, where the stimulus is coded relative to the self. Interestingly, this egocentric reference frame can change with the presence of another person. Immersive virtual reality (IVR) offers several advantages over paper-and-pencil tests typically used to assess HN, such as a realistic and controlled environment, standardized stimulus presentation, and sensitive response acquisition. In this study, we developed a new serious game "Peach test" in IVR to assess HN. Here we investigated (1) the feasibility and user experience of this serious game. We made the hypothesis that individuals with HN would perform worse than individuals without HN, and that the presence of an avatar would reverse the HN caused by a shift in perspective taking.

Methods: We first tested a group of 60 control individuals (CI), followed by a group of post-stroke 11 individuals with hemiparesis without HN (SI:HP-HN), 6 with hemiparesis and HN (SI:HP+HN), and 17 resampled age matched group of control individuals (CI). All participants performed the "Peach test", which required them to find and respond to a target presented among distractors, either alone or in the presence of an avatar. Response time (RT) and omissions were measured. The SI: HP-HN and SI: HP+HN groups also completed a paper-and-pencil test for HN and a user experience questionnaire.

Results: The first analysis of results with CI showed no differences in responding to the target when in contra- compared to ipsi-lateral spaces, nor in peri- compared to extra-personal spaces. There were also no differences in responding to the target in the no-avatar condition relative to the two avatars conditions. In the second analysis, SI:HP+HN were slower than SI:HP-HN and CI. Although an interaction between group and laterality was predicted, the results showed that there was no laterality effect for any of the groups. An interaction between group and proximity, showed that both SI groups were slower in the extra- compared to peri-personal spaces. The user experience was globally positively rated by the SI.

Conclusion: We developed a serious game in IVR for the assessment of HN. Although most our findings were inconclusive, the Peach test showed excellent user experience results.

1. Introduction

Hemineglect (HN), also known as unilateral neglect, spatial neglect, or hemispatial neglect, is a complex disorder of spatial cognition (perception and motor planning), attention (spatial and non-spatial; inhibition) and arousal, caused by parietal-frontal damage of the superior longitudinal fasciculus (Barrett et al., 2006; Duncan et al., 1999; Mesulam, 1999; Vallar, 1998). It is a condition characterized by a failure to attend or respond to a stimulus or stimuli presented on the opposite side of space to a brain lesion (contra-lesional space), and cannot be attributed to sensory or motor deficits (Buxbaum et al., 2004; Heilman et al., 1987; Kerkhoff, 2001). The estimated prevalence of HN ranges from 30% following stroke of either or both hemispheres (Esposito et al., 2021) and 50% after a right-hemisphere lesion versus 30% after a left-hemisphere lesion (Chen et al., 2015). In addition to lateralised attentional bias, HN can manifest differentially in peri-personal space (i.e. space within reach) and extra-personal space (i.e. space outside of reach) (Butler et al., 2004; Ten Brink et al., 2019). For example, Van der Stoep et al. (2013) reported 109 stroke patients showing 47% had HN in both peri- and extra-personal spaces, 25% had HN only in extra-personal space, with the remaining patients showing a mix of profiles depending on the task used for the assessment.

HN is typically assessed using paper-and-pencil tests (or more recently, digitised paper-and-pencil tests) (Bailey et al., 2000; Grattan & Woodbury, 2017b). Checketts et al. (2021) administrated a survey examining the tools used for hemineglect cognitive assessment by 454 clinicians. The results showed that most responders were psychologists and occupational therapists, and most reported using the Behavioural Inattention Test battery (Wilson et al., 1987) (BIT) consisting of 15 sub-tests, including cancellation tests (Checketts et al., 2021). In a similar survey, Evald et al. (2021) reported that 49% of their respondents (psychologists, occupational therapists, and speech therapists) used paper-and-pencil assessment, while few respondents used computerized tests. This latter finding is surprising because computerized tests bring several advantages to HN cognitive assessment, mostly addressing weaknesses in the use of conventional paper-and-pencil tests such as ecological validity, sensitivity, and standardization (Azouvi, 2017; Capitani, 1997; Reynolds & Mason, 2009). Computerized tests, such as the Test Attentional Performance (TAP) battery (Zimmermann & Fimm, 1995b), involves precise control of the stimuli presentation, stimuli randomization (increasing reliability), multiple response measures (omission, error, response time) with increased accuracy (increasing test sensitivity and specificity) and automated score analyses and data comparison relative to control participant performance (norms) (Kane & Kay, 1992; Parsey & Schmitter-Edgecombe, 2013; Rengachary et al., 2009). One potential explanation for the slow adoption of computerised tests by clinicians might be that the tests are often digitised forms of the paper-and-pencil tests, lacking ecological validity, and not bringing significant advancement to justify changing their standard clinical routine.

Virtual reality is a sophisticated computerised technology and a promising solution to enhance the quality of cognitive assessment (Riva, 2009; Rizzo et al., 2004). It is a combination of hardware and software allowing for the manipulation of objects within a virtual environment (Anthes et al., 2016; Kalawsky, 1996), bringing all the advantages of computerized tests with ecologically relevant stimuli. Here, we use the term "Immersive Virtual Reality" (IVR) to refer to technology that allows users to immerse themselves into a three-dimensional simulation, giving the feeling of being situated within the virtual environment (i.e. sense of presence) (Kardong-Edgren et al., 2019; Ryan et al., 2019). The application of IVR to clinical assessment has been the subject of several reviews (Garrett et al., 2018; Massetti et al., 2018; Pourmand et al., 2017; Rizzo & Koenig, 2017). For example, Tsirlin et al. (2009) analysed the scientific literature and summarized that IVR offers opportunities to display ecologically relevant and attractive stimuli within a controllable, safe, familiar and meaningful context to users, increasing engagement. Engagement can be further gained through IVR-based serious games (Burke et al., 2009; Feng et al., 2018; Ma & Zheng, 2011), which can be defined as entertaining or fun exercises that motivate users to engage in performance or learning. They can be theory-driven and based on existing psychometric tests, providing multisensorial feedback, and meaningful gameplay through intriguing and enjoyable storytelling (Alankus et al., 2010; Burke et al., 2009; Mubin et al., 2022; Tong & Chignell, 2014). Serious games can be designed to provoke users to perform at their maximal level of ability (i.e. to achieve a high score; improving test/re-test reliability), as well as provide a means to simulate everyday life situations that use the assessed cognitions. Several studies have already demonstrated the added value that serious games bring for cognitive assessment (Fordell et al., 2011; Huygelier et al., 2022; Knobel et al., 2020; Tanaka et al., 2005).

HN is thought to result from impairment to the spatial coordinate systems and specific frames of reference used to code the location of stimuli in space (Behrmann & Moscovitch, 1994; Farah et al., 1990; Mozer, 2002b). Typically, HN is defined by an egocentric frame of reference, where the location of a stimulus is spatially coded relative to the self (Calvanio et al., 1987; Driver & Pouget, 2000; Pouget & Driver, 1999) (e.g., stimuli are typically neglected when presented on the contralesional relative to ipsilesional side of space relative to body position). While eye movements can be used to evaluate HN (Kaiser et al., 2022b), making eye movements rarely influences HN, suggesting no impairment of the retinotopic frame of reference (Chokron, 2003; Ladavas, 1987; Stein, 1992) (i.e. moving the eyes does not reduce HN). The egocentric reference frame can change with the presence of another person in the scene (Kampis & Southgate, 2020; Southgate, 2020; Vogeley & Fink, 2003; Wang et al., 2020; Zaehle et al., 2007). When alone, environment spatial stimuli are coded with reference to an egocentric frame of reference (own perspective). However, when another person is present, the viewer may spontaneously take the perspective of the other person, representing spatial stimuli from the other’s perspective (Mainwaring et al., 2003; St. Jacques & Iriye, 2022; Tversky & Hard, 2009). This effect causes congruency conflicts between peripersonal and extrapersonal space for the self-perspective compared to other-perspective (i.e. stimuli within physical reach from the viewer become coded in extrapersonal space from the other person’s perspective, and vice versa). Furthermore, stimuli presented on the egocentric left of the viewer becomes egocentric right when viewing the same stimuli from the other’s perspective. These reversal effects present interesting opportunities that could be useful for better understanding HN, as well as using the effects caused by the presence of another person (an avatar) to facilitate diagnosis.

The effect of perspective in the expression of HN has already been reported for representational (memory) HN (Bisiach & Luzzatti, 1978; Sala et al., 2004). In Sala et al. (2004), patients with representational hemineglect viewed a visual scene and then recalled objects from the scene, either from their own perspective, or from an opposite perspective (where they imagined themselves stood at a different location in the room facing the direction of their physical position). The data showed that the patients failed to recall stimuli presented on the contra-lesional side of space relative to their (own or opposite) perspective, demonstrating that items were neglected based on the relative position of the stimuli. For example, when patients with a right lesion causing left HN recalled stimuli using their own perspective, they neglected to recall stimuli to the left of their perspective. However, when they used the opposite imagined perspective, they again neglected the stimuli to the left of the opposite perspective (i.e. to the right of their physical position), and they recalled the stimuli to the right of the opposite perspective (i.e. to the left of their physical position; the stimuli that they neglect from their own perspective). A similar study was reported by Becchio et al. (2013). They asked left HN patients to recall the positions of objects placed in a hidden grid consisting of three rows and two columns, either from their own first-person perspective or from the perspective of an avatar. Their findings demonstrated that objects presented on the left (contra-lesional) side were omitted when viewed from their own perspective, but not when the same stimuli were perceived from the opposite avatar perspective, suggesting a strong effect of perspective on HN. The authors argued that the transformation of HN was caused by a remapping of space with reference to the avatar's frame of reference (e.g., an altercentric frame of reference).

Perspective taking has been systematically investigated by Samson et al. (2010) in a series of experiments in which participants were asked to perceive environmental stimuli from their own perspective versus an avatar's perspective. The coloured stimuli where either congruent (the same) for the self (own perspective) and avatar perspective (e.g., two dots placed in front of the avatar), or different (incongruent) for the self and avatar perspectives (e.g., one dot placed in front of the avatar and one dot placed behind of the avatar creating a perception of two dots for the self and one dot for the avatar perspective). The results showed that participants were faster and more accurate when perceiving the stimuli from the avatar's perspective relative to when perceiving it from their own perspective, particularly in the incongruent condition. The authors proposed that the avatar's perspective automatically interfered with self-perspective, even when the avatar's perspective was irrelevant to the task. In another series of experiments, Cavallo et al. (2017) tested right-handed participants that were asked to verbally report the location of a stimulus presented on the right versus left, and near versus far space, from either their own perspective or from an avatar's perspective (present opposite). The results showed that when participants responded from their own perspective, mean response time was faster when the stimulus was on the right than left, and in near than far space. However, the effect reversed when participants responded from the perspective of the avatar, with faster responses now made when the stimulus was on the left than right, and when in far than near space (Cavallo et al., 2017) showing a remapping of space relative to perspective (Frith & Frith, 2010; Tosi et al., 2020; Tversky & Hard, 2009). Other research shows that perspective-taking can be modulated by numerous other factors (e.g., emotions (Bukowski & Samson, 2016; Yang et al., 2010), prosocial behaviour (Carlo et al., 1999), culture (Wu & Keysar, 2007)), and social perception (i.e. the capacity to analyse the intentions and dispositions of others (Allison et al., 2000)).

In the present paper, we present a new IVR-based computerized serious game (the “Peach test”), which combines the assessment of egocentric, peri- and extra-personal HN, including perspective manipulation (self-versus other perspective; and the inclusion of social manipulation within the avatar). The Peach test simulates a daily living (ecological) activity involving a simple and playful storyline. The participant has to search for a target peach that is presented within a hidden grid, allowing systematic manipulation of target spatial position, with equal presentation of the target on the ipsilateral versus contralateral side, and peri- versus extra-personal distance across trials (randomized) (requiring similar behaviour to cancellation tasks; the most frequently used HN assessment method) (Bowen et al., 1999; Golisz, 1998). The task is performed three times, once with no avatar, and twice with an avatar stood at the opposite side of the table to the participant’s viewpoint, one block with a friendly avatar and one block with a non-friendly avatar. Participants responded to the target by making a rapid key press when they saw the peach target.

We performed three analyses of data. In the first analysis, we examined the feasibility of the “Peach test” with a large group of healthy control individuals (CI). For the dependent measures of omissions and response time, we hypothesised that (1) there would be no evidence of HN, showing no differences in target responses between ipsilateral compared to contralateral space, and for response time; (2) an interaction between the avatar and proximity showing that for the no avatar condition, slower response times to targets placed in extra- than peri-personal space, whereas in the avatar condition, faster response times to targets placed in extra- than peri-personal space (showing a reversal) ((3) perhaps further moderated by the social characteristics of the avatar). In analysis 2, we tested a group of stroke individuals with hemiparesis and hemineglect (SI:HP+HN), a group of stroke individuals with hemiparesis, but without hemineglect (SI:HP-HN), and a re-sampled age-matched group of healthy control individuals (CI) (selected from the previous CI group to match the SI groups). In addition to the same hypotheses of analysis 1, we hypothesised that, (1) omissions would be greater and response time would be slower for the SI:HP+HN and SI:HP-HN groups relative to the CI group; (2) an interaction between group and laterality showing that the SI:HP+HN group would be slower to respond to contralateral compared to ipsilateral targets (i.e. showing HN), whereas the SI:HP-HN and CI would show no lateral differences; (3) an interaction between group, laterality and avatar showing that for the SI:HP+HN group, the no avatar condition would show more omissions and slower response times to contralateral compared to ipsilateral targets (showing HN), but that in the avatar condition, the effect would be reversed, showing less omissions and faster response times to contralateral compared to ipsilateral targets (a perspective shift). We predicted that there would be no lateral effects for the SI:HP-HN and CI groups, and consequently, no reversal. (4) This interaction may be further moderated by the friendliness of the avatar. Finally, in the third analysis, we evaluated the user experience in the two SI groups.

2. Methods

2.1 Participants

We tested 61 healthy control individuals (CI) (32 females, 3 left-handed; aged between 30 and 77 years (M = 55, SD = 10.6)) and 17 post-stroke individuals (SI) (3 females, 9 left-handed (less-affected); aged between 46 and 79 years (M = 60, SD = 10)). The CI were recruited using convenience sampling from the University of Louvain participation panel and social media groups. The inclusion criteria were: (1) corrected-to-normal vision, and (2) a good understanding of the task instructions. They were excluded if they reported a history of neurological conditions. The first analysis considered all 61 participants of the CI group, whereas the second analysis involved the 17 SI and a selection of 17 CI from the 61 participants that were matched by age to the SI participants. The SI were recruited from the physical medicine and rehabilitation department of the Cliniques universitaires Saint-Luc in Brussels. Clinicians introduced our experiment to their patients. If the patients expressed willingness to be contacted, we would then connect with them through phone or in person to provide an explanation of the experiment's objectives and procedure. If they agreed to participate to the study, an appointment was scheduled. The inclusion criteria were: (1) presence of an ischemic or haemorrhagic first stroke according to the World Health Organization, with lesions confirmed by medical imagery, (2) clinical diagnosis of HN and HP from a clinical neuropsychological or physical medicine evaluation report, and (3) a good understanding of the task instructions. They were excluded if they (1) presented other neurological or orthopaedical conditions (such as dementia) that would interfere with the use of IVR, or (2) had uncorrected vision. All the SI participants had a hemiparesis, and 6 SI additionally had a clinical diagnosis of HN documented in an evaluation medical report (SI:HN+) (see Table 1 for precise details of each anonymised post-stroke individual). The SI:HP+HN and SI:HP-HN groups were contrasted to the re-sampled age-matched CI group. The three groups (SI:HP+HN, SI:HP-HN, and CI) consisted of 6, 11 and 17 participants (SI:HP+HN: 0 females, 3 left-handed *post-stroke*; aged between 49 and 67 years, M = 59, SD = 7.01; SI:HP-HN: 3 females, 6 left-handed *post-stroke*, aged between 47 and 79 years, M = 60.5, SD = 12.01). A t-test showed no differences between groups for age ($t(32) = -0.069$, $p = 0.95$). All procedures were approved by the Saint-Luc UCLouvain-Hospital-Faculty Ethics Committee, and registered on clinicaltrial.org (NCT04694833). All participants volunteered to participate, and provided written informed consent prior to the experiment. The third analysis of user experience was tested only with the SI groups.

Table 1: The demographic characteristics of the post-stroke individuals (SI groups)

	Id	Gender	Age	Stroke site	Stroke type	Months post-onset	Diagnosed Hemineglect (side L/R) (note 1)	Asymmetry Apples Test (note 2)
Individuals with HP and No HN (SI: HP-HN)	SI01	F	51	Left middle cerebral artery	ischemic	3,5	No (L)	0
	SI02	M	56	Right thalamus	ischemic	1,5	No (R)	0
	SI05	M	69	Left paramedian pontine	ischemic	38	No (L)	1
	SI06	M	46	Left middle cerebral artery	ischemic	22,8	No (L)	0
	SI07	M	62	Right lacunar internal capsule	ischemic	18	No (R)	0
	SI09	F	79	Left posterior capsulo-thalamic	ischemic	1,6	No (L)	0
	SI12	M	74	Right posterior branch of the right sylvian artery	ischemic	10	No (R)	2
	SI13	M	73	Right sylvian fissure	ischemic	2	No (R)	-1
	SI15	M	47	Left temporal lobe	ischemic	0,2	No (L)	-1
	SI16	M	47	Left lenticulostriate artery	haemorrhagic	7	No (L)	0
	SI17	F	62	Right sylvian fissure	ischemic	20	No (R)	0
Individuals with HP and HN (SI: HP+HN)	SI03	M	49	Left middle cerebral artery	ischemic	15	Yes (L)	1
	SI04	M	64	Left parietal intraparenchymal	haemorrhagic	13	Yes (L)	0
	SI08	M	52	Right superficial and deep sylvian and secondary occipital	ischemic	17,5	Yes (R)	0
	SI10	M	61	Left capsulo-thalamic	haemorrhagic	4,6	Yes (L)	1
	SI11	M	61	Right superficial middle cerebral vein	ischemic	5,8	Yes (R)	0
	SI14	M	67	Right sylvian fissure	ischemic	19,4	Yes (R)	3
	Mean All (SD)		**60 (10.30)**			**11,75 (10.12)**		
	Mean SI: HP-HN (SD)		**60.54 (12.01)**			**11.32 (12.02)**		
	Mean SI: HP+HN (SD)		**59 (7.01)**			**12.55 (6.10)**		

SI = Post-stroke individuals; F = Female; M = Male; SD = Standard deviation; (note 1) Hemineglect was determined by clinical evaluation during the acute phase post-stroke; (note 2) At the time of the present study, patients were evaluated using the Apple Cancellation Test to assess hemineglect status on the day of the experiment

2.2 Materials, stimuli, and experimental design

We used a VR headset (Oculus Quest 2) and one Oculus Quest motion controller. The visual display presented to participants was monitored by the experimenter through live stream of the Oculus App on a digital tablet (Huawei MediaPad T, model AGS2-W09). The virtual environment was built with Unity 2019.3 software (in C # language), using virtual objects purchased in Unity Asset Store. We purchased two 3D avatars, consisting of middle-aged male and female humanoids (*Figure 1d*). The avatar animations (e.g., head movements, eye blinks, speech) were performed using SALSA Lip Sync[2]. The IVR simulated a 3D kitchen environment consisting of worktops, wall cupboards, a cooker, fridge-freezer, and a table (*Figure 1a*), on which a hidden grid (6 columns and 4 rows; 24 cells) was placed. The table dimensions were 120cm (L), 120 cm (W), and 73 cm (H), and the cells of the hidden grid measured 20 cm (L) and 20 cm (W). The target stimulus was a Peach (presented in 3D), and the distractor stimuli were different fruits and vegetables (all presented in 3D). The target Peach was developed in-house using Blender. The distractor fruit objects were taken from two Unity Asset Store packages that we purchased: Food Pack Mixed and Modern Supermarket (Technologies, n.d.-a, n.d.-b). All stimuli were placed within the centre of each cell, with the target stimulus appearing in each of the 24 cells (randomly) across the trial set. The distractors were presented in the other 23 cells, with random allocation on every trial (*Figure 1b*).

The CI held the controller in their dominant hand, and the SIs held the controller in their less-affected hand. Before each trial, a red basket was displayed floating in front of the participant, positioned along their sagittal axis, at the level of the table (*Figure 1b*). To initiate a trial, the participant had to fixate the red basket (alignment measured with the Oculus head position tracker). Once the head position was correctly located, the basket turned green, and the stimuli appeared. This fixation procedure assured a central fixation starting point for each trial. The participants were instructed to push on a button of the Oculus Quest motion controller when they saw the target stimulus (*Figure 1c*). All the trial stimuli appeared for 7000 milliseconds maximum, and if the participants made no response during target presentation trials, the serious game registered an omission (failure to find the target). On 5 additional trials (randomly presented within the 24-target trial set), no target was presented (catch trials; on these trials, 24 distractors were presented). The participant was instructed to make no response, but if a response was made, a false-positive error was recorded.

There were three blocks of trials, with each block composed of 29 trials (24 target trials and 5 catch-trials). In the control condition, no avatar was presented (the participant was the only person in the virtual room). In the avatar conditions, one of two avatars entered the virtual kitchen and stood facing the participant, at the opposite side of the table (the virtual distance between the participant and the avatar was 1m40) (*Figure 1e*). The sex of the avatar was selected by the participant before the experiment, and the two avatars were of the selected sex. In one block, the selected avatar acts as the friendly avatar, it positively interacted with the participant by giving verbal and physical encouragement, while in a second block, the avatar that was not chosen acts as the non-friendly avatar, it does not interact with the participant (no display of verbal and physical encouragement). The order of these three blocks were randomized across participants (*see Table 2 for a summary of the Peach test scenario and task*). Before each trial block, written and audio instructions were played, and the participants were consistently instructed to respond as fast as they could to the target Peach.

The performance was logged and stored in “CSV” format in the headset storage. This contained various standard data entries including participant (anonymised) ID, trial number, and block number. Target and Catch Trials were registered, and depending upon the participant’s response, the result of the response was recorded (i.e. correct response to the target; omission - failure to respond to the target; error - response to a distractor; correct non-response to a catch trial, and a false positive error to a catch trial). The row and column coordinates of the target location were registered. Response time was recorded in milliseconds.

Table 2: A summary of the Peach test sequence. The participant was exposed to a series of visual scenes, in which the participant performed a task.

Scene	Content	Task	Interactions and software
1	The study begins with the experimenter using the Oculus Quest 2. A simple user interface (UI) containing the title of the serious game and a dialog box is presented: "*Enter the participant's ID*".	The experimenter indicates the participant's (anonymised) ID (for data logging).	Interactions with the UI are made using a virtual laser controlled using the Oculus controller (implemented using a prefab of the Oculus library; UIHelpers).
2	The participant is now wearing the Oculus. A gif animation shows which controller button must be pressed to respond to the target, accompanied by written and auditory instructions. They are then invited to "*Press the button to start*".	The participant listens to the instructions and then presses the virtual button to initiate the study.	The written and audio instructions are presented. The audio was recorded using iOS Voice Memos. To press the virtual button, the same laser-based control is used to interact with the UI.
3	A second set of written and auditory instructions are presented with the same gif as the previous scene. They are requested to click "continue" to move forward.	The second set of instructions explain that the participant can choose the gender of the avatar ("sous-chef" in the SG storyline).	The same laser-based button is used to interact with the UI and move to the next screen.
4	Pictures of the two avatars and their names are presented (*Figure 1d*), along with a "*continue*" button.	The participants chose one of the avatars by clicking on the button to select the gender of their "sous-chef" avatar.	The laser-based button is aimed to one of the avatar pictures. A visual feedback is shown to indicate selection. They then press continue.
5	The participants enter the virtual 3D visual kitchen. They are situated in front of	The text-audio instructions are displayed explaining	The audio is presented in a male or female voice based on the choice of avatar (i.e. Philippe vs Françoise).

	a wooden table, with a semi-transparent grey screen hanging in front of them, on which written and illustrated instructions are displayed. A "*continue*" button is also presented.	the storyline to the participants ("*A Pastry Chef needs help to make a Peach Pie*"). They must gather peaches as fast as they can. They will be accompanied by their chosen sous-chef, and by a second sous-chef (i.e. the avatar that they did not choose). The participant needs to press "continue" button to move forward.	The same laser-based button is used to interact with the UI.
6	Another instruction is displayed on the semi-transparent screen using image and audio. It shows a red basket turning green, and a 2D illustration of the target Peach. A "*continue*" button is also presented.	Participants are instructed to fixate the red basket until it turns green to launch the serious game. They need to press "continue" button to move forward.	To detect if the participants is looking at certain objects in the virtual environment, the Unity function Raycasting is used (a virtual ray from the headset central camera to the basket).
7	A tutorial is launched after pressing a "continue" button UI. The tutorial is composed of 12 sample trials. The table is first presented with the red basket, at the level of their hand. After fixation, the stimuli appear on the table (1 target and 23 distractors, and no avatar).	Before each trial, participants fixate the red basket, and upon turning green, the trial begins. Participants are requested to search and respond to the target Peach presented among other fruits and	The participant has up to 7000ms to respond to the target, otherwise the trial ends and another red basket fixation task appears. The target appears in every cell of the hidden grid, in every block.

		vegetables by pressing a button when they see the target (responding as fast as they can).	
8	A final text-audio instruction is displayed, with a "continue" button. Once the serious game is launched, three consecutive blocks are displayed. A break is provided between blocks, to allow the change of avatars and for participant rest.	Participants launch the serious game by pressing the "continue" button when they feel ready.	The presentation of the stimuli is similar to the tutorial, but additionally containing catch trials (no target) and trial with the presence of the avatar. The animations of the avatars were taken from Mixamo data base, and the facial expressions were created using Blend Shapes Editor in Unity.
9	Once the three blocks are complete, the participant is presented with an empty table, with the semi-transparent screen giving written-audio instructions.	The text-audio instructions inform the participant that they gathered enough peaches, and that this is the end of the game. The instruction thanks the participant for their participation.	This is the end of the experiment. The participant removes the headset.

Figure 1a: The 3D simulation of the kitchen where the participants were immersed. The kitchen contained a table on which the stimuli appeared.

Figure 1b: Before each trial, the participant had to fixate the red basket to regulate the eye starting position for each trial. When fixated, the basket turned from red to green.

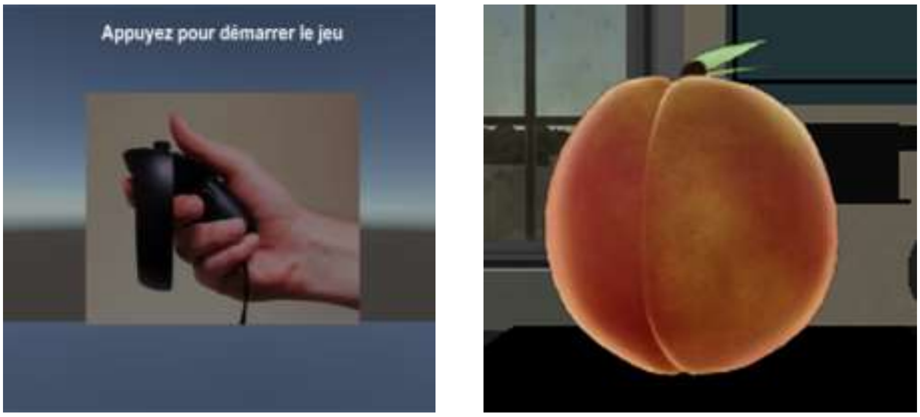


Figure 1c: The target Peach and the controller button for responding (shown as an animated gif).

Figure 1d: the selection of either the female or male avatar

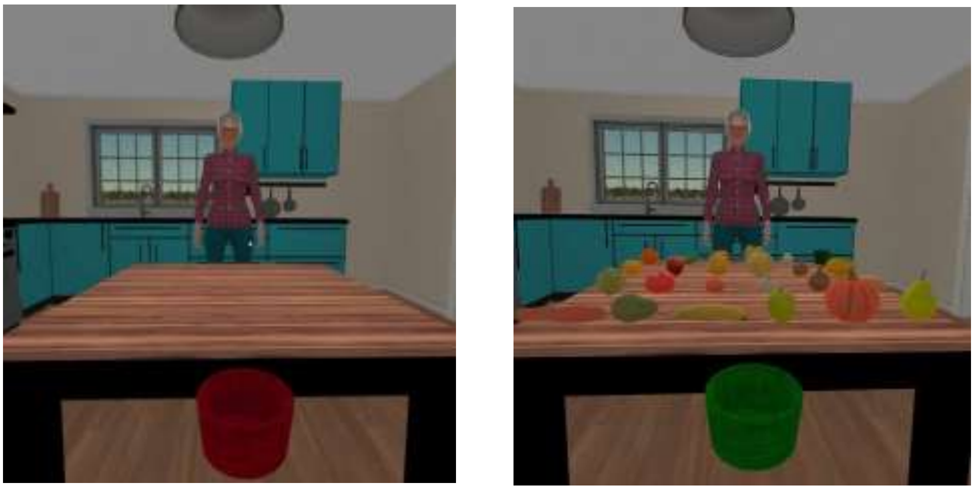


Figure 1e: An example of the avatar presented within the kitchen scene.

To evaluate users' experience, we used the User Experience Questionnaire (UEQ) considering hedonic and pragmatic measures (Laugwitz et al., 2008a), represented by 6 scales with twenty-six items in total: (1) Attractiveness: refers to the overall impression of the serious game (*Do users like or dislike it?*); (2) Perspicuity: refers to how easy it is to get familiar with the serious game (*Is it easy to understand?*); (3) Efficiency: refers to the ease with which interactions can be conducted within the serious game (*Is the interaction efficient and fast?*); (4) Dependability: refers to the sentiment of control over the serious game (*Does the user feel in control of their interactions?*); (5) Stimulation: refers to the motivation and pleasure that the user experience when using the serious game (*Is it exciting and motivating to use the serious game?*); (6) Novelty: refers to the novelty of the serious game (*Is the serious game novel and creative?*) (Laugwitz et al., 2008a; Schrepp et al., 2014). The Attractiveness scale correspond to 6 items, whereas all the other scales correspond to 4 items. The items format consisted of semantic differential with a 7-points Likert scale. The questionnaire is accessible and available for free in multiple languages, and a data analysis tool is provided to facilitate the evaluation.

2.3 Procedure

The study was conducted in controlled laboratories based at the Institute of Psychological Sciences Research Institute, University of Louvain and in the Cliniques universitaires Saint-Luc, Brussels. The experiment session lasted one hour. At the beginning of the session, the participants were instructed on the experimental design, and they were invited to sign a consent form. They were then invited to sit on a chair at the edge of a physical table, wearing the IVR headset and holding the controller in their dominant (less-affected) hand. They were then immersed in the virtual environment. They were told a back story of a pastry chef that needed help to make a peach pie. To assist the pastry chef, the participant had to collect as many peaches as they could during the game. They were also told that they would sometimes be accompanied by a sous-chef (the avatar). They were immersed in the virtual environment and invited to select their sous-chef avatar by pressing on a button (i.e. allowing the selection of a male or female avatar) (see *Figure 1*; each having the friendly and non-friendly versions). Once their choice was made, they were instructed to push on a start button allowing them to enter the virtual kitchen containing the virtual table that corresponded in position to the physical table. The participants could view and visually explore the kitchen and the empty table (containing no stimuli). Written and auditory instructions were then displayed to the participant, and they were invited to push on a button to initiate a training session containing 12 trials (including 2 catch-trials). The objective of this training session was to confirm that the participants understood the instructions, that they could correctly identify the target, and that they engaged and experienced the immersion of the task. At the end of this training session, they were then invited to again push a button to initiate the experiment (three blocks of 29 trials) (see *Table 2* for the sequence of the serious game). After completing the three blocks of the Peach test, the patients were then asked to complete UEQ. At the end of the session, the participants were thanked for their participation, and the CI received a payment of 10 EUROS for their participation. All participants completed the experiment.

2.4 Methods of data analyses

For analyses 1 and 2, a Shapiro-Wilk normality test indicated that the data were normally distributed ($W(25) = 0.92$, $p > 0.05$). Therefore, the data were analysed using repeated measures ANOVAs (using SPPS IBM). The independent variables were Group (CI, SI:HP+HN, SI:HP-HN), Laterality (ipsilateral vs contralateral space relative to the dominant hand in CI/ non-HP hand in SI), Proximity (peri-personal vs extra-personal space), and Avatar (no avatar, friendly avatar, non-friendly avatar). The targets were semi-randomly presented across a 6 column and 4 row hidden grid. Targets presented in columns 1-3 and columns 4-6 were defined as ipsi- or contra-lateral space relative to the dominant hand. For right-handed participants (SI with a left HP), contralateral space corresponded to targets displayed in columns 1-3 and ipsilateral space corresponded to targets displayed in columns 4-6, whereas for left-handed participants (SI with a right HP), contralateral space corresponded to targets displayed in columns 4-6 and ipsilateral space corresponded to targets displayed in columns 1-3. For proximity, peri-personal space corresponded to targets presented in rows 1 and 2, and extra-personal space corresponded to targets presented in rows 3 and 4 (see Figure 1b). The dependant variables were the number of omissions for target trials (i.e. a failure to respond to the target by pressing the button when the target stimulus appeared) and mean response time (RT) to correctly respond to target stimuli (i.e. the time between the presentation of the target stimuli and the moment the participant correctly pressed the button; measured in milliseconds). Post-hoc analyses were performed using Bonferroni correction.

In the first analyses, all response to catch trials (i.e. 3 blocks or 5 trials x 61 CI participants, 915 trials) were removed from the total data set (i.e. 3 blocks of 29 trials x 61 participants; 5307 total trials). All the data from three participants were excluded as they pressed the response button when no target stimulus was presented for more than 6/15 catch trials. From the remaining 4176 total trials (58 participants), omissions (38 trials) and abnormal responses (< 250 ms) (2 trials) were removed. Outlier data were identified numerically using a confidence interval of three standard deviations above and below the mean, causing a further 92 trials to be deleted. The analysis was performed on the remaining data set of 4044 trials.

In the second analyses, all response to catch trials (i.e. 15 trials x 34 participants, 510 trials) were removed from the total data set (i.e. 3 blocks of 29 trials x 34 participants; 2958 total trials). From the re-sampled CI data set (i.e. 82 trials x 17 CI; 1224 total trials), 15 omission trials were removed (and there were no abnormal responses, < 250 ms). From the SI:HP-HN groups (i.e. 82 trials x 11 SI: HP-HN; 627 total trials), 32 omission trials and 2 trials showing abnormal responses (< 250 ms) were removed. From SI:HP+HN data set (i.e. 82 trials x 6 SI: HP+HN; 432), 24 omissions (see *Table 1*) and 13 abnormal responses (< 250 ms) were removed. Outliers were identified using a three standard deviation confidence interval above and below the mean, causing a further 26 trials to be delated in CI group data. The analysis was performed on the remaining 2336 data set (see *Table 3*).

Table 3: The number of omissions made by the SIs.

	ID	Total number	Ipsi- and (contra-) lateral space	Near and (far) space	With friendly avatar	With no avatar	With non-friendly avatar
SI:HP-HN	SI01	0	0 (0)	0 (0)	0	0	0
	SI02	0	0 (0)	0 (0)	0	0	0
	SI05	0	0 (0)	0 (0)	0	0	0
	SI06	2	1 (1)	0 (2)	2	0	0
	SI07	2	1 (1)	1 (1)	0	1	1
	SI09	26	11 (15)	6 (20)	5	11	10
	SI12	2	1 (1)	0 (2)	0	1	1
	SI13	0	0 (0)	0 (0)	0	0	0
	SI15	0	0 (0)	0 (0)	0	0	0
	SI16	0	0 (0)	0 (0)	0	0	0
	SI17	0	0 (0)	0 (0)	0	0	0
SI:HP+HN	SI03	13	6 (7)	1 (12)	5	3	5
	SI04	7	6 (1)	2 (5)	1	1	5
	SI08	2	1 (1)	2 (0)	0	0	2
	SI10	0	0 (0)	0 (0)	0	0	0
	SI11	1	1 (0)	0 (1)	1	0	0
	SI14	1	1 (0)	0 (1)	1	0	0

The UEQ was completed by the SI only, as they are the *end-users*. Their scores were analysed using the data analysis tool (an excel sheet) provided by the authors (Laugwitz et al., 2008a). The results were encoded in the tool, then an automatic transformation was performed, scaling the items from -3 to +3. Then, the mean and standard deviation of each scale were computed. Scores ranging from -1 to 1 indicate a neutral evaluation of the corresponding scale, scores below -1 indicate a negative evaluation, and scores above 1 represent a positive evaluation of the corresponding scale. These results were compared to a classification benchmark value, containing 468 evaluation study. The evaluated product (here, Peach test) was classified, based on the benchmark, into 5 categories per scale: Excellent, Good, Above average, Below average, and Bad (Schrepp, 2015; Schrepp et al., 2017).

3. Results

3.1 Analysis: General effects for the large CI group

The analysis of mean RT showed no main effects for Laterality, $F (1, 57) = 2.29$, $p = 0.14$, $\eta 2 = 0.04$, Proximity, $F (1, 57) = 0.12$, $p = 0.74$, $\eta 2 = 0.002$, and Avatars, $F (2, 114) = 0.27$, $p = 0.76$, $\eta 2 = 0.005$. There were also no significant interactions between Laterality and Avatars, $F (2, 114) = 2.04$, $p = 0.13$, $\eta 2 = 0.034$, Proximity and Avatars, $F (2, 114) = 1.34$, $p = 0.27$, $\eta 2 = 0.02$, and the three-way interaction between Laterality, Proximity and Avatars, $F (2,114) = 0.48$, $p = 0.62$, $\eta^2 = 0.008$. However, there was a significant interaction between Laterality and Proximity, $F (1, 57) = 8.08$, $\eta 2$, $p < 0.001$, $\eta 2 = 0.12$ (*Figure 2a*). A separate ANOVA was run for each proximity space. As hypothesized, this showed no significant effect of laterality in both the peri-personal space, $F (1,57) = 3.70$, $p = 0.06$, $\eta^2 = 0.06$ and extra-personal space, $F (1, 57) = 1.65$, $p = 0.20$, $\eta^2 = 0.03$ (*Figure 2b*).

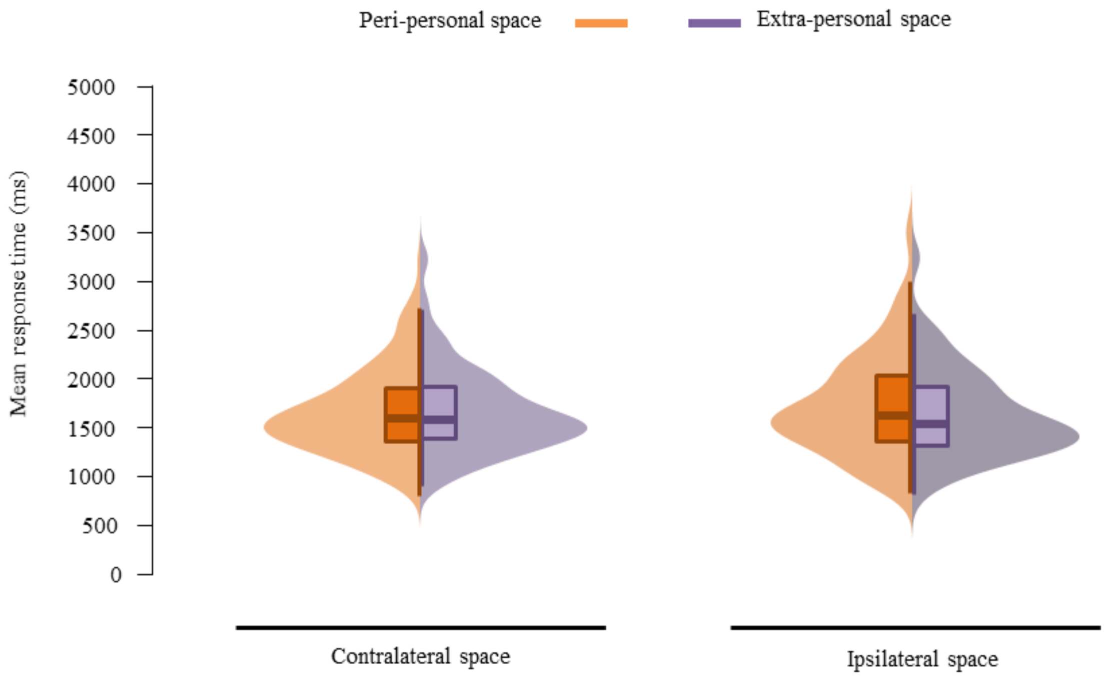


Figure 2a: Violin plots with boxplots illustrating mean response time (milliseconds) to the Peach target in ipsi- and contra-lateral spaces, and in peri- and extra-personal spaces.

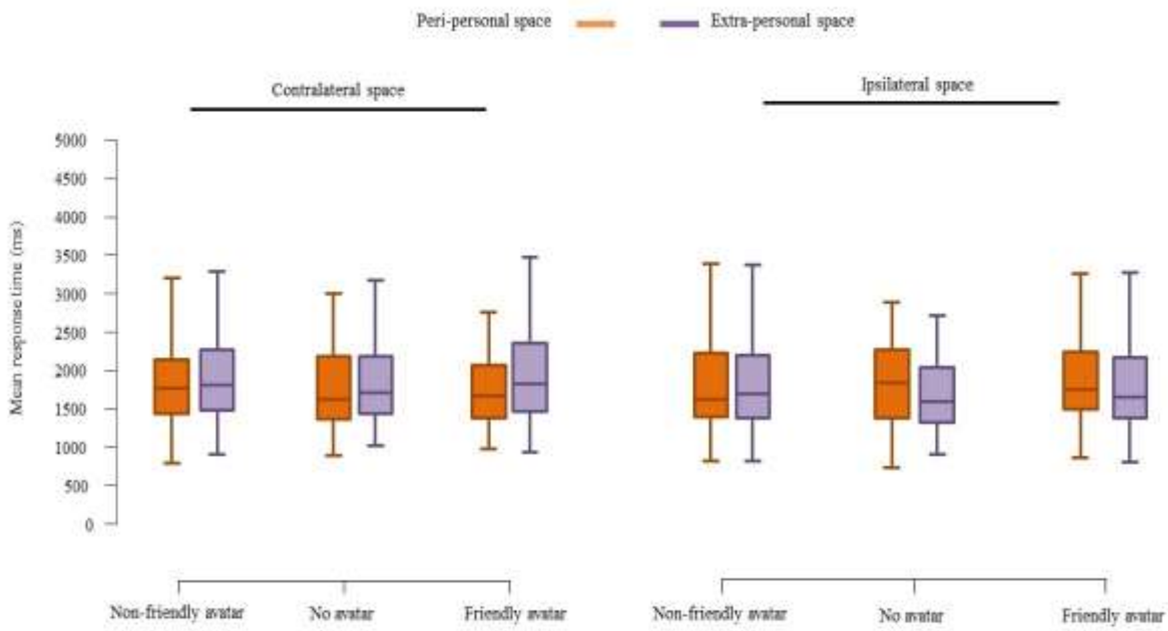


Figure 2b: Boxplots illustrating mean response time (milliseconds) to the Peach in ipsi- and contra-lateral spaces, and in peri- and extra-personal spaces, in the three avatar conditions.

3.2 Analysis: Group comparison study

Table 3 shows the total omission scores. As omissions were too few, analyses by ANOVA were not possible. The analysis of mean response time showed no main effect of Laterality, $F(1, 31) = 1.62$, $p = 0.21$, $\eta 2 = 0.05$, or for Avatars, $F(2, 62) = 0.81$, $p = 0.45$, $\eta 2 = 0.02$. There were no significant interactions between Avatars and Group, $F(4, 62) = 0.68$, $p = 0.61$, $\eta 2 = 0.04$, Avatar and Laterality, $F(2, 62) = 0.01$, $p = 0.99$, $\eta 2 = 0.00$, Avatar and Proximity, $F(2, 62) = 0.87$, $p = 0.42$, $\eta 2 = 0.03$, and Proximity and Laterality, $F(1, 31) = 0.48$, $p = 0.49$, $\eta 2 = 0.01$. There were also no significant three-way interactions between Avatars, Laterality, and Group, $F(4,62) = 1.00$, $p = 0.41$, $\eta 2 = 0.06$, Avatars, Proximity, and Group, $F(4,62) = 0.56$, $p = 0.69$, $\eta 2 = 0.03$, and Avatars, Laterality, and Proximity, $F(2,62) = 0.02$, $p = 0.98$, $\eta 2 = 0.00$.

As predicted, there was a main effect of Group, $F(2,31) = 10.49$, $p < 0.001$, $\eta 2 = 0.40$. This showed that the SI: HP+HN group was the slowest, then the SI: HP-HN group, and that both SI groups were slower than the CI group (SI: HP+HN: M = 2961.26, SD = 247.17; SI: HP-HN: M = 2290.36, SD = 182.55; CI: M = 1691.17, SD = 146.84). Also, as predicted, there was a main effect of Proximity, $F(1,31) = 22.44$, $p < 0.001$, $\eta 2 = 0.42$, with all participants being slower in extra-personal compared to peri-personal space (Peri-personal space: M = 2164.87, SD = 100.13; Extra-personal space: M = 2463.66, SD = 133.18). There were significant interactions between Group and Laterality, $F(2,31) = 3.28$, $p < 0.001$, $\eta 2 = 0.17$, and Group and Proximity, $F(2,31) = 8.57$, $p < 0.001$, $\eta 2 = 0.36$ (*Figures 3*). Separated ANOVAs were run for each Group. For each of the three groups, there was no effects of laterality for CI, $F(1,16) = 0.03$, $p = 0.86$, $\eta 2 = 0.00$; SI: HP-HN, $F(1,10) = 0.44$, $p = 0.52$, $\eta 2 = 0.04$, and; SI: HP+HN, $F(1,5) = 0.4.41$, $p = 0.09$, $\eta 2 = 0.47$. For proximity, the CI group showed no effects, $F(1,16) = 0.33$, $p = 0.57$, $\eta 2 = 0.02$, but there were significant effects for both SI groups: SI: HP-HN, $F(1,10) = 7.74$, $p < 0.001$, $\eta 2 = 0.43$, and SI: HP+HN group, $F(1,5) = 7.27$, $p < 0.001$, $\eta 2 = 0.59$. Both analyses showed that the SI: HP+HN and SI: HP-HN were slower in extra-personal (SI: HP+HN: M = 3251.76, SD = 289.97 vs. SI: HP-HN: M = 2460.09, SD = 214.16) than in peri-personal (SI: HP+HN: M = 2670.77, SD = 218.02 and SI: HP-HN: M = 2120.62, SD = 161.02).

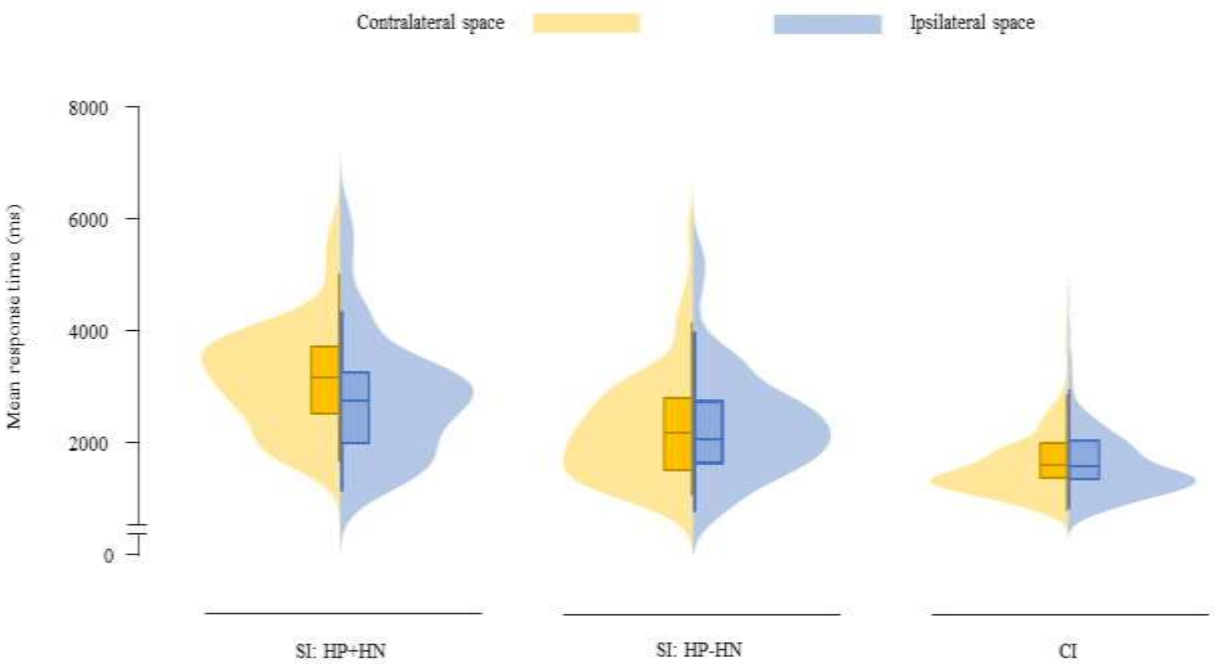


Figure 3a: Violin plots with boxplots illustrating mean response time (milliseconds) to the Peach (target) in contra- and ipsi-lateral space in SI: HP+HN, SI: HP-HN and CI groups.

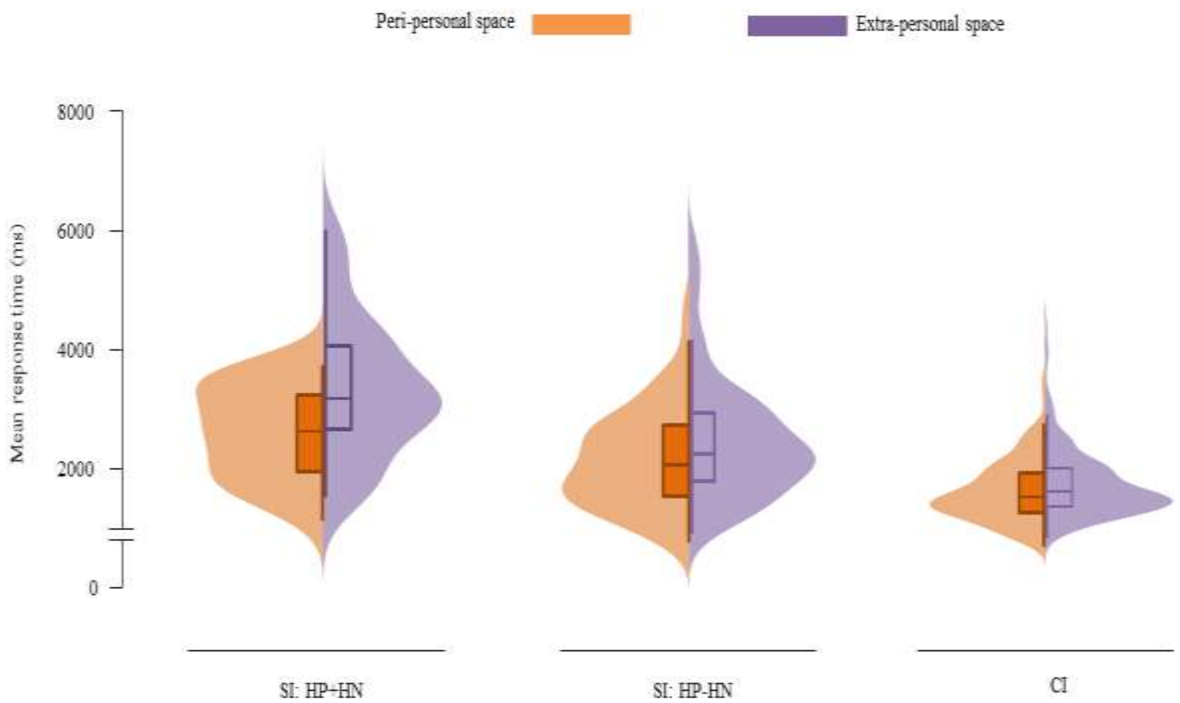


Figure 3b: Violin plots with boxplots illustrating mean response time (milliseconds) to the Peach (target) in peri- and extra-personal spaces in SI: HP+HN, SI: HP-HN and CI groups.

3.3 Analysis: Peach test user experience

The analysis of the 17 SI responses to the UEQ showed that overall, the Peach test had positive evaluations. For all the evaluated dimensions, our results were in the positive range (*Figure 4a*). The highest values obtained were on the Perspicuity dimension (M = 2.69; SD = 0.24), indicating that the Peach test is clear, very easy to understand and participants easily learn how to perform the tasks. The Attractiveness dimension showed a positive rating (M = 1.88; SD = 1.62), showing that the Peach test was enjoyable and attractive, and gave an excellent overall impression. On the Efficiency dimension (M = 1.84; SD = 0.72), participants found the interaction with the test to be efficient and fast. On the Stimulation dimension (M = 1.38; SD = 1.83), participants thought that the Peach test was exciting, motivating, and fun to use. On the Novelty dimension (M = 1.37; SD = 1.95), participants found the Peach test to be innovative and creative. Finally, on the Dependability dimension (M = 1,29; SD = 0.95), participants reported a feeling of safety, and control of their interaction with the virtual environment.

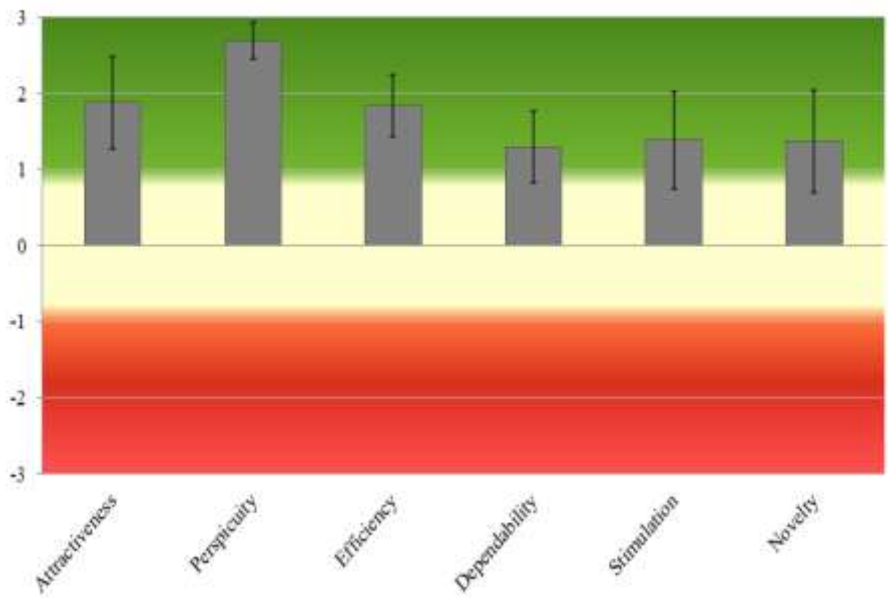


Figure 4a: A graphical representation of the UEQ dimension values given by the SIs.

Based on the UEQ Data Analysis tool, a benchmark was conducted, comparing the Peach test to the 468 products included in the data set. The results demonstrated that Peach test had an excellent mean value on the Attractiveness and Perspicuity dimensions (M = 1.88, & M = 2.69, respectively), meaning that Peach test lies in the range of the 10% best results. It has a good mean value on the Efficiency, Stimulation, and Novelty dimensions (M = 1.84, M = 1.38, & M = 1.37, respectively), meaning that 10% of the products included in the benchmark data set have better results than Peach test, and 75% of these products have worst results. The analysis also showed an above average mean value on the Dependability dimensions (M = 1.29), meaning that 50% of the products included in the benchmark data set had better results than the Peach test, and 25% of these results had worst results (*Figure 4b*).

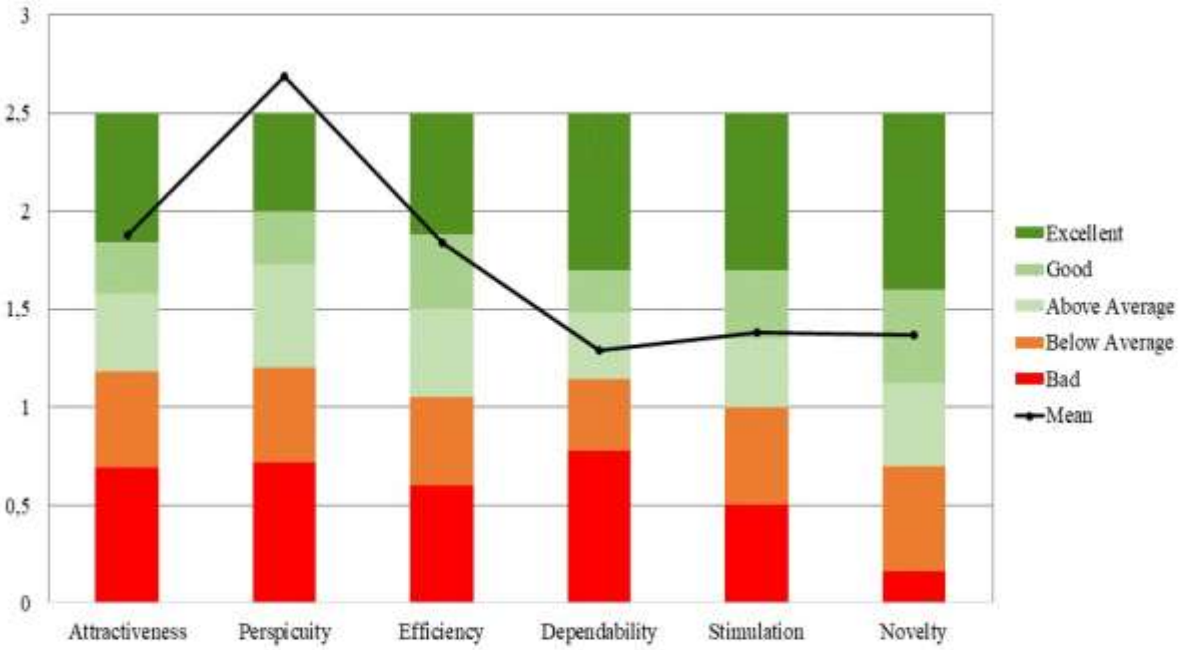


Figure 4b: A graphical representation of the benchmark on Peach test.

4. Discussion

In this paper, we presented a new IVR serious game to evaluate spatial attention by contrasting responses to targets presented in ipsi- versus contra-lateral, and peri- versus extra-personal spaces. The assessment used an interactive serious game, where participants were immersed in a kitchen simulation, and requested to perform a simple visual search task in the presence of avatars. Our first objective was to evaluate the feasibility and user experience of this serious game. For this, we tested a group of sixty healthy control individuals. We hypothesized that the CI would show no laterality effect, but show a proximity effect, and that there would be an interaction between avatar and proximity. Our findings indicated no significant differences when responding to a target presented in the different space contrasts (ipsilateral / contralateral, and peri-personal / extra-personal spaces), and no significant differences in responding to the target presented in the peri- and extra-personal spaces in the no-avatar and the two avatar conditions for both omissions and response time. These results were surprising, because there is a substantial body of evidence showing that perspective taking of a third person presented in front of a participant can automatically influence response performance (Freundlieb et al., 2017; Gunalp et al., 2019; Surtees et al., 2013; von Salm-Hoogstraeten et al., 2020). Further, several papers have demonstrated evidence that participants spontaneously took the spatial perspective of another's perspective causing reversal effects for right/left or near/far spaces (Cavallo et al., 2017; Furlanetto et al., 2013; Samson et al., 2010; Tversky & Hard, 2009). Despite these null effects, the advantage is a stable data profile on which to contrast patients.

In the second analysis of this paper, we contrasted results from a group of post-stroke individuals with hemiparesis without hemineglect, a group of post-stoke individuals with hemiparesis and hemineglect, and a resampled selection of age-matched controls. We hypothesized that SI: HP+HN would show a laterality effect, whereas SI: HP-HN and CI would not show laterality effects, and further, that there would be an interaction between group, laterality and avatar. Our findings indicated that both SI groups were slower than CI, with SI: HP+HN being the slowest group, but that there was no significant effect of laterality in the SI: HP+HN group for both omissions and response time measures, thereby not supporting our hypotheses. This lack of lateralised effect can likely be explained by the SI no longer showing HN at the time of testing, evaluated by standardized test (e.g., Apples test (Bickerton et al., 2011)). Despite these inconclusive results for the SI groups, the present Peach test could still be used to detect spatial attention impairments from omission and response time measures, contrasting target ipsi- and contra-lateral spaces as well as peri-personal and extra-personal spaces. The predicted hypotheses may have more likely demonstrated significant results with acute patients who showed HN at the time of testing.

Our results showed an effect of proximity for both SI groups, with slower responses to the target presented in extra- compared to the peri-personal space. However, there were no interaction effects between group, proximity and avatar, and between group, laterality and avatar. This suggest that there was no shift in the proximity effects for both SI groups with the presence of the avatar, and that the predicted shift for laterality with the SI: HP+HN for perspective was not found. This reversal effect may have been better demonstrated in neurological patients showing representational hemineglect (Becchio et al., 2013; Bisiach & Luzzatti, 1978; Della Sala et al., 2004), or as proposed earlier, with patients having HN at the time of testing. It is possible that acute HN individuals would have shown a lateral bias without the avatar, and a reversal lateralised effect with the presence of the avatar. The same argument can be made for responses to targets in peri- and extra-personal spaces, with the effect for proximity with the SI groups not showing reversal effects with compared to without the avatar due to the SI not being acute. Alternatively, this result may indicate that the avatars were not suitable to provoke reverse effects. Clearly, more studies are needed to test whether the presence of animated 3D avatars can cause perspective taking shifts. These additional studies would add to growing evidence and challenges for the perspective taking paradigm (Cole et al., 2016; Cole & Millett, 2019; Santiesteban et al., 2014).

In traditional neuropsychology assessment, omission measures are currently the standard metric to assess asymmetry bias in spatial attention (Basagni et al., 2017; Demeyere et al., 2019; Plummer et al., 2003; Rorden & Karnath, 2010). When combined with response time, the test diagnostic sensitivity to detect spatial attention impairment is increased, by providing more measures to distinguish between patients with and without hemineglect (Montedoro et al., 2018;

Zimmermann & Fimm, 1995b). HN is a heterogenous syndrome that is more frequent and/or severe after a right lesion, but there is also evidence of right HN after a left lesion (Azouvi et al., 2002; Ogden, 1985; Smania et al., 1998; Vallar, 1998; Vallar et al., 1995). Furthermore, HN can differentially moderate in peri-personal and/or extra-personal space (Aimola et al., 2012; Ten Brink et al., 2019). It is possible that these different sub-types of HN are not systematically evaluated with the current tools used in the clinics. Our peach test can be used to detect biases in responding to ipsi- and contra-lateral space, and it can also simultaneously assess peri- and extra-personal spaces, thus increasing future clinical utility with a broader post-stroke population. An important advantage of using IVR here was that it allowed for the use of large virtual spaces that simulate real-world environments, which can lead to a more ecological task performance.

We evaluated the user experience of the post-stroke patients using UEQ (Laugwitz et al., 2008a). These results showed that the Peach test was easy to understand and use, due to clear and intuitive interactions. The post-stroke individuals, as the end-users, were able to perform the serious game fully without aid from the experimenter. The overall experience was rated positively, and both SI groups enjoyed the serious game and were motivated by implementing a clear and fun storyline, that they engaged with. This is compatible with several recommendations that support the development of ecologically relevant and entertaining neuropsychological measures to enhance the adherence of the participants and present usable and efficient devices (Bauer et al., 2012; Krohn et al., 2020; Lumsden et al., 2016). Our results suggest that aged post-stroke individuals can easily interact with sophisticated technologies, enjoying the experience, thereby confirming the usability of the Peach test as a viable concept for assessment of SI (Cavedoni et al., 2022).

This paper had several limitations that need to be addressed in future studies. Testing the feasibility of the Peach test with neurological patients showing HN at the time of testing is needed, demonstrated using standardised measures. These neurological hemineglect patients must show lateral bias effects in order to test if the presence of an avatar causes reversal effects. It could also be that a larger sample of patients are tested, perhaps showing differences for the avatar perspective taking effects. Additional improvements could be implemented to the

Peach test, such as replacing the key-button response by a more naturalistic interaction with the targets, dispensing the need for catch trials. For this, the inclusion of hand tracking that is available with the head mounted display could be more efficient and useful, since it would enhance the user-experience and provide with action metrics. The compromise will be that the test can only be performed in peri-personal space. Another improvement could be to vary the difficulty of the task to increase test sensitivity for different severities of patients, allowing detection of HN in chronic patients. Moreover, the presence of different difficulty levels could help personalizing the adaptation of the assessment to a treatment based serious game for patients (Bilder & Reise, 2019; Brooks et al., 2009).

To sum up, we have used IVR to develop a novel serious game for the assessment of spatial attention and hemineglect. Although our findings were inconclusive, the Peach test showed excellent usability and acceptance by SI. The serious game comprehended a scenario where participants interacted with avatars. Future studies should focus on investigating the impact that the presence of an avatar has on spatial attention performance, and clinical validity and reliability of Peach test should be studied to allow the use of this virtual test in clinical settings.

Chapter 3

A feature and conjunction visual search immersive virtual reality serious game for measuring spatial and distractor inhibition attention using response time and action kinematics

Background: Treisman and Gelade (1980) proposed that visual-spatial attention to targets presented with distractors involves parallel and serial cognition. When the target is different from distractors by a single feature, the number of distractors does not influence search speed (parallel). However, when the target is different from the distractor by a conjunction of features, increased numbers of distractors increase task difficulty (serial). Here, we developed a serious game in immersive virtual reality (IVR) for evaluating spatial and distractor inhibition attention.

Methods: We tested 60 healthy participants. They performed the serious game in which they had to find a target mole wearing a red miner's helmet. In the single feature parallel conditions, the distractor moles wore blue (miner's or horned) helmets, and in the conjunction feature serial conditions, the distractor moles wore blue miner's helmets or red horned helmets. There were 11-17-23 distractors. Responses were made with the dominant hand by hitting the target with a virtual hammer. We measured mean response time (RT), mean velocity (MV) and coefficient of variation of speed (CV).

Results: Participants were significantly slower (RT and MV) and showed greater CV when responding to targets in conjunction compared to single feature search tasks. Further, participants were slower (RT and MV) and showed greater CV when the number of distractors increased. A significant interaction between search tasks and distractors showed that RT and CV only increased with distractor number for the conjunction search tasks. MV decreased with distractor number for both single and conjunction tasks, with a stronger decrease for conjunction relative to single feature search.

Conclusion: The results replicated previous findings, providing support for the use of immersive virtual reality technology for the simultaneous evaluation of spatial and distractor inhibition attention using complex 3D objects.

Reference: Khawla Ajana, Gauthier Everard, Thierry Lejeune & Martin Gareth Edwards (2023): A feature and conjunction visual search immersive virtual reality serious game for measuring spatial and distractor inhibition attention using response time and action kinematics, Journal of Clinical and Experimental Neuropsychology, DOI: 10.1080/13803395.2023.2218571

1. Introduction

In 1980, Triesman and Gelade reported the results from a series of visual search experiments that lead to the definition of “feature integration theory” (Treisman & Gelade, 1980). In the visual search task, a display was presented to participants containing a target stimulus and several distractor-stimuli. The participant was instructed to find the target, responding rapidly and accurately, and their response time (RT) was measured (Duncan & Humphreys, 1989; Treisman & Gelade, 1980). They systematically moderated the feature similarity between the target stimulus and distractor stimuli. The target could have a distinct single feature shared with the distractors or a conjunction of features shared with the distractors. When the target stimulus was distinguished from distractor stimuli by a single feature (e.g., colour or shape; a red circle target presented with blue circle distractors), Triesman and Gelade defined the search as conducted in *parallel*. They proposed that attention was divided between the target stimulus and distractor stimuli, and the visual features were automatically registered at a pre-attentional level of processing. This phenomenon is now described as the “pop-out effect”. A participant can spontaneously locate the target stimulus as it ‘pops-out’ from the distractor stimuli. Triesman and Gelade showed that when the number of distractors was manipulated in single feature search, the response time was not moderated by the number of distractor stimuli. For example, in a visual field containing a red circle target presented among increasing numbers of blue circle distractors, attention is automatically and rapidly captured by the red circle target relative to the blue distractor circles as the unique feature defining the target from distractors is colour.

Importantly, Triesman and Gelade (1980) proposed that when a target-stimulus is defined by a conjunction of two or more features with the distractor stimuli, the search is conducted in *serial*. Attention is focused on the stimuli features and acts as a “spotlight” that shifts successively to the different stimuli locations in the visual field to process the features one at a time. This attentional processing is slow and effortful and requires memory of which spatial areas have already been searched and spatial planning for which areas of space need to be searched next (i.e. executive function). Treisman and Gelade (1980) showed that this type of visual search was moderated linearly by the number of distractors. For example, in a visual field containing a red circle target presented with a blue circle and red square distractor stimuli (i.e. where the target shares two features with the distractor stimuli), attention is focused on the colour and shape conjunction of the stimuli to find and select the target stimulus from the distractor stimuli, and increased numbers of distractors slow RT as more search is required (Duncan & Humphreys, 1989; Treisman & Gelade, 1980; Wolfe et al., 1989). Feature integration theory has since been criticized and challenged by several research groups (for example, (Driver, 2001; Duncan & Humphreys, 1989; Prinzmetal, 1981; Wolfe et al., 1989)).

Proficiency in visual search can be reduced following brain damage, for example in patients with hemineglect (Milner & McIntosh, 2005). Clinical assessment of visual-spatial search typically presents the patient with a paper or a computer screen, and an array of stimuli containing one or several targets and several distractors (e.g., the Bells test by Gauthier et al. (1989) or the hearts cancellation test by Demeyere et al. (2015)). In these tasks, the patient is asked to mark a line through or point to the targets using a pencil or digital pen, often within a fixed time limit. Patients typically show lateralized impairments by omitting to respond to the target or finding the target more slowly when presented in contralesional relative to ipsilesional space, and in contrast to non-brain-damaged participants (who show no lateralized differences) (Montedoro et al., 2018).

Patients with impairments in spatial search frequently have additional impairments in non-spatial or inhibition attention (Husain & Rorden, 2003; Huygelier & Gillebert, 2020; Pisella & Mattingley, 2004). However, routine clinical assessment of spatial attention rarely includes measures of distractor inhibition (i.e. by systematic manipulation of distractor properties). Furthermore, current clinical assessments are frequently criticized for their limited ecological validity, their lack of coherent measures (e.g., only reliant on omissions), and their lack of detailed modelling of patient performance (Azouvi, 2017; Howieson, 2019; Lezak, 2000). Recent technology-based assessment tools such as Immersive Virtual Reality (IVR) and serious games overcome these limitations (Kato & de Klerk, 2017; Neguț et al., 2016; Rizzo et al., 2004). Tests using IVR significantly reduce external distraction (which is particularly important when testing patients in a clinical setting), and responses made with the IVR controllers are very accurate, providing response time, as well as virtual object interaction and action kinematic measures (which are necessary to better understand interactive behaviour and potential compensation, therefore providing additional data on which to develop efficient clinical interventions). Serious games provide a motivating task that drives the patient to perform at their best ability, increasing test/re-test reliability by reducing variance in performance across different test sessions within a patient. Several studies have used IVR to assess visual search impairment in patients, demonstrating that IVR-based technology could be more sensitive than paper-and-pencil tests, and facilitate patients' motivation and participation (e.g., Jannink et al. (2009), and Knobel et al. (2020)).

Based on recent calls in the literature to improve neuropsychological evaluations using new technologies, our objective was to extend the effects reported by Triesman and Gelade (1980) using a novel 3D immersive virtual reality display and 3D target interaction. The principal goal was to build a new serious game that simultaneously evaluated spatial and distractor inhibition attention using measures of omissions (as in classic paper and pencil tasks), response time (as in new computerized evaluations) and using movement kinematics (novel and currently not possible in the clinic). The additional kinematic measures bring novelty to the paradigm, as well as add multiple measures to potentially improve diagnostic criteria (with the diagnosis of hemineglect based on omissions, reaction time and kinematic variables). Our test extends the paper of Erez et al. (2009) who proposed a (non-immersive) computerized visual search test that involved finding a two-dimensional simple visual red circle target presented among a set of visual blue circle distractors for the single feature search, or blue circle and red square distractors in the conjunction search task. They evaluated the response performance of a group of patients with a right hemisphere lesion showing left-hemineglect, compared to three groups all without hemineglect: patients with a right hemisphere lesion, patients with a left hemisphere lesion, and age-matched healthy participants. Participants had to search for the red circle target that could randomly appear in one of 25 fixed locations and presented with between 3 and 23 distractors randomly presented across trials. The results showed that right hemisphere hemineglect patients showed less correct hit-rate and slower response time for responses to contra- compared to ipsi-lesional targets, whereas healthy control participants showed no lateral differences. All four participant groups showed slower response time for conjunction relative to single feature search, but the analyses did not consider if the differences in conjunction relative to single feature search were greater between groups, and there were no analyses of the interaction between search and distractor number, making it difficult to interpret the effect of inhibition attentional load on the results.

We extend the paper of Erez et al. (2009) by using three-dimensional animated virtual stimuli, by having participants directly respond to the stimuli rather than making a button press, and by measuring omissions, response time and action kinematics. Our objective was to create a clinical diagnostic test based on a well-replicated paradigm that can systematically measure spatial and distractor inhibition attention. As in Erez et al. (2009), we defined spatial attention based on the participant’s ability to find a spatial target presented amongst distractors, contrasting performance laterality in left versus right spatial fields. Using the Triesman and Gelade paradigm, we defined distractor inhibition attention by contrasting the interaction between search type (single feature versus conjunction search) and the number of distractors (with increased numbers of distractors causing reduced performance in conjunction search because of increased distractor inhibition demands). The paradigm was embedded in an IVR serious game, with 3D dynamic stimuli (providing novelty). In the present paper, we describe the technical implementation and the feasibility of this serious game with a group of healthy-aged participants. The rationale for making a feasibility study was that it was not sure that the implementation of 3D animated stimuli presented within an IVR serious game environment, and using direct target responses would replicate the effects demonstrated with simple 2D stimuli. However, based on Zhang and Pan (2022), we were confident that profiles of attention could transfer between 2D computer displays and 3D dynamic IVR displays. They performed two studies evaluating the effects of perspective, memory, and dynamic displays on spatial search. The stimuli were Lego brick configurations presented in 2D or 3D on a screen (Experiment 1) or in IVR (Experiment 2). Participants had to search for a target stimulus that matched a referent presented in the middle of the display (where the referent remained visible during the task, or disappeared, requiring memory). The distractor stimuli differed by shape (all different to the target), evoking a serial search (albeit, not based on conjunction features), and the number of distractors was manipulated. The target could appear in one of 16 possible spatial locations, with the stimuli set presented within concentric rings. Participants responded by pressing a key on a QWERTY keyboard to indicate the presence or absence of the target. Experiment 1 contrasted spatial search for 2D versus 3D objects (0 degrees vs 35 degrees of declination). The results relevant to the present paper showed no differences in accuracy (correct trials) and reaction time measures between the search for 2D versus 3D stimuli but showed that with increased stimuli sets, accuracy was reduced and reaction time increased. Experiment 2 created 3D stimuli (35 degrees), and this time contrasted whether the display was static or dynamic, where the concentric stimuli set rotated on a virtual turntable. They showed no differences in accuracy and reaction time results between Experiments 1 and 2 for the static 3D stimuli (screen vs IVR), and no differences in Experiment 2 between the static and rotating stimuli sets. These data suggest that spatial serial search to complex 3D animated IVR stimuli should replicate search results demonstrated by simple 2D static stimuli.

Consistent with the current literature, we hypothesized : (1) response performance to find the target will be better in the single feature than conjunction feature search tasks (quicker response time and mean velocity, and less coefficient of variance of speed; CV); (2) an interaction between search tasks and the number of distractors will show that for the single feature search task, there will be no change in response time, mean velocity and CV for increased numbers of distractors, whereas, for the conjunction search task, increased numbers of distractors will cause a significant increase in response time, mean velocity and CV; (3) no differences in response performance to find the target on the ipsilateral versus the contralateral side of space.

2. Methods

2.1 Participants

Sixty participants took part in the study aged between 21 and 83 years (M = 48.03, SD = 17.74; 30 females, 11 left-handed). They were recruited through the University of Louvain participation panel and social media groups. The inclusion criteria were: (1) corrected-to-normal vision, (2) a good understanding of French (the language of the task instructions), and (3) no reported history of neurological or psychiatric disorders or motor dysfunction. The exclusion criteria were errors in data capture. Two participants were removed from the full data set for errors in kinematics data. All procedures were approved by the Ethics Committee of the Cliniques Universitaires Saint-Luc, Brussels. Participants received information and gave their informed consent prior to the experiment. No participants withdrew.

2.2 Materials, stimuli, and experimental design

The hardware used in this study consisted of a VR headset (Oculus Quest 2) and one Oculus Quest motion controller. A digital tablet (Huawei MediaPad T, model AGS2-W09) was used by the experimenter to monitor the experiment through a live stream from the Oculus App. The serious game was developed using Unity 2019.3 software (in C# language) and the 3D object models were developed using the modelling software Blender (GPL). The IVR environment consisted of a simulated cartoon-like garden displaying a patch located in front of a fence and composed of twenty-four molehills (4 x 6 grid; see Figure 1a). The three-dimensional position of each molehill was defined in the software. The stimuli were moles that appeared from the molehills (through animation). The target was a stylized mole wearing a red miner’s helmet and distractors were stylized moles wearing different coloured and style helmets (a blue miner’s helmet, a red helmet with horns, and a blue helmet with horns). The participant held a virtual hammer in their dominant hand, operated with the Oculus Quest motion controller (with synchrony between the movement of the virtual hammer and hand controller). The software tracked the position of the virtual hammer and the headset (70hz), and responses were defined by the position of the virtual hammer terminating at the position of a molehill. For each trial, the software defined the molehills from which the targets and distractors appeared. Multimodal visually written and spoken verbal instructions were played at the beginning of the serious game, instructing the participants to hit the target with the virtual hammer.

Before each trial, two red cubes were displayed floating in front of the participants, positioned along their mid-sagittal axis as shown in Figure 1b. One was positioned on the same level as the participant’s eyes and had an illustration of an eye on the cube, and the second was positioned on the level of the participant’s arms and had an illustration of a hammer on the cube. The participants had to simultaneously fixate on the eye-cube and place their hammer on the hammer-cube to initiate each trial. Fixation was defined by head position recorded from the Oculus headset. The two red cubes turned green when the participant’s head position and virtual hammer were correctly located on the two cubes assuring alignment of their attention and action to the sagittal axis of the stimulus display. This was done to ensure a central fixation and starting position for each trial.

The participants were instructed to respond as fast as they could to the target stimulus (red-helmet mole) and to not respond to the distractor stimuli. All the stimuli appeared for a maximum time of 7 seconds. If the participant made no response, the trial was considered as an omission, while if they responded to distractor stimuli, the trial was considered a failed response. If a correct response was made within 7 seconds, the trial was terminated, and the next trial was initiated. There were six levels, with each level consisting of 24 trials (i.e. the target appearing from each molehill in the 6x4 array). The levels were blocked because the test is later intended to be used with patients for cognitive attention diagnosis, and for some patients, the more difficult levels will not be possible. The three first levels involved the feature search task where the target stimulus was presented with 11, 17, and 23 blue-helmet moles (random equal distribution of moles wearing a miner’s helmet or a helmet with horns; levels 1, 2, and 3 respectively). The latter three levels involved the conjunction search task where the target stimulus was presented with 11, 17, or 23 moles wearing either a blue miner’s helmet or a red helmet with horns (random equal distribution; levels 4, 5, and 6 respectively) (Figure 1c). Once the participant finished the game, two ‘CSV’ (comma-separated values) text files were registered on the headset. The first contained the summary measures (i.e. the target position, the level, whether the response was correct, an omission or an error, and for correct responses, the time to reach to the target; the response time). A correct response was defined by the virtual hammer ‘colliding’ with the position of the molehill from which the target stimulus appeared. The second file contained the raw 3D kinematic data for the controller (i.e. X, Y, Z coordinates at 70 frames a second).

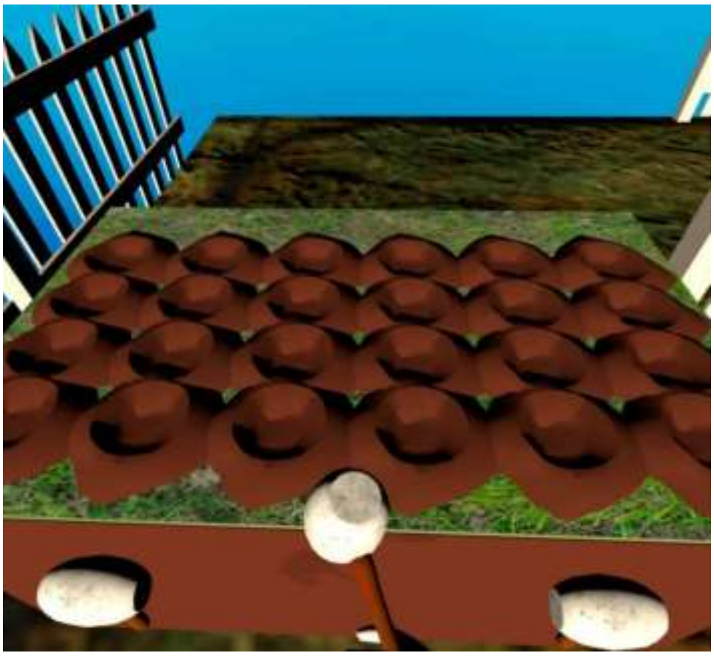


Figure 1a: The mole target and distractor stimuli were presented within a 4 x 6 grid of 24 molehills from which they could appear; three columns in the contralateral space and three columns in the ipsilateral space, relative to the dominant hand of the participant.

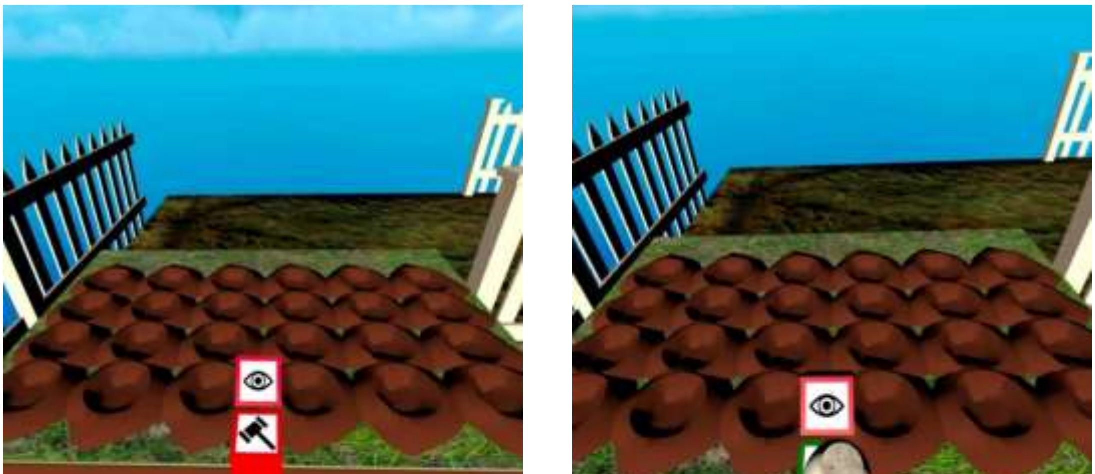


Figure 1b: Before each trial, the participants viewed the 24 empty molehills and two reference cubes, one with an image of an eye that they had to fixate (aligned with head tracking), and one with an image of a hammer, on which they placed their virtual hammer (aligned with the VR controller). This enabled a consistent starting point for each trial.

Figure 1c: The target stimulus was a mole wearing a red miner's helmet. The distractor stimuli were blue-helmet moles (miner's helmet and a helmet with horns) for the single feature task, or moles wearing a blue miner's helmet or a red helmet with horns for the conjunction task. The example display shows the target with 23 random distractors, with 4 stimuli in each column.

2.3 Procedure

The study was run in a controlled laboratory at the Psychological Sciences Research Institute of the University of Louvain and in the Cliniques universitaires Saint-Luc, Brussels. The total test session lasted one hour. Before the study, participants were given instructions regarding the experimental design, and they were invited to sign a consent form. Next, they were invited to sit on a chair at the edge of a table, wearing the VR headset and with the controller in their hands. The participants were then immersed in the simulation, viewing the garden containing molehills. Instructions were displayed and the participant pushed on a virtual start button to initiate a training session containing 10 trials. At the end of this training session, the participant again pushed on a virtual start button to initiate the experiment (a total of 144 trials). Each participant completed the 6 levels consecutively, with a 60-second break after the completion of every level. At the end of the experiment, the participants were thanked for their participation, and they received a payment of 10 EUR for their participation. All participants completed the experiment.

4.1 Methods of data analyses

Data analyses were performed using SPSS 27.0 (IBM) and repeated measures ANOVAs. The independent variables were search task (feature vs conjunction search), distractors (11, 17, and 23), and laterality (ipsilateral vs contralateral space relative to the dominant hand response). Ipsilateral space was defined by the target stimuli being presented in the three columns on the same side as the participant's dominant hand and contralateral stimuli were defined by target stimuli being presented in the three columns on the opposite side of space as the participant's dominant hand.

For correct responses only, the dependent variables were 'means' for the measures of response time (RT) (the time between the presentation of the target stimulus and the moment the hammer hit the target; measured in milliseconds), mean velocity (MV) (the distance covered by the virtual hammer action divided by the response time; measured in meters per second) and coefficient of variation of speed (CV) (the standard deviation of the virtual hammer velocity divided by mean velocity). The kinematic variables were analysed from the three-dimensional X, Y and Z positions of the virtual hammer / hand controller extracted from 'CSV' files registered to the hard drive of the headset for each participant. Analysis of kinematic metrics was made using software developed in Python. Before the analysis, the noise was reduced using a Butterworth 10Hz cut-off frequency filter. Three-dimensional controller positions were then plotted by time to visually ensure that data had been correctly acquired.

From the total data set (i.e. 144 trials x 58 participants; 8352 trials), 195 error responses to distractor stimuli (2.3%) and 265 trials showing omissions (3.2%) were removed. A further 13 trials were removed because they showed abnormal response times (< 250 ms) or trials with null kinematic values. Outlier data was defined using a confidence interval of three standard deviations applied to the mean response time of the remaining data, causing a further 98 trials to be deleted from the total dataset (these trials were removed for all dependent variables). No outlier filter was applied to the kinematic dependent variables.

3. Results

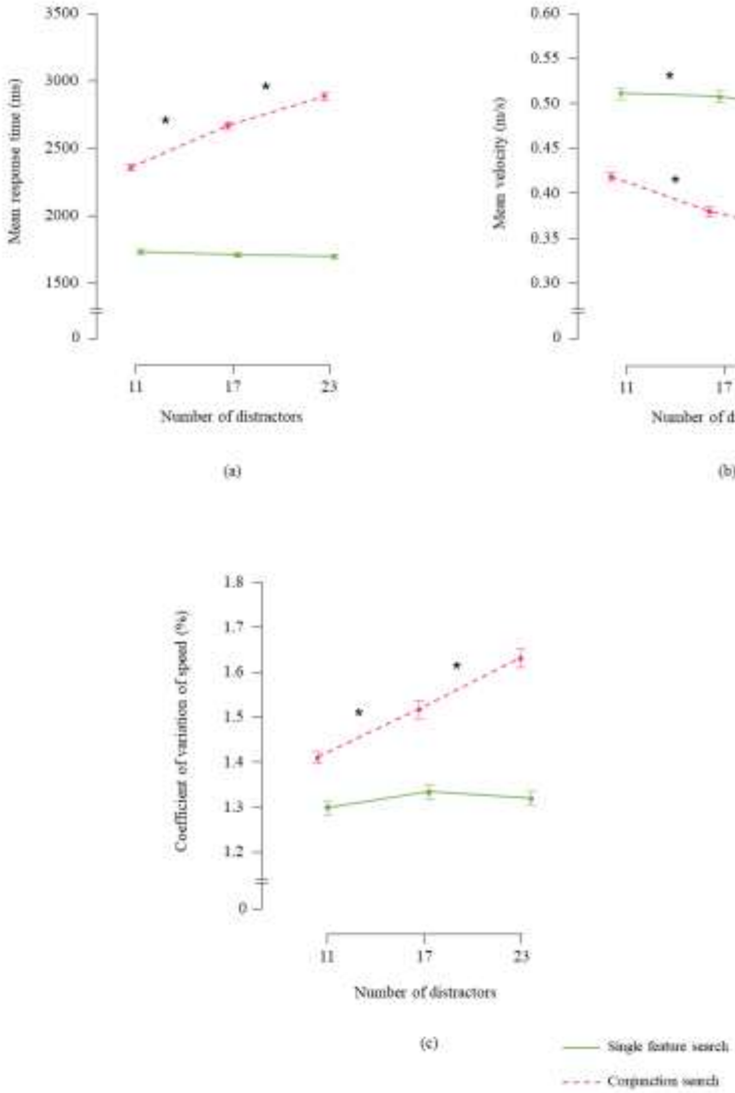
The analysis of response time (RT) showed a main effect of search task, $F(1,57) = 1803.23$, $p < 0.001$, $\eta^2 = 0.97$, where RT was significantly faster in the single ($M = 1713.65$, $SD = 28.67$) compared to conjunction search task ($M = 2636.50$, $SD = 32.74$). It showed a main effect of distractors, $F(2,114) = 103.23$, $p < 0.001$, $\eta^2 = 0.64$, where RT was faster to a target presented with 11 distractors than 17 or 23 distractors, and faster to a target presented with 17 distractors than 23 distractors ($M = 2045.57$, $SD = 31.25$; $M = 2188.46$, $SD = 30.93$; and $M = 2291.18$, $SD = 29.17$ for 11, 17 & 23 distractors respectively). There was no effect of laterality, $F(1,57) = 0.05$, $p = 0.83$, $\eta^2 = 0.001$. As predicted, there was a significant interaction between search task and distractors, $F(2,114) = 117.58$, $p < 0.001$, $\eta^2 = 0.67$ (Figure 2a). A separate ANOVA was run for each search task. This showed that the effect of distractor number was not significant in the feature search task, $F(2,114) = 2.01$, $p = 0.14$, $\eta^2 = 0.034$, but it was significant in the conjunction search task, $F(2,114) = 149.16$, $p < 0.001$, $\eta^2 = 0.72$. A Bonferroni post hoc analysis showed that RT increased as a function of the increased number of distractors in conjunction search task ($M = 2357.61$, $SD = 40.08$; $M = 2667.22$, $SD = 36.77$ and; $M = 2884.66$, $SD = 34.63$ for 11, 17 & 23 distractors respectively). There were no other significant effects.

The analysis of mean velocity (MV) showed a main effect of search task, $F(1,57) = 386.40$, $p < 0.001$, $\eta^2 = 0.87$, where MV was faster for actions made in single feature ($M = 0.50$, $SD = 0.010$) compared to conjunction search ($M = 0.38$, $SD = 0.008$). It showed a main effect of distractors, $F(2,114) = 47.70$, $p < 0.001$, $\eta^2 = 0.46$, where MV was faster for actions made to a target presented with 11 than 17 or 23 distractors, and faster for actions made to a target presented with 17 than 23 distractors ($M = 0.46$, $SD = 0.010$; $M = 0.44$, $SD = 0.009$; and $M = 0.42$, $SD = 0.008$, for 11, 17 & 23 distractors). It also showed a main effect of laterality, F

(1,57) = 27. 21, $p < 0.001$, $\eta^2 = 0.32$, where MV was faster for actions made in contralateral (M = 0.46, SD = 0.010) compared to ipsilateral space (M = 0.42, SD = 0.009). The analysis of MV showed a significant interaction between search task and distractors, F (2,114) = 11.28, $p < 0.001$, $\eta^2 = 0.16$ (Figure 2b). A separate ANOVA was run for each search task. This showed that the effect of distractor number was significant in single feature task, F (2,114) = 4.79, $p < 0.001$, $\eta^2 = 0.08$, and significant in conjunction task, F (2,114) = 61.16, $p < 0.001$, $\eta^2 = 0.52$ (with the interaction likely explained by the difference in the F ratio). A Bonferroni post hoc analysis showed that in both the single and conjunction search tasks, MV decreased (became slower) as a function of the increased number of distractors (single feature search: M = 0.51, SD = 0.012; M = 0.51, SD = 0.011; and M = 0.49, SD = 0.01; conjunction search: M = 0.42, SD = 0.01; M = 0.38, SD = 0.009; M = 0.35, SD = 0.008, with significant differences between MV for 11, 17 & 23 distractor levels). There were no other interactions.

The analysis of the coefficient of variation of speed (CV) showed a main effect of search task, F (1,57) = 51.46, $p < 0.001$, $\eta^2 = 0.47$, where CV was higher for actions made in conjunction (M = 1.52, SD = 0.04) compared to single feature search (M = 1.32, SD = 0.028). It showed a main effect of distractors, F (2,114) = 37.15, $p < 0.001$, $\eta^2 = 0.39$, where CV was higher for actions made to a target presented with 23 distractors than 17 or 11 distractors, and higher in actions made to a target presented with 17 than 11 distractors (M = 1.35, SD = 0.03; M = 1.43, SD = 0.032; and M = 1.47, SD = 0.035, for 11, 17 & 23 distractors). The analyses also showed a main effect of laterality, F (1,57) = 7.13, $p < 0.001$, $\eta^2 = 0.11$, where CV was higher for actions made in ipsilateral (M = 1.44, SD = 0.034) compared to contralateral space (M = 1.40, SD = 0.03). The analysis of CV also showed a significant interaction between search task and distractors, F (2,114) = 24.60, $p < 0.001$, $\eta^2 = 0.30$ (Figure 2c). A separate ANOVA was run for each search task. This showed that the effect of distractor was not significant in single feature task, F (2,114) = 1.74, $p = 0.18$, $\eta^2 = 0.03$, but it was significant in conjunction search, F (2,114) = 53.70, $p < 0.001$, $\eta^2 = 0.48$. A Bonferroni post hoc analysis showed that in conjunction search, CV increased as a function of the increased number of distractors (M = 1.41, SD = 0.037; M = 1.52, SD = 0.041; and M = 1.63, SD = 0.046; with significant differences between each distractor level). There were no other interactions.

Figure 2: (a) Mean response time (milliseconds) to single feature versus conjunction feature target-distractor stimuli with 11, 17, or 23 distractors. (b) Mean velocity (meter per second) to single feature versus conjunction feature target-distractor stimuli with 11, 17, or 23 distractors. The error bars are between participant standard deviation. (d) Coefficient of variation of the speed (%) to single feature versus conjunction feature target-distractor stimuli with 11, 17, or 23 distractors. The error bars are between participants' standard error.



4. Discussion

In the present study, we developed a new IVR serious game based on the visual search paradigm by Treisman and Gelade (1980). As in the classic paradigm, we manipulated distractor features using single versus conjunction feature search tasks, each with increasing numbers of distractors. The objective was to develop a systematic assessment of spatial and distractor inhibition attention. Several measures were taken, including RT, and the kinematic measures of MV and CV. We evaluated the test feasibility with a group of 60 healthy control participants. We observed an interaction between search task and distractor number, with single feature search having no differences between distractor number, but conjunction search showing reduced performance with increased distractor number. Furthermore, we showed no laterality effects.

For the analysis of response time, the results were consistent with our hypotheses. We showed that the IVR serious game adaptation of the paradigm perfectly replicated previous data that used more simple two-dimensional shape and colour stimuli (see, (Duncan, 1985; Kim & Cave, 1995; Müller & Mühlenen, 2000; Ogawa et al., 2002; Quinlan & Humphreys, 1987; Thomas & Lleras, 2009; Wolfe et al., 1989; Wolfe & Pokorny, 1990)). In our single feature search task, the number of distractors had no effect on response time. As in the original paradigm, the 3D animated target mole wearing a red miner's helmet 'popped out' from the 3D animated distractor moles wearing blue helmets, irrespective of the number of distractors. However, in the conjunction search task, where the participants were asked to find the 3D animated target mole wearing a red miner's helmet presented with 3D animated distractor moles wearing either a blue miner's helmet or a red helmet with horns (i.e. the distractors sharing two features with the target), participants were slower to find the target compared to the single feature search task, and increased numbers of distractors in the conjunction search task lead to a greater search time. This base replication of the well-established effects is important for future studies, and particularly important given the step change between the current stimuli (based on the hats worn by 3D animated moles) relative to simple shape/colour stimuli (e.g., a circle or square, red or blue, etc. as in the majority of other single and conjunction feature visual search tests).

The analyses of mean velocity and coefficient of variance of speed (CV) were similar to response time and largely followed our predictions. These variables showed reduced performance when responding to targets presented with conjunction relative to single feature search stimuli. For conjunction relative to single feature stimuli, like response time, mean velocity was slower and the coefficient of variation of speed was greater (more variable). These results are likely explained by the increased inhibition demands for the conjunction relative to single feature stimuli. For the interaction between search and distractors, the dependent variable of the coefficient of variation of speed (CV), showed identical results to response time. For single feature search, there were no significant differences in CV for the number of distractors, but for conjunction search, CV increased as a function of the number of distractors, indicating that CV is clearly influenced by distractor inhibition demands. A similar result was also shown for mean velocity, whereby MV decreased (was slower) for both search types with increased numbers of distractors, but the F ratio was greater for conjunction relative to single feature search, again indicating that increased inhibition demands decreased movement performance. This observed effect is consistent with action-based attention theories. Several studies have shown that kinematics is affected by the presence of distractors and the layout of the target and distractors (Chang & Abrams, 2004; Fischer & Adam, 2001; Pratt & Abrams, 1994; Song & Nakayama, 2006, 2008; Welsh & Elliott, 2004). The presence of distractors influences responses caused by competition for action control, thus reducing performance caused by increasing planning and execution time (Meegan & Tipper, 1999; Tipper et al., 1997; Welsh et al., 1999), as well as movement speed and trajectory (Castiello, 1996; Fischer & Adam, 2001; Welsh & Elliott, 2004).

In the hypotheses, based on prior data for visual search, we predicted no differences in response performance to find and respond to the target placed in ipsilateral versus contralateral space. The results for mean response time supported this hypothesis and replicated previous literature. However, the analyses of the kinematic variables showed lateralization effects. When the 3D animated target mole appeared in the contralateral space (relative to the acting hand), mean velocity was faster and the coefficient of variation of speed decreased compared to when this target appeared in ipsilateral space. This finding can be explained by movements being faster and less variable when they crossed the body’s sagittal axis to respond to targets in contralateral relative to ipsilateral space. This lateralized difference could be explained by the differences in neuronal processing associated with a motor response, after the localization of the target in space, but also in terms of muscular activation and biomechanical constraints operating in the two movements. Indeed, the movement performed, when the target is presented in the contralateral space, consists of a combination of adduction and flexion (which could be more natural physiologically), whereas the movement performed, when the target is presented in the ipsilateral space, consists of a combination of shoulder abduction and extension (which could be less natural physiologically) (Fisk & Goodale, 1985).

The long-term objective of developing the present task was to create a new diagnosis measure of spatial and distractor inhibition attention in a visual search task (extending Erez et al. (2009)) using an IVR serious game with 3D animated stimuli (complementing Zhang and Pan (2022)). We compare performance responses to targets placed on the ipsilateral versus the contralateral side of space to systematically compare spatial responses, and demonstrate if patients show lateralized spatial bias in their performance (Bickerton et al., 2011; Demeyere et al., 2015; Gauthier et al., 1989; Guilbert, 2022). In the present study, as hypothesized, we did not predict lateral differences, for RT, demonstrating that the time taken to find a target was equal for ipsilateral compared to contralateral space. However, there were laterality effects for MV and CV, likely explained by hemispace responses and biomechanical factors. These variables need to be evaluated with hemineglect patients to determine whether they can contribute to spatial lateralization diagnosis (i.e. showing reduced performance to the contra-lesional side). For distractor inhibition, we evaluated the interaction between search type (single vs conjunction feature) and distractor number. We demonstrated significant interactions for RT, MV and CV, all showing reduced performance for the conjunction relative to serial search, and the conjunction search showing reduced performance with increased distractors. This systematic manipulation measures distractor inhibition attention independent of lateralized spatial bias and can be used to better understand if patients with hemineglect show distractor inhibition impairments (for example, showing an increased difference between serial and conjunction search, or a steeper cost of increasing distractor number in the conjunction search task).

We developed our serious game in IVR to improve neuropsychological testing (Pieri et al., 2023; Rizzo et al., 2004; Spreij et al., 2022) by providing a flexible and ecological environment that can combine cognitive and motor response measures (Adams et al., 2017; Faria et al., 2018; Rand et al., 2009). The use of IVR provides the ability to track action responses (as in the present study), as well as add supplementary measures such as eye-gaze tracking to measure visual search prior to target selection (Hougaard et al., 2021; Kaiser et al., 2022a; Ogura et al., 2019). Furthermore, it offers a controlled environment to adapt experimental paradigms to clinical practice demands (Brown et al., 2020; Garrett et al., 2018; Schultheis et al., 2002). Here, we based our development on the visual search paradigm proposed by Treisman and Gelade (1980), as it is considered one of the most influential theories in visual attention research, with a significant number of replications (Arguin et al., 1993; Kristjánsson & Egeth, 2020). It is important to translate other well-developed cognitive paradigms to clinical tests, to provide more detailed clinical assessments (for example, the contextual cueing paradigm (Chun, 2000; Chun & Jiang, 1998; Sisk et al., 2019; Zang et al., 2022)).

In conclusion, we present a systematic combination of spatial and distractor inhibition attention evaluation using an IVR serious game with 3D animated stimuli based on the paradigm reported by Treisman and Gelade (1980). Our results show a replication of the paradigm effect, demonstrating stability in cognitive effects for the transformation of stimuli from simple 2D to complex 3D animated presentations (supporting Zhang and Pan (2022)). There is an urgent need to coordinate between cognitive experimental research and clinical neuropsychology, in order to develop precise and efficient computerized assessment tests (R. P. Kessels, 2019; Treviño et al., 2021), integrating cognitive measurements (e.g., reaction time, errors / omissions) and action response kinematics measurement (e.g., movement velocity, arm path) (Boone et al., 2019; Evans et al., 2009) using realistic ecological environments. Our study demonstrated the feasibility of adopting such improvements for application to clinical assessment. Future studies will involve tests with patients with and without hemineglect to evaluate the validity and reliability of this serious game, as well as the user experience.

Chapter 4

An immersive virtual reality serious game for the assessment of spatial attention and distractor inhibition in stroke individuals: A normative, validity, reliability and user experience study

Background Ajana et al (2023) recently developed a new immersive virtual reality serious game measuring visual-spatial attention and distractor inhibition. It consists of a visual search where a spatial target was presented with two forms of distractors, causing parallel or serial search. The number of distractors does not influence search speed in parallel search, whereas for serial search, increased numbers of distractors increases search speed (with the contrast allowing a measure of distractors inhibition). In this study, we present normative, validity, reliability and user experience analyses of the serious game.

Methods: We firstly tested a group of 31 controls individuals (CI), then a group of 29 post-stroke individuals (9 with hemineglect (SI:HN+) and 20 without hemineglect (SI:HN-). The CI performed REASmash with their dominant hand, and the two SI group performed it with their less-effected hand. The SI also performed two standardized tests. Based on CI performance normative data was created. Validity was evaluated between REASmash and the two standardized tests through correlations. Reliability was measures with test-retest, minimal detectable change, and Bland-Altman plots. User experience was evaluated with user experience questionnaire. We measure response time (RT), mean velocity (MV), coefficient of variance (CV), and omissions.

Results: The results of the CI performance, replicated previous findings (Ajana et al., 2023). Validity analysis was not significant for omissions, and was significantly moderated for (RT). Reliability was excellent of RT and CV, moderated for MV, and poor for omissions. Minimal detectable was established for future use, and Bland-Altman plots showed that overall measures in two testing session are interchangeable.

Conclusion: REASmash, a serious game developed for the assessment of spatial and distractor inhibition attention, demonstrated psychometric standard for concurrent validity, reliability that can be improved, and an excellent user experience in IVR.

1. Introduction

Following a stroke, patients are frequently left with a combination of cognitive and motor impairments (Lezak et al., 2004; Mellon et al., 2015; Sun et al., 2014; Vakhnina et al., 2009), that require precise assessment (Brainin et al., 2015; Demeyere et al., 2016). The most common cognitive impairments after a stroke are attentional deficits, with a prevalence frequency estimated from 30% to 50% (Barker-Collo et al., 2010; Esposito et al., 2021; Hyndman & Ashburn, 2003). These attentional impairments manifest in different forms (Loetscher et al., 2019; Spaccavento et al., 2019). Individuals who have difficulties attending to a stimulus or stimuli in their contra-relative to ipsi-lesional space have a condition known as hemineglect (HN) (Mesulam, 1999; Vallar, 1998). HN is a heterogenous and inconsistent syndrome that manifests by the patient sometimes omitting to find stimuli in contra-lateral space, or making slower responses when finding a target in contra-lateral space (Anderson et al., 2000; Buxbaum et al., 2004; Samuelsson et al., 1998). The cause of HN is related to a disruption of higher-level spatial attention that includes non-spatial inhibition (Corbetta & Shulman, 2011; Heilman et al., 1984; Rode, Pagliari, et al., 2017).

A precise neuropsychological assessment of cognitive functioning in post-stroke patients is considered fundamental for the management of cognitive interventions and rehabilitation (Donders, 2020; Jokinen et al., 2015; Van Zandvoort et al., 2005). Historically, neuropsychology assessment has relied on paper-and-pencil methods (Casaletto & Heaton, 2017; Witsken et al., 2008), but over the past decade, these methods have faced several criticisms for their lack of theoretical modelling and their limited ecological validity (Azouvi, 2017; Barr, 2001; Howieson, 2019; Kessels, 2019). For example, the cognitive processes of inhibition manifest in several daily-life activities, but inhibition is rarely systematically assessed using ecologically relevant methods (Bennett, 2001; Harvey, 2019; Jaillard et al., 2009; Sachdev et al., 2014). Other criticisms include the neuropsychological test batteries that typically take a long time to administer (Cerrato & Ponticorvo, 2017; Vakil, 2012), and the cost of conducting neuropsychological assessment remaining expensive (Collie et al., 2001; Wilken et al., 2003). Rapid advances in technological development allow for several improvements of these criticisms (Fichman et al., 2014; Libon et al., 2021; C. Marques-Costa et al., 2022).

Immersive Virtual Reality (IVR) is a technology that allows users to interact with simulated three-dimensional environments through hardware that is composed of a head-mounted display (containing two offset visual screens) and sensory inputs (e.g., sounds, motion) (Biocca, 1992; Huygelier et al., 2021; Milgram & Kishino, 1994). The two screens create a 3D display that provides a sense of presence and immersion in the virtual environment, enhanced through congruent (actual and virtual) head and arm movement interactions (North & North, 2016; Servotte et al., 2020; Wilkinson et al., 2021). The recent proliferation of (affordable) IVR has allowed widespread development in the field of neuropsychological assessment (Diaz-Orueta et al., 2020; Parsons et al., 2013; Rizzo et al., 2004; Terruzzi et al., 2023). IVR simultaneously offers the benefits of controlled simulated real world visual scenes, and the ability to perform interactive activities that can be recorded, providing precise and detailed performance measures (Parsey & Schmitter-Edgecombe, 2013; Rizzo & Buckwalter, 1997). IVR also provides a safe ecological environment for testing, specifically benefitting patients who could be at risk within an ecological physical environment (e.g., post-stroke patients with mobility and balance risks) (Fernandez Montenegro & Argyriou, 2017; Kalantari & Neo, 2020; Kalantari et al., 2021), but still allowing flexible testing conditions by customizing the simulated environment, and adjusting task difficulty to the performance capabilities of each patient (Parsons et al., 2008; Schultheis et al., 2002). Furthermore, IVR brings the potential to enable fun experiences that can be more motivating and engaging than traditional pencil-and-paper tests (Chang et al., 2019; Doumas et al., 2021a; Parsons & Reinebold, 2012). These several advantages have been acknowledged by the National Academy of Neuropsychology and the American Academy of Clinical Neuropsychology (Bauer et al., 2012; Kourtesis & MacPherson, 2021).

Serious games for assessment can be defined as games testing skills through motivating tasks (Ajana et al., 2023; Lumsden et al., 2016). When combined with IVR, there bring additional benefits to IVR assessment of post-stroke attentional deficits (Martino Cinnera et al., 2022; Nolin et al., 2019; Ogourtsova et al., 2017). For example, Kim et al. (2010) developed a three-dimensional immersive virtual reality simulation of street crossing for the assessment of hemineglect. The main goal was to cross the virtual street without any accident. This required the participant to make a rapid button presses in response to cars approaching an avatar that crossed the road, with the button press moving the avatar forward and no longer on the same path as the moving car. The velocity of the car was used to regulate difficulty. They tested a group of post stroke patients with hemineglect and a group of post-stoke patients without hemineglect on the virtual game and on two standardized paper-and-pencil tests. The results showed a disparity between the two groups, indicating a higher response time and greater use of cues (that attract attention) on the left compared to right side of the display for the patients with hemineglect, whereas patients without hemineglect did not show any significant difference between left and right parameters. Additionally, they demonstrated that the virtual game correlated with the results on the Line Bisection Test, thus demonstrating test validity for the assessment of hemineglect (Kim et al., 2010; Schenkenberg et al., 1980). Another example was reported by Knobel et al. (2021). They tested an IVR visual search serious game with a group of patients diagnosed with hemineglect, compared to a young and older group of healthy controls. The participants had to detect and tag a flying chicken (i.e. a visual target) before the chicken disappeared after a fixed time, with several levels of difficulty. Their hand movements were recorded, and the results showed that while the controls had symmetrically distributed movements, patients with HN showed movements that were bias shifted to the right. The study also showed high usability and acceptance scores for HN patients, making a valid tool for the evaluation of hemineglect (Knobel et al., 2021). These two examples demonstrate how serious games can be adapted to test spatial attention using a fun and motivating test.

Despite advances in the use of IVR for cognitive assessment, currently there are no assessments that systematically measure spatial attention and distractor inhibition using a 3D IVR serious game. We present a novel IVR serious game, the REASmash, developed to systematically assess spatial attention and distractor inhibition deficits (Ajana et al., 2023). Based on the paradigm of Treisman and Gelade (1980), the REAsmash involves the participant searching for a target placed amongst distractors. The target can appear in one of 24 hidden cells (6 columns x 4 rows), providing spatial attention measures by contrasting performance to different spatial locations. The distractors vary by number (11, 17 and 23) and type (High vs

Low target distractors saliency; evoking a parallel vs serial search), providing a measure of inhibition. The REASmash involves a simple and engaging gameplay of a well-known funfair game, where a target mole appears from the ground and the participant was asked to swiftly smash the mole with a virtual hammer before it disappeared back into the hole. The target and distractor stimuli were randomized, reducing practice effects. The test included multiple sensitive measures, including omissions, response accuracy, response time and kinematic measures. In the present paper, our objectives were to validate the REASmash and to evaluate user experience. In the first analysis, we replicated the results of Ajana et al. (2023) with a new group of aged control individuals (CI), and then used these data to create norms. We then used these norms to detect spatial and distractor inhibition attention deficits in 9 post-stroke individuals diagnosed with hemiparesis and HN (SI:HN+). Secondly, we analysed the validity of the REASmash on post-stroke individuals, making correlations between performances on the REAsmash and the Broken Hearts (Demeyere et al., 2015), and the Visual Search sub-test from the Test for Attentional Performance (TAP) (Zimmermann & Fimm, 1995a). We also analysed the reliability of the REASmash on a sub-group of CI using test-retest analyses and Minimal Detectable Change (MDC). Thirdly, we evaluated the user experience on the post-stoke individuals using the User Experience Questionnaire (Laugwitz et al., 2008b).

2. Methods

2.1 Participants

Nine post stroke individuals with hemiparesis and a history of HN diagnosis (none showed HN at the time of testing using standard diagnosis tests) (SI:HN+) (2 females, 3 left-handed), twenty post stroke individuals with hemiparesis and without a history of HN diagnosis (SI:HN-) (7 females, 8 left-handed (*less-effected*)), and thirty-one healthy (17 females, 2 left-handed) control individuals (CI) took part of the study. We used convenience sampling to recruit the SI participants from the physical medicine and rehabilitation department of the Cliniques universitaires Saint-Luc in Brussels, and the CI group was recruited from the University of Louvain participation panel. For the SI participants, two occupational therapist clinicians from Cliniques universitaires Saint-Luc in

Brussels introduced our experiment to their patients. Subsequently, if the patients showed an interest in participating in the experiment, they were contacted by the experimenters being contacted over the phone or in person to explain the experiment's goals and procedures. If they consented to participate, an appointment was scheduled. The SI:HN+ were selected if (1) they presented a first ischemic or haemorrhagic stroke confirmed by CT or magnetic resonance imaging, (2) they presented HN and/or hemiparesis (HP) diagnosed clinically and documented in an evaluation medical report. Any SI having severe communication impairments preventing them from understanding the instructions were excluded. Both the SI and CI were included if (1) they presented normal or corrected-to-normal vision, and if (2) they self-reported a good understanding of French or English (the languages of the task instructions). The CI were excluded if they self-reported a history of neurological, psychiatric or orthopaedic disorders that could have affected their performance.

The SI:HN+ group was aged between 49 and 74 years (M = 58.22, SD = 9.37). At the time of testing, they were between 15.4- and 119.3-months post-stroke on-set (M = 31.54, SD = 33.01), with 3 out of 9 participants having had a haemorrhagic stroke. The SI:HN- group was aged between 62 and 80 years (M = 61.2, SD = 11.02). At the time of testing, they were between 0.2- and 146.2-months post stroke on set (M = 18.80, SD = 33.20) (see *Table 1*). The CI were aged between 50 and 69 years (M = 60, SD = 5.37). There were no exclusions or withdrawal from any of the groups. All participants volunteered to take part in the study, and they received information about the procedure and provided written informed consent prior to the experiment. The CI were given a compensation of 10 euros for their participation. All procedures were approved by the Cliniques universitaires Saint-Luc Ethics Committee, which was registered on Clinical.gov (NCT04694833).

Table 1: SI demographic characteristics. The data for the Broken hearts OCS sub-test and Visual Search TAP subtest shows omissions data for contralateral subtracted from ipsilateral (whereby a negative number indicates more omissions on the contralateral side of space).

	Patient ID nb.	Gender	Age	Handedness pre-stroke	Handedness post-stroke	Stroke site	Stroke type	Stroke laterality	Months post-onset	Broken hearts OCS sub-test (omission in contralateral space)	Visual Search TAP sub-test (omission in contralateral space)
SI:HN+	1	M	49	Right	Left	Left sylvien fissure	Ischemic	L	15,4	6 (4)	8 (4)
	2	M	52	Right	Right	Superficial and deep Sylvian and secondary right occipital	Ischemic	R	15,4	13 (5)	5 (3)
	3	M	64	Right	Left	Left parietal intraparenchymal	Haemorrhagic	L	12,9	9 (1)	24 (12)
	4	M	67	Right	Right	Right sylvien fissure	Ischemic	R	19,1	6 (1)	7 (3)
	5	M	61	Right	Left	Left thalamus	Haemorrhagic	L	4,3	4 (3)	8 (5)
	6	F	74	Right	Right	Right sylvien fissure	Ischemic	R	30,6	10 (6)	12 (9)
	7	M	55	Right	Right	Right thalamus	Hemorrhagic	R	24	2 (0)	7 (4)
	8	F	44	Right	Right	Right sylvien fissure	Ischemic	R	119,3	4 (3)	6 (2)
	9	M	58	Right	Right	Right superficial sylvien fissure	Ischemic	R	42,9	1 (1)	6 (5)

SI:HN-	1	M	47	Right	Left	Left lenticulostriate intraparenchymal hematoma	Hemorrhagic	L	6,8	0 (0)	11 (4)
	2	F	62	Right	Right	Right sylvien fissure	Ischemic	R	19,6	1 (1)	9 (1)
	3	M	56	Right	Right	Right thalamus	Ischemic	R	1,3	2 (1)	4 (1)
	4	F	51	Right	Left	Left sylvien fissure	Ischemic	L	3,7	1 (0)	5 (2)
	5	M	62	Right	Right	Right internal capsule lacunar	Ischemic	R	17,6	1 (0)	13 (6)
	6	M	69	Right	Left	Left paramedian pontine	Ischemic	L	36	1 (1)	2 (0)
	7	M	46	Right	Left	Left sylvien fissure	Ischemic	L	22,4	1 (0)	8 (0)
	8	F	79	Right	Left	Left sylvien fissure	Ischemic	L	2,3	4 (3)	5 (3)
	9	M	73	Right	Right	Right sylvien fissure	Ischemic	R	1,6	1 (1)	18 (13)
	10	M	74	Right	Right	Right sylvien fissure	Ischemic	R	9,8	3 (2)	13 (10)
	11	M	61	Right	Right	Right superficial and deep sylvien fissure	Ischemic	R	5,5	2 (0)	8 (5)
	12	M	47	Right	Left	Left temporal	Ischemic	L	0,2	3 (1)	0 (0)
	13	F	56	Left	Right	Right internal capsule	Ischemic	R	3	0 (0)	1 (1)

	14	M	65	Right	Right	Right capsulo-lenticular territory	Ischemic	R	0,95	2 (0)	1 (1)
	15	F	72	Right	Right	Right sylvien fissure	Ischemic	R	146,2	1 (1)	10 (7)
	16	F	50	Right	Right	Right deep temporal	Hemorrhagic	R	48,2	1 (0)	2 (2)
	17	M	50	Right	Left	Left pontine	Hemorrhagic	L	39,9	0 (0)	0 (0)
	18	F	55	Left	Right	Right sylvien fissure	Ischemic	R	3,4	6 (2)	10 (9)
	19	M	69	Right	Right	Right frontoparietal intraparenchymal	Hemorrhagic	R	4,1	2 (1)	15 (7)
	20	M	80	Right	Left	Left corona radiata	Ischemic	L	3,6	15 (8)	12 (5)
SI: HN+ Mean (SD)			58.22(9.3)						31.54(33.0)		
SI: HN- Mean (SD)			61.2(11.0)						18.8(33.2)		

2.2 Materials, Stimuli and Experimental Design

The IVR equipment used in this study consisted of a standalone headset device (Oculus Quest 2) integrating four infrared cameras that tracked the head and hand positions (acquisition frequency = 70 Hz). The equipment also consisted of a digital tablet (Huawei MediaPad T, model AGS-W09) used to stream the REASmash in real time allowing the experimenter the ability to follow the participants interactions within the virtual environment. The virtual environment was developed in C# language using Unity 2019.3 software, and the 3D objects were developed using Blender software (GPL).

Participants were invited to sit on a chair wearing the headset. One motion controller was used. The SI held the controller in their non-hemiparetic hand (i.e., the post-stroke dominant hand) and the CI held the controller in their dominant hand. Once immersed in the virtual environment, the participants could see a simulated cartoon-like garden composed of a raised-bed garden patch with twenty-four molehills, organized within a 6 column by 4 row grid. From these molehills, animated moles could randomly appear. The target was stylized mole wearing a red miner's helmet and the distractors were stylized moles wearing blue miner's helmets or helmets with horns that were coloured blue or red. Responses were made by hitting the target-mole with a virtual hammer (corresponding to the movement of the hand controller).

Before starting the experiment, written and spoken instructions were presented within the IVR to the participants (see *Figure 1a*). The participants were instructed to only respond to the target mole, and to make their responses as fast as possible. The target and distractor moles appeared for a period of 7000 milliseconds maximum. If the participants responded correctly, the trial was recorded as a *success*. If the participants did not respond within the 7000 milliseconds, the trial was recoded as an *omission*. If the participants responded to the incorrect mole (i.e. a distractor-mole), the trial was recorded as a *fail*. The trials were automatically initiated after a fixation task to confirm a consistent central fixation and starting position before each trial. This consisted of fixating a central red cube marked with an illustration of an eye placed at the level of the participant's eyes (tracked with head position), and placing their virtual hammer on a second central red cube marked with an illustration of a hammer, placed at the level of the participant’s arm. Once the head and hand positions were correctly aligned, the cubes turned from red to green, assuring alignment of attention and action to the mid-sagittal axis of the stimulus display.

Figure 1a: Multimodal visually written and spoken instructions were displayed at the beginning of the REASmash (in EN: (1) “Welcome to REASmash! Let’s play! Here is your mission: Hit the mole wearing a red helmet as fast as you can”, (2) “We will train first.”).

The REASmash consisted of 6 levels, with each level consisting of 24 trials (i.e. the target mole appearing randomly from each of the 24 molehills). In the three first levels, the target appeared with 11, 17 and 23 distractor moles (levels 1, 2 and 3 respectively), with the distractor moles all wearing blue helmets (a miner’s helmet or a helmet with horns; forming a high saliency contrast and provoking parallel search). In the latter three levels, the target appeared with 11, 17 and 23 distractors (levels 4, 5 and 6 respectively), with the distractor moles all wearing helmets with horns colored red or blue (forming a low saliency contrast and provoking serial search). The distribution of distractor types was close to equal among the 6 levels (e.g., 5 blue miner’s helmet moles and 6 blue horned helmet moles in level 1 or 11 red horned helmet moles and 12 blue horned helmet moles in level 6). Distractors were evenly spread across the grid, with 2, 3 and 4 distractors placed in each column associated to level increase. The position of the distractors within the columns of the grid were randomized for every trial. As the REASmash was designed for individuals with cognitive impairments, the six levels were blocked to ensure that the clinical test could be adapted to suit the performance capability of the patient, without the test being overly easy / challenging and discouraging (*Figure 1b*).

Two standardized hemineglect diagnosis tests were administered to the participants to assess their cognitive performance and to validate the REASmash. These consisted of The Broken hearts sub-test from the Oxford Cognitive Screen (OCS) (Demeyere et al., 2015) and The Visual Search sub-test from the Battery for Attentional Performance (TAP) (Zimmermann & Fimm, 1995a). The Broken hearts sub-test from the Oxford Cognitive Screen (OCS) (Demeyere et al., 2015) was used to verify visuo-spatial attention performance through omission measures. Participants were instructed to cross out complete hearts (a total of 50 complete hearts) presented amongst broken heart distractors (a total of 100 broken hearts). The target hearts were displayed randomly within in an invisible grid composed of 10 cells, with 5 targets in each cell. The total omissions (independently of the space) and the omissions asymmetry between ipsi- and contra-lesional hemispaces (i.e. the difference of omissions between the two hemispaces) were analysed. The test is accessible and available in different languages. The Visual Search sub-test from the Battery for Attentional Performance (TAP) (Zimmermann & Fimm, 1995a) was used to measure the visuo-spatial attention performance through omissions and response time measures (matching the REASmash). Participants were instructed to detect a target stimulus that appeared among a set of distractors stimuli. These stimuli were presented within an invisible grid of 5 columns and 5 rows. The total omissions, the total mean response time for correct responses, the omissions asymmetry between the ipsi- and contra-lesional hemifields, and the mean response time asymmetry for correct responses between the ipsi- and contra-lesional hemifields were analysed.

User experience was evaluated using the User Experience Questionnaire (Laugwitz et al., 2008b; Schrepp, 2015). The questionnaire consisted of six scales: Attractiveness, Efficiency, Perspicuity, Dependability, Stimulation, Novelty. The attractiveness scale consisted of 6 items, whereas the other scales consisted of 4 items. The total of 26 items were presented as opposite pairs (e.g., for efficiency, rating fast vs slow), to which the SI were required to respond by rating each pair on a 7-point Likert scale. The standard expected value of each scale was between -3 and +3. The questionnaire is accessible in various languages, with a data analysis tool that facilitates evaluation (Schrepp, 2023).

2.3 Procedure

The experiment took place in a controlled laboratory in the Cliniques universitaires Saint-Luc – Brussels and in the Psychological Sciences Research Institute of the University of Louvain. It lasted approximately one hour. The study started with the participants receiving oral information from the experimenter about the experimental design. The participants were then invited to sign the informed written consent as an agreement to take part of the study. They were invited to sit on a chair with a back support, and with their feet on the ground. They performed, the REASmash and the two standardized clinical tests in a random order. To execute the REASmash, the headset and controller were adjusted. Once immersed in the virtual environment, oral and written instructions were displayed within the IVR. Following the instructions, a training session consisting of 10 trials was given to the participants to ensure that they understood the task, and to enhance their sense of familiarity with the stimuli and the environment prior to experimentation. After this training session, the participants pushed a start button to initiate the full serious game (i.e. the 6 levels; 24 trials x 6). A 60 second break was provided between each level to reduce fatigue.

At the end of the REASmash game, two separated CSVs files were compiled and stored in the IVR headset. The response time CSV contained a summary of measures (e.g., position of the target, type of response, response time). The action kinematic CSV contained the raw kinematics data from the controller (i.e., X, Y, and Z coordinated at 70 frames a second). The SI participants used the same location to perform the two standardized tests, and the User Experience Questionnaire (given at the end of the REASmash). The CI were only required to perform the REASmash (and not the two standardized tests and User Experience Questionnaire). A randomly selected sub-group of the CI were invited back to redo the REASmash to measure test reliability and minimal detectable change.

2.4 Methods of data analyses

The data analyses were run using SPSS 27.0 (IBM). The independent variables were search task (High vs Low distractors saliency), number of distractors (11, 17, 23), and laterality (ipsilateral vs contralateral space relative to the dominant hand). The dependent variables were response time (RT; the duration between when the target was presented and when the hammer hit the target; milliseconds), mean velocity (MV; the average speed of the virtual hammer action between the starting position and target position; computed as the distance travelled divided by response time; meters per second), and coefficient of speed of variation (CV; the standard deviation of the virtual hammer velocity divided by mean velocity). The analysis of these variables used the three-dimensional X, Y and Z positions of the virtual hammer extracted from the 'CSV' files saved on the headset hard drive for each participant.

The first analysis consisted of an ANOVA, with the aim to replicate the data presented in Ajana et al. (2023). For this analysis, we removed from the total data set (i.e. 144 trials x 31 CI; 4464 trials), 62 trials showing fails (1.38%), and 36 trials showing omissions (0.81%). 65 trials in which RT deviated more than 3 standard deviations from the mean for all dependent variables were discarded and removed as outliers (1.45%). There were no trials in which CI responded incorrectly (<250ms), and no outlier filters were applied to kinematic measures.

Norms were created from the CI group REASmash performance using 95% confident intervals derived from the repeated measures ANOVA. The objective was to provide a case comparison of the SI:HP+HN relative to the CI group. As we were primarily interested in using the REASmash for the diagnosis of HN, we created norms for contrasted responses to contralateral versus ipsilateral hemispace targets for each dependent variable (as direct contrasts would only be able to show if HN individuals were slower than the CI group). These contrasts instead allowed evaluation of a bias in response between hemifields. We additionally created norms for contrasted responses to easy (high salience contrast) versus difficult (low salience contrast) tasks for each dependent variable, which allowed evaluation of a bias in distractor inhibition. The multiple case analyses were used due to the relatively small sample size of individuals with HN, the large heterogeneity between individuals with HN, and because not all individuals with HN showed evidence of HN at the time of testing with the standardized tests (see *Table 1*). The SI:HN+ data set consisted of 9 participants and 144 trials (1296 total trials). Trials in which the SI:HN+ participants responded incorrectly (26 fails, and 80 omission errors) were removed. There were no abnormal responses (<250 ms).

Concurrent validity analysis (Mokkink et al., 2010) consisted of verifying if the contralateral and ipsilateral contrast omissions and RT results obtained with the REASmash were correlated to the results obtained with the two standardized tests (OCS Broken hearts sub-test and TAP Visual search sub-test). This analysis was performed on all the SI participants (who performed the REASmash and the two standardized tests). The normality of each analysis was verified using Shapiro-Wilk test. Correlation coefficients of $\rho < 0.25$ were considered as small; 0.25–0.50 as moderate; 0.50–0.75 as good; and > 0.75 as excellent (Portney & Watkins, 2009).

To evaluate REASmash reliability, a subgroup of 20 CI was selected based on availability. A two-way mixed model Intraclass Correlation Coefficient (ICC) based on absolute agreement between two repeated measures of REASmash from the same person were performed (Bravo & Potvin, 1991; Koo & Li, 2016; Li et al., 2015; Shrout & Fleiss, 1979). Values less than 0.40, between 0.40 and 0.75, and greater than 0.75 were indicative of poor, moderate, and excellent reliability, respectively (Anderson et al., 2000). The standard error of measurement (SEM), and the minimal detectable change (MDC) were used to determine whether the change observed in the performance represent real improvement at the 95% confidence interval (CI) level, and Bland Altman analysis was used to quantify absolute reliability with 95% limits of agreements (LoA) (Dontje et al., 2018; Lee et al., 2013; Weir, 2005). The SEM indicated the within-subject variability attributable to repeated measures to a group of individuals (Charter, 1996; Kovacs et al., 2008). It was used to compute the MDC, following these calculations: $SEM = SD * \left(\sqrt{1 - ICC}\right)$; $MDC = SEM * 1.96 * \sqrt{2}$, with SD referring to the standard deviation for all observation in the test and re-test sessions (Overend et al., 2010; Ries et al., 2009). The Bland-Altman plots visually depict the differences between-session difference (y-axis) versus the test-retest mean for each measurement (x-axis) (i.e. RT and Kinematics measures). The LoA were computed using $\bar{d}$, the mean difference per measure, and SDdifference, the standard deviation of the mean difference, following use of the following calculation: $LoA = \overline{d} \pm 1.96\ SD$difference. These LoA represents the range within which 95% of the differences between the two measurements (from two sessions) are expected to align (Bland & Altman, 1986; Doğan, 2018).

The analysis REASmash user experience was performed using the data analysis tool (excel sheet) provided by the authors (Laugwitz et al., 2008b). The results were encoded in the tool, followed by an automatic transformation scaling the items from -3 to +3. The tool calculated the mean, and standard deviation. These results were compared to classification benchmark value. The mean and standard deviation was computed for each scale. A mean score below - 1 indicates a poor experience, above 1 indicates an excellent experience, and a mean score ranging from -1 to 1 indicates a neutral experience.

3. Results

3.1 Analysis: CI group Replication analysis

The analysis of mean response time (RT) showed a main effect of search task, $F(1,30) = 894.09$, $p < 0.001$, $\eta^2 = 0.97$, where RT was significantly slower in the low compared to high target distractors saliency (Low: M = 2954.59, SD = 51.44; High: M = 1869.74, SD = 42.95). There was also showed a main effect of distractors, $F(2,60) = 70.69$, $p < 0.001$, $\eta^2 = 0.70$, where RT was significantly slower in tasks where the target appeared with 23 distractors, than 17 or 11 distractors, and where it appeared with 17 than 11 distractors (M = 2553.48, SD = 46.30; M = 2415.81, SD = 46.05; M = 2267.20, SD = 45.44, for 23, 17, and 11 distractors respectively). However, there was no main effect of laterality, $F(1,30) = 1.17$, $p = 0.29$, $\eta^2 = 0.04$. As hypothesized, there was a significant interaction between search task and distractors, $F(2,60) = 38.30$, $p < 0.001$, $\eta^2 = 0.56$ (*Figure 2a*). A separated ANOVA was performed for each search task. This showed a significant effect of distractors in the low target distractors saliency, $F(2,60) = 61.74$, $p < 0.001$, $\eta^2 = 0.67$, but no significant effect of distractors in the high target distractors saliency search tasks, $F(2,60) = 2.60$, $p = 0.08$, $\eta^2 = 0.08$. For the low target distractors saliency search tasks, a Bonferroni post hoc analysis showed that RT increased with an increasing number of distractors (M = 3223.07, SD = 58.86, M = 2948.26, SD = 55.76, M = 2692.44, SD = 60.38, for 23, 17, and 11 distractors respectively). There were no other interactions.

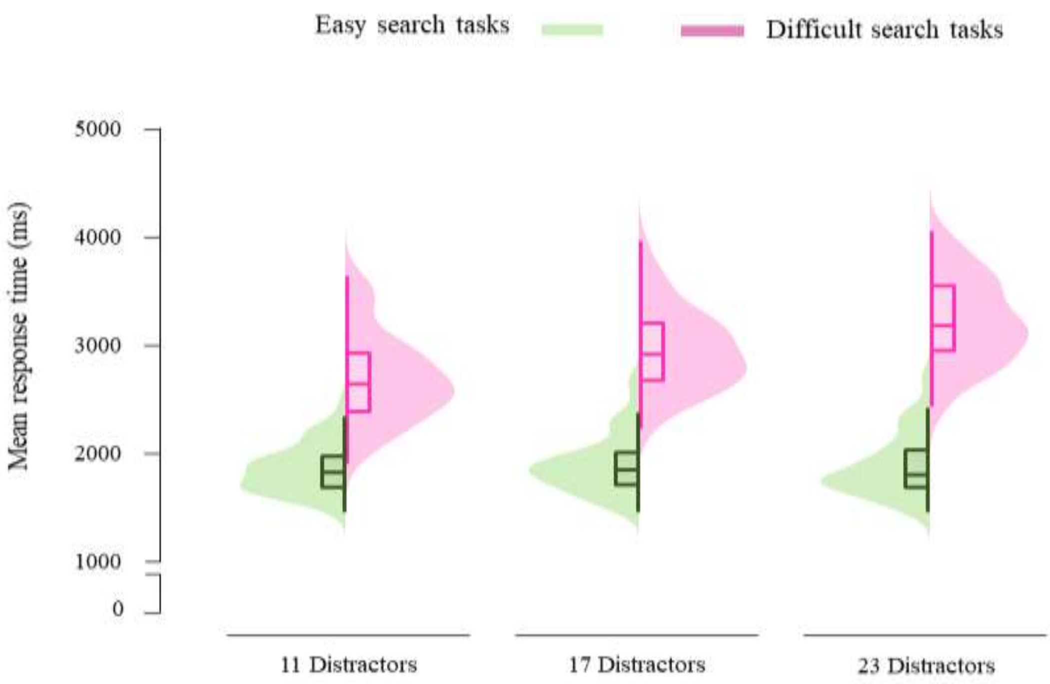


Figure 2a: Violin plots with boxplots illustrating mean CI performance to a target presented in easy and difficult search tasks with 11, 17, and 23 distractors for RT

The analysis of mean velocity (MV) showed a main effect of search task, F (1,30) = 211.11, $p < 0.001$, $\eta^2 = 0.87$, where MV was significantly slower in the low compared to high target distractors saliency versions of task (difficult: M = 0.33, SD = 0.01; easy: M = 0.44, SD = 0.01). There was a main effect of distractors, F (2,60) = 10.84, $p < 0.001$, $\eta^2 = 0.26$, where MV was significantly slower in tasks where the target appeared with 23 distractors, than 17 or 11 distractors, and where it appeared with 17 than 11 distractors (M = 0.37, SD = 0.1; M = 0.38, SD = 0.1; M = 0.39, SD = 0.12, for 23, 17, and 11 distractors). There was also a main effect of laterality, F (1,30) = 19.30, $p < 0.001$, $\eta^2 = 0.39$, where MV was significantly slower for responses to targets presented in the ipsilateral compared to contralateral space (ipsilateral space: M = 0.37, SD = 0.01; contralateral space: M = 0.40, SD = 0.01). As for RT, the analysis of MV showed a significant interaction between search task and distractors, F (2,60) = 10.41, $p < 0.001$, $\eta^2 = 0.26$ (*Figure 2b*). A separated ANOVA for each search task showed a significant effect of distractors in the low target distractors saliency search task, $F(2,60) = 18.22$, $p < 0.001$, $\eta^2 = 0.38$, but no significant effect of distractors in the high target distractors saliency task, $F(2,60) = 1.26$, $p = 0.29$, $\eta^2 = 0.04$. For the low target distractors saliency search tasks, a Bonferroni post hoc analysis showed that MV decreased (was slower) with more distractors (M = 0.31, SD = 0.01; M = 0.33, SD = 0.01; M = 0.35, SD = 0.01, for 23, 17, and 11 respectively). There were no other interactions.

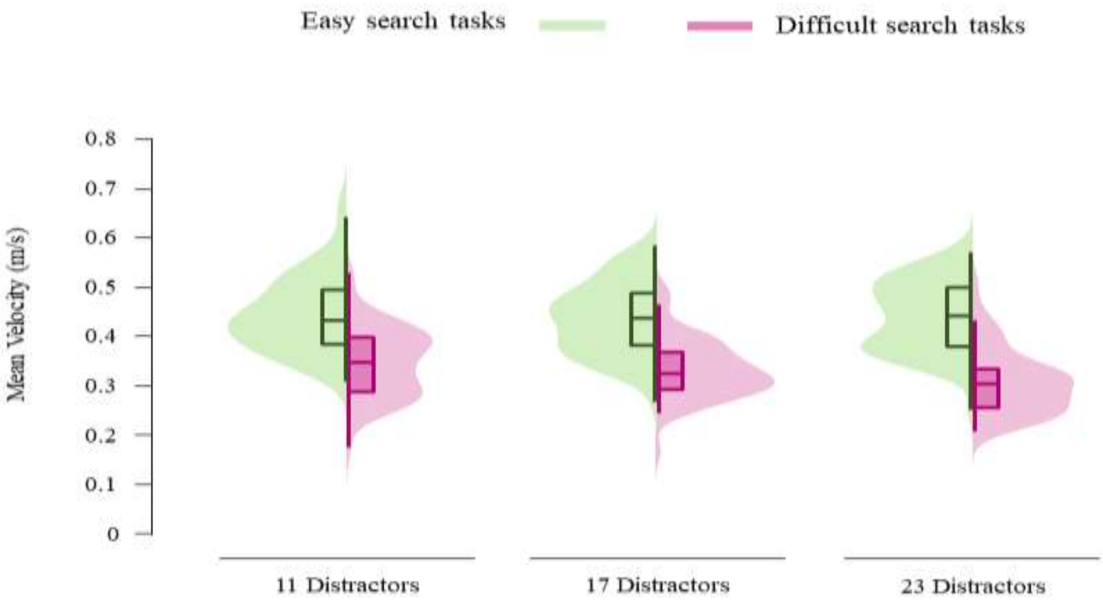


Figure 2b: Violin plots with boxplots illustrating mean CI performance to a target presented in easy and difficult search tasks with 11, 17, and 23 distractors for MV.

The analysis of coefficient of variation of speed (CV) showed a main effect of search task, $F(1,30) = 48.41$, $p < 0.001$, $\eta^2 = 0.62$, where CV was greater for actions made in the low compared to high target distractors saliency tasks (difficult: M = 1.64, SD = 0.7; easy: M = 1.37, SD = 0.05). There was a main effect of distractors, $F(2,60) = 21.10$, $p < 0.001$, $\eta^2 = 0.41$, where CV was greater for actions made in tasks where the target appeared with 23 distractors, than 17, or 11 distractors, and where it appeared with 17 than 11 distractors (M = 1.57, SD = 0.058; M = 1.48, SD = 0.057; M = 1.46, SD = 0.055, for 23, 17, and 11 respectively). There was also a main effect of laterality, $F(1,30) = 11.04$, $p < 0.001$, $\eta^2 = 0.27$, where CV was greater for actions made in ipsilateral compared to contralateral space (ipsilateral space: M = 1.54, SD = 0.06; contralateral space: M = 1.47, SD = 0.05). The analysis of CV again showed a significant interaction between search task and distractors, $F(2,60) = 18.25$, $p < 0.001$, $\eta^2 = 0.38$ (*Figure 2c*). A separated ANOVA was performed for each search task. This showed a significant effect of distractors in the low target distractors saliency, $F(2,60) = 33.77$, $p < 0.001$, $\eta^2 = 0.53$, but no significant effect in the high target distractors saliency tasks, $F(2,60) = 0.081$, $p = 0.92$, $\eta^2 = 0.003$. For the low target distractors saliency search tasks, a Bonferroni post hoc analysis showed that CV increased as a function of increasing number of distractors (M = 1.77, SD = 0.8; M = 1.60, SD = 0.07; M = 1.55, SD = 0.06, for 23, 17, and 11 distractors respectfully). There were no other interactions.

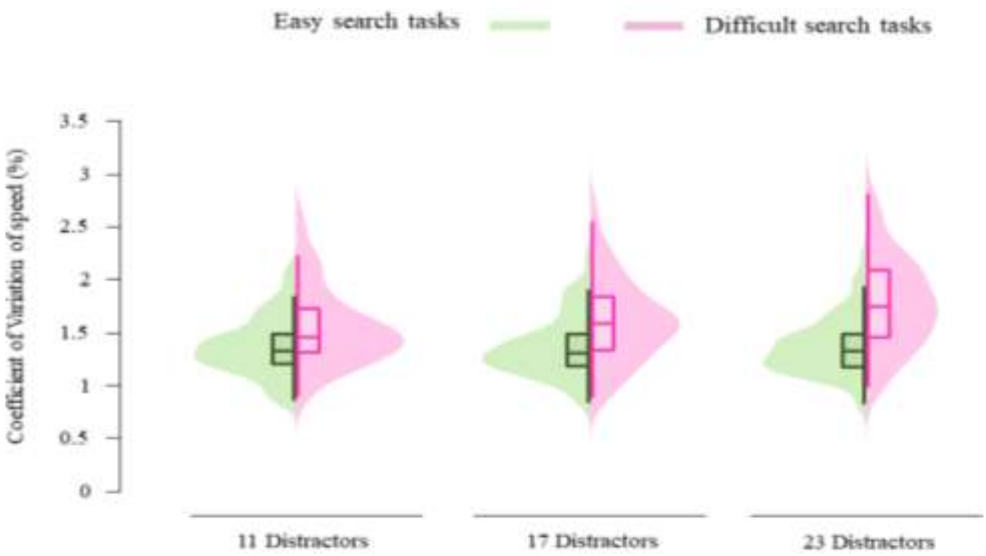


Figure 2c: Violin plots with boxplots illustrating mean CI performance to a target presented in easy and difficult search tasks with 11, 17, and 23 distractors for CV.

3.2 Analysis: CI Group REASmash Norms and SI:HN+ comparisons

Tables 2 and 3 show the norms for the RT, MV and CV dependent variables for the CI responses to the REASmash across the three independent variables combinations for contrasts between contralateral and ipsilateral space (calculation: ipsilateral - contralateral; a negative number indicates a contralateral bias; Tables 2a-c) and for contrasts between easy and difficult tasks (calculation: difficult - easy; a positive number indicates reduced performance for the difficult relative to easy tasks; Tables 3a-c). In the subsequent rows, the mean data for each SI:HN+ mean data is compared to the norms.

For contrasts between contralateral and ipsilateral space, stroke individuals (SI:HN+) 3 and 6 showed consistent significantly longer RT in contralateral space, with SI 1 and 2 showing a similar but less consistent significant result (i.e. 5/6 significant effects). SI:HN+ 5 showed an opposite to HN bias, with consistently longer RT in ipsilateral than contralateral space. For MV, SI 1, 2 and 8 showed consistent significant lateral bias (slower MV for contralateral targets), with SI 3 and 4 showing less consistent significant effects. For CV, only SI:HN+ 7 showed consistent significantly more CV in contralateral space (*Tables 2a-c*).

For contrasts between easy and difficult tasks, only SI:HN+ 4 showed consistent significantly slower RT for difficult relative to easy tasks and only SI:HN+ 6 showed consistent significantly slower MV for difficult relative to easy tasks. For CV, SI:HN+ 3, 4 and 7 showed consistent significantly greater CV for difficult relative to easy tasks, with SI:HN+ 9 showing a similar but less consistent significant result (i.e. 5/6 significant effects) (Tables 3a-c).

Table 2: Laterality contrast between norms for the dependent variables: (a) RT; (b) MV; (c) CV. Laterality contrasts were made for ipsilateral minus contra-lateral results, which was approximatively zero for CI. For each SI:HN+, a significant lateral bias is indicated by a result outside the boundaries of the confidence interval. The results in blue are below the confidence interval, in red are above the confidence interval, and in black are within the confidence interval. Individuals

*marked with ** signify consistent significant effects, whereas individuals marked with * signify 5/6 significant results and one neutral result.*

	Laterality contrast					
	Easy tasks			Difficult tasks		
	11	**17**	**23**	**11**	**17**	**23**
Upper	-7	30	-19	166	125	137
Lower	-123	-109	-152	-168	-199	-205
SI:HN+ 01*	-582	-957	-357	-1262	-19	-551
SI:HN+ 02*	-361	-67	-683	-759	-1694	-526
SI:HN+ 03**	-513	-585	-377	-1151	-925	-833
SI:HN+ 04	-122	-477	-705	228	-626	-1408
SI:HN+ 05**	392	397	317	490	1297	1273
SI: HN+ 06**	-669	-308	-220	-543	-1871	-730
SI:HN+ 07	-248	-115	-46	-31	1136	1399
SI:HN+ 08	-205	80	-479	-1345	-1257	-1042
SI:HN+ 09	4	18	77	85	350	566

Table 2a: Laterality contrast between norms for RT

	Laterality contrast					
	Easy tasks			Difficult tasks		
	11	**17**	**23**	**11**	**17**	**23**
Upper	-0.01	-0.02	-0.02	-0.01	0.00	-0.01
Lower	-0.05	-0.05	-0.06	-0.04	-0.04	-0.03
SI:HN+ 01**	0.12	0.07	0.05	0.07	0.00	0.00
SI:HN+ 02**	-0.01	0.00	0.03	0.00	0.08	-0.01
SI:HN+ 03*	-0.02	0.06	0.05	0.10	0.04	0.04
SI:HN+ 04*	0.03	0.08	0.05	-0.02	0.04	0.07
SI:HN+ 05	-0.02	-0.03	-0.05	-0.04	-0.13	-0.06
SI:HN+ 06	0.00	-0.09	-0.06	-0.01	0.01	-0.01
SI:HN+ 07	0.02	-0.06	-0.02	-0.02	-0.05	-0.08
SI:HN+ 08**	0.08	0.03	0.09	0.00	0.10	0.05
SI:HN+ 09	0.02	-0.01	-0.03	-0.02	-0.02	-0.06

Table 2b: Laterality contrast between norms for MV

	Laterality contrast					
	Easy tasks			Difficult tasks		
	11	17	23	11	17	23
Upper	0.09	0.13	0.11	0.14	0.10	0.13
Lower	0.002	0.05	0.02	-0.003	-0.03	-0.003
SI:HN+ 01	-0.06	-0.07	0.09	0.02	0.16	0.10
SI:HN+ 02	0.00	0.14	-0.03	-0.09	-0.32	0.55
SI:HN+ 03	0.08	0.01	0.09	-0.28	0.06	-0.07
SI:HN+ 04	0.00	0.02	0.05	0.31	0.01	-0.09
SI:HN+ 05	0.13	0.08	-0.16	-0.05	0.17	0.39
SI:HN+ 06	0.06	0.32	0.12	0.07	-0.35	-0.25
SI:HN+ 07**	0.17	0.37	0.23	0.22	0.41	0.57
SI:HN+ 08	-0.10	-0.02	-0.10	-0.88	-0.27	0.14
SI:HN+ 09	0.07	0.13	0.18	0.25	0.26	0.48

Table 2c: Laterality contrast between norms for CV

*Table 3: Search task contrast between norms for dependent variables: (a) RT, (b) MV, and (c) CV. Search task contrasts were made for difficult minus easy results. For each SI, a significant lateral bias is indicated by a result outside the boundaries of the confidence interval. The results in blue are below the confidence interval, in red are above the confidence interval, and in black are within the confidence interval. Individuals marked with ** signify consistent significant effects, whereas individuals marked with * signify 5/6 significant results and one neutral result.*

	Search task contrast					
	Contralateral space			Ipsilateral space		
	11	17	23	11	17	23
Upper	891	1094	1361	943	1112	1401
Lower	746	1033	1265	822	1020	1329
SI:HN+ 01	645	805	691	-35	1743	496
SI:HN+ 02	1144	1799	1941	746	172	2098
SI:HN+ 03	1243	2134	2228	605	1794	1772
SI:HN+ 04**	1395	1848	2205	1746	1699	1502
SI:HN+ 05	217	473	1214	315	1373	2170
SI:HN+ 06	1607	1951	1562	1734	388	1052
SI:HN+ 07	887	988	1122	1104	2239	2567
SI:HN+ 08	1946	1946	1878	806	609	1315
SI:HN+ 09	737	1147	1123	818	1480	1612

Table 3a: Search task contrast between norms for RT

	Search task contrast					
	Search task contrast			Search task contrast		
	11	17	23	11	17	23
Upper	-0,103	-0,112	-0,142	-0,095	-0,098	-0,124
Lower	-0,097	-0,106	-0,137	-0,091	-0,090	-0,122
SI:HN+ 01	-0,071	-0,012	-0,031	-0,126	-0,089	-0,077
SI:HN+ 02	-0,051A	-0,113	-0,068	-0,043	-0,032	-0,110
SI:HN+ 03	-0,193	-0,142	-0,119	-0,074	-0,153	-0,131
SI:HN+ 04	-0,196	-0,167	-0,148	-0,242	-0,209	-0,126
SI:HN+ 05	-0,038	-0,135	-0,250	-0,055	-0,235	-0,262
SI:HN+ 06**	-0,080	-0,082	-0,129	-0,088	0,013	-0,074
SI:HN+ 07	-0,069	-0,153	-0,110	-0,112	-0,145	-0,168
SI:HN+ 08	-0,294	-0,096	-0,133	-0,371	-0,029	-0,166
SI:HN+ 09	-0,115	-0,148	-0,115	-0,154	-0,162	-0,148

Table 3b: Search task contrast between norms for MV

	Contralateral space			Ipsilateral space		
	Search task contrast			Search task contrast		
	11	17	23	11	17	23
Upper	0,19	0,31	0,45	0,23	0,26	0,47
Lower	0,14	0,23	0,35	0,15	0,17	0,34
SI:HN+ 01	0,10	0,03	0,27	0,17	0,26	0,28
SI:HN+ 02	0,20	0,65	0,39	0,11	0,20	0,98
SI:HN+ 03**	0,82	0,73	0,92	0,47	0,78	0,77
SI:HN+ 04**	0,40	0,76	0,98	0,71	0,75	0,84
SI:HN+ 05	0,07	0,20	0,46	-0,11	0,29	1,01
SI:HN+ 06	0,10	0,71	0,77	0,12	0,04	0,40
SI:HN+ 07**	0,29	0,47	0,61	0,34	0,52	0,94
SI:HN+ 08	0,93	0,49	0,53	0,15	0,25	0,78
SI:HN+ 09*	0,27	0,48	0,41	0,46	0,60	0,70

Table 3c: Search task contrast between norms for CV

3.3 Analysis: REASmash SI concurrent validity

For omission data, the normality test showed that REASmash ($p < 0.05$), TAP Visual search sub-test ($p < 0.05$) and OCS Broken hearts sub-test ($p < 0.05$) were not normally distributed. This is likely due to the relatively low number of omissions. Therefore, a Spearman's rank correlation coefficient was used to assess concurrent validity between the SI group total omissions asymmetry (ipsilateral minus contralateral) between the REASmash and the standardized tests. This analysis showed that there was no significant correlation for total omission asymmetry between the REASmash and the TAP visual search sub-test ($\rho = 0.92$, $p = 0.32$), nor REASmash and the Broken hearts test ($\rho = -0.13$, $p = 0.25$). For reaction time data, the normality test showed that the REASmash data was normally distributed ($p > 0.05$), whereas the results of the TAP Visual search sub-test were not normally distributed ($p < 0.05$). Therefore, a Spearman's rank correlation coefficient was used to assess the concurrent validity for RT asymmetry (ipsilateral minus contralateral) between the REASmash and the TAP visual search sub-test. This analysis showed a moderate correlation ($\rho = 0.36$, $p < 0.05$).

3.4 Analysis: REASmash reliability and agreement

ICC estimates and their 95% confident intervals were based on a mean-rating ($k = 2$) absolute-agreement 2-way mixed effects model. For omissions, the analysis showed a poor reliability (ICC = 0.02 [-1.67, 0.62], $p = 0.48$). However. there was an excellent reliability for total RT (ICC = 0.86 [0.45, 0.95], $p < 0.001$), moderate reliability for total MV (ICC = 0.73 [0.30, 0.89], $p < 0.001$), and excellent reliability for total CV (ICC = 0.79 [0.47, 0.92], $p < 0.001$).

The MDC for the REASmash was calculated using the SME of total RT (161ms), total MV (0.05 $m.s^{-1}$), and total CV (0.014%). This indicated that to show a pre- versus post-improvement in performance in the REASmash, a difference of at least 161ms on total mean RT, 0.05 $m.s^{-1}$ on total mean MV, and 0.014 % total CV would be needed. The MDC of the percentage of total omissions could not be computed as the ICC for this variable was not significant.

The Bland Altman plots were generated using JASP (Version 0.16.4). *Figure 5* shows the difference between sessions against mean for each variable.

Figure 5: (a) Bland-Altman plot of RT showing a mean of 71.8 ms [28.85, 114.72] (indicating that the two measures differ on average by 71.8ms). The LoA are -108.03 [-182.66, -33.38] and 176.97 [176.97, 326.25], which means that 95% of the differences between the two RT measures fall within this range, with two outliers shown in the plot. (b) Bland-Altman of omissions showing a mean

difference of 0.05 [-0.585, 0.685], indicating that the two measures differ on average by 0.05 units. The LoA are -2.61 [-3.712, -1.505] and 2.71 [1.605, 3.812], meaning that 95% of the differences between the two measures fall within this range, with one outlier showed in the plot. (c) Bland-Altman plot of MV showing a mean difference of – 0.004 m.s^{-1}[-0.041, 0.033], indicating that the two measures differ on average by -0.004 units. The LoA are -0.161 [-0.227, -0.096] and 0.153 [0.088, 0.219], which mean that 95% of the differences between the two MV measures fall within this range. (d) Bland-Altman plot of CL showing mean difference of 0.001% [-0.003, 0.006], indicating that the two measures differ on average by 0.001 units. The LoA are -0.017 [-0.025, -0.009] and 0.020 [0.012, 0.027], which mean that 95% of the differences between the two CV measures fall within this range, with one outlier.

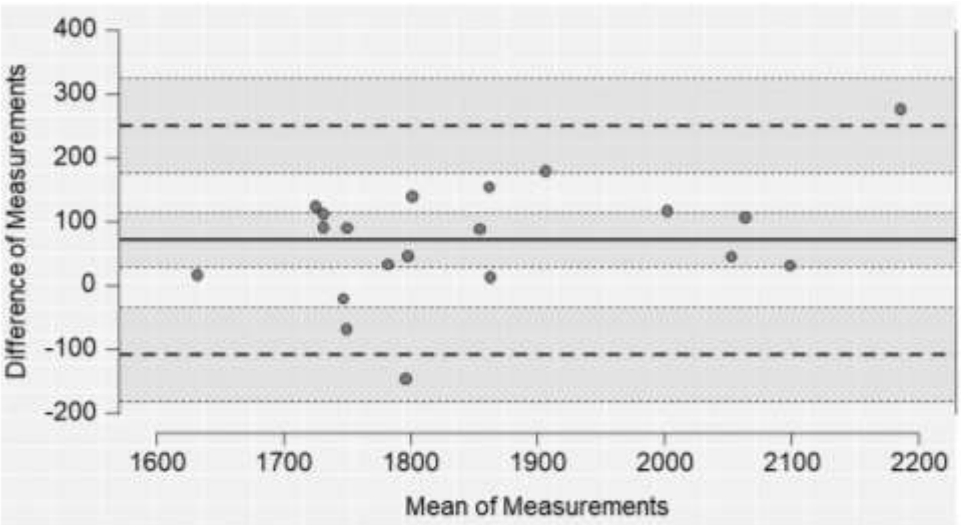


Figure 5

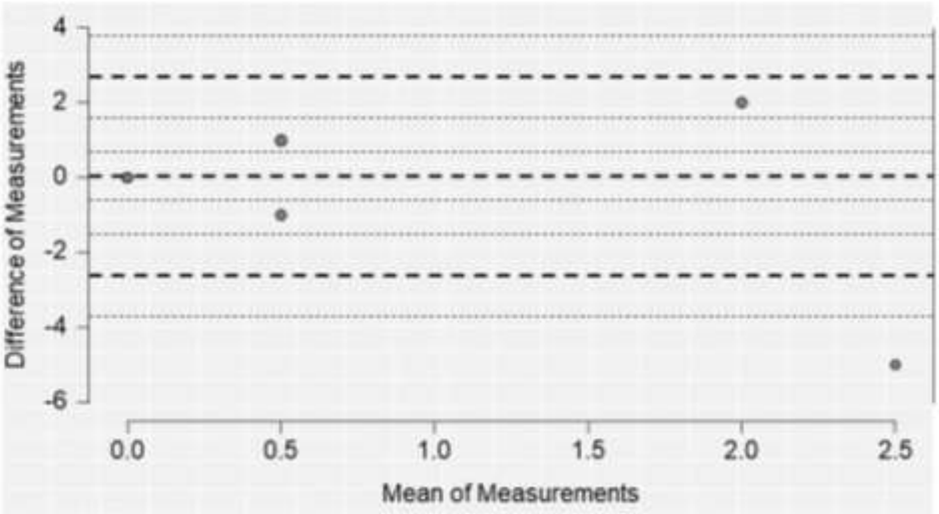


Figure 5b

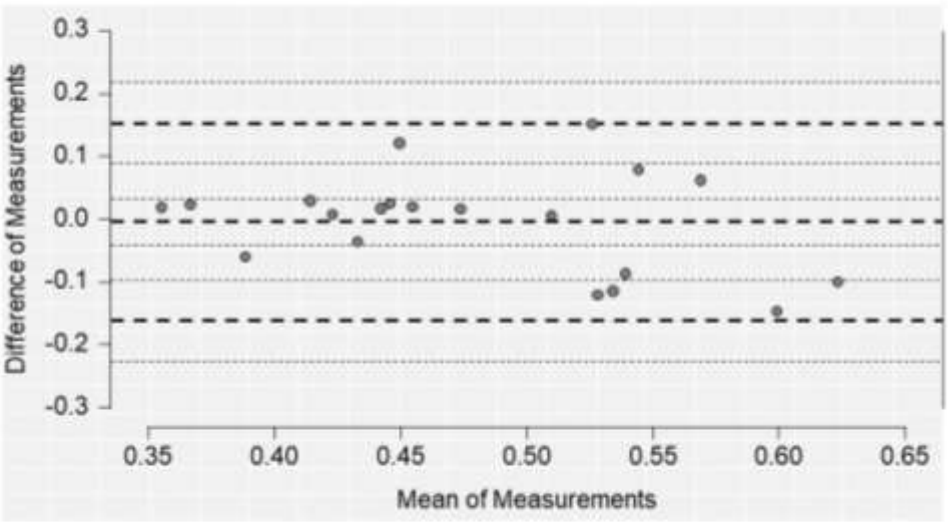


Figure 5c

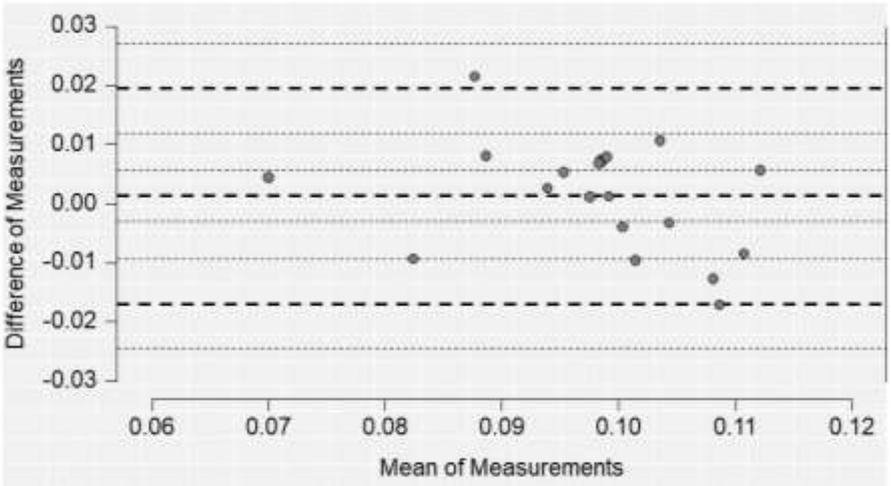


Figure 5d

3.5 Analysis: REASmash user experience

The analysis of the 29 SIs that took part of this study showed that the REASmash was globally rated as a positive user experience. All the dimensions were scored in a positive range (> 0.8). In order of score, the highest mean value was on the Perspicuity dimension (M = 2.46, SD = 0.56), then the Attractiveness dimension (M = 2.37, SD = 0.50), the Stimulation dimension (M = 2.03, SD = 0.83), the Efficiency dimension (M = 1.97, SD = 0.63), the Novelty dimension (M = 1.63, SD = 1.34), and then on the Dependability dimension (M = 0.91, SD = 1.58) (*Figure 6a*).

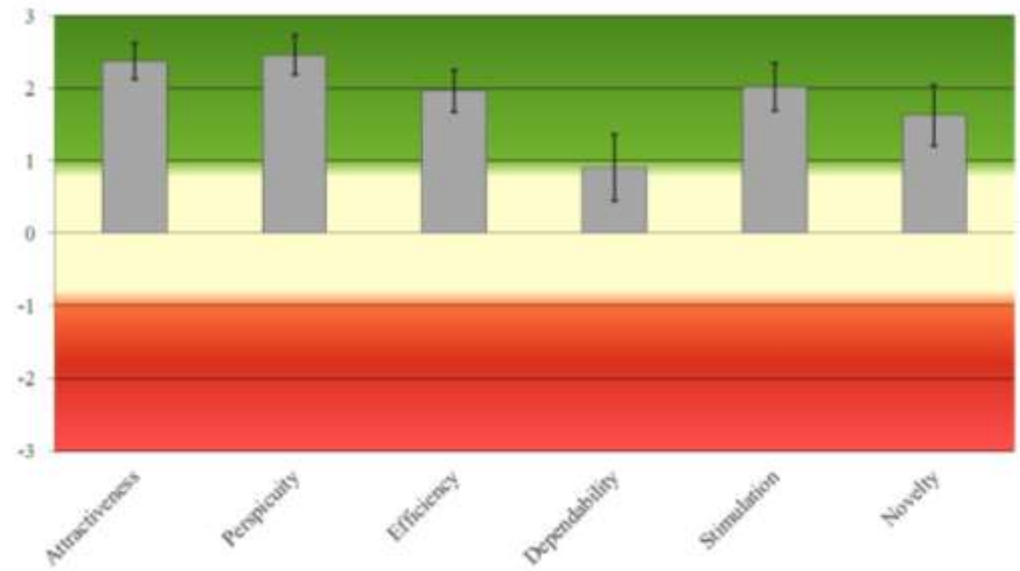


Figure 6a: SI scores of REASmash on the six scales composing the UEQ

A benchmark analysis was conducted using the UEQ data analysis tool, comparing the REASmash to the 468 products included in the data set. The analysis showed that the REASmash has an excellent score on Perspicuity, Attractiveness, Stimulation, Efficiency, and Novelty dimensions, indicating that the REASmash lies in the top 10% of results. The analysis also showed that the REASmash was below average on Dependability dimension, with 50% of the products included in the data set having a better score than the REASmash, and 25% of products have worst scores (*Figure 6b*).

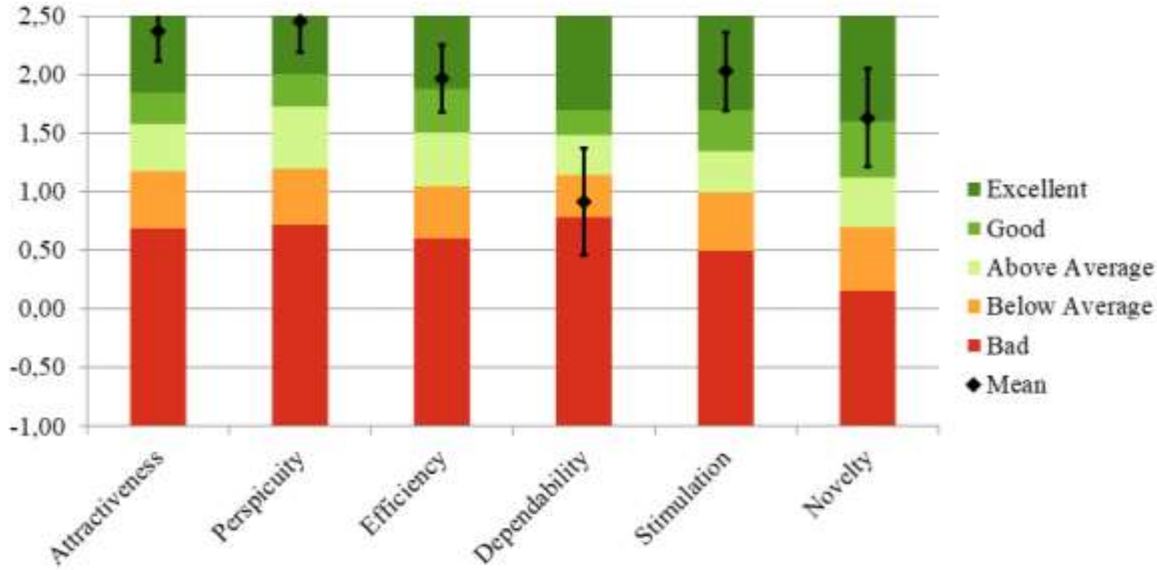


Figure 6b: The benchmark analysis of the REASmash relative to 468 products.

4. Discussion

In the present paper, our primary objectives were to validate the REASmash and to evaluate user experience. We performed three analyses. Firstly, we replicated the results of Ajana et al. (2023), with a new group of aged control individuals (CI). Then we used these data to create norms to evaluate spatial attention and distractor inhibition deficits in 9 post-stroke individuals diagnosed with hemiparesis and HN (SI:HN+). Secondly, we analysed the validity of the REASmash on post-stroke individuals with and without HN, making correlations between omission performance on the REAsmash and the Broken Hearts test (Demeyere et al., 2015), and between omission and RT performance on the REAsmash and the Visual Search sub-test from the Test for Attentional Performance (TAP) (Zimmermann & Fimm, 1995a). We also analysed the reliability of the REASmash on a sub-group of CI using test-retest analyses, Minimal Detectable Change (MDC), and Bland Altman plots. These analyses showed reliable validity for omissions and RT dependent variables, and reliability for the RT dependent variable. Thirdly, we evaluated user experience on the post-stoke individuals using the User Experience Questionnaire (Laugwitz et al., 2008b). This showed excellent results.

In the first analysis of data, we replicated the results of Ajana et al. (2023). For RT and MV, we showed that responses were slower to targets in the more difficult than easy versions of the task (serial versus parallel search), slower with increased numbers of distractors, and we showed an interaction effect between task and distractors (replicating the Triesman effect for RT). For the easy version of the task, there was no effect on RT and MV with increased numbers of distractors, suggesting that the target 'pops-out' from the distractors (parallel search). However, for the difficult version of the task, there was an effect on RT and MV with increased numbers of distractors, suggesting that the participant had to serially search each item in the display to find the target, and that increased numbers of (distractor) items caused delay in finding the target. Furthermore, our results showed similar effects for CV, with variance increasing in the difficult compared to easy task, and with increased numbers of distractors causing more variance. We also showed a task and distractor interaction, replicating the effects of RT and MV, showing no change of CV with increased numbers of distractors in the easy task, but showing a significant increase in CV with increased numbers of distractors in the difficult task. For the analyses of the independent variable of laterality and RT, we expected no differences. Our results supported our null expectations. However, as in (Ajana et al., 2023), we did find significant effects of laterality for MV and CV, with MV being faster and CV being reduced for responses to contra- than ipsi-lateral space, we previously explained this lateralized difference by a variations in neuronal processing, muscular activation, and biomechanical constraints involved in the two different movements performed in response to the target presented in the contra- and ipsi-lateral space. Therefore, in summary, these results replicate Ajana et al. (2023) showing significant main effects of search task and distractors for the three dependent variables (i.e. RT, MV, and CV), and a significant effect of laterality for MV and CV. The interaction between search task and distractors that we have demonstrated here for RT, MV, and CV also replicate Ajana et al. (2023). This indicates that findings reported in Ajana et al. (2023) can be reproduced with precision, adding confidence in the REASmash test reliability.

Using the ANOVA, we created two sets of 95% confidence interval norms to evaluate spatial versus distractor inhibition contrasts in 9 post-stroke individuals diagnosed with hemiparesis and HN (SI:HN+). These analyses showed many significant effects for the independent variable combinations (i.e. SI responses that were outside the boundaries of the confidence interval, and therefore indicating a significant difference from the CI group). However, caution should be placed on the interpretation of these significant effects due to statistical probability of finding significant results with many uncorrected t-test analyses (i.e. a 5% chance of finding a significant effect that is not true). We can counter this issue by using a conservative approach and only discuss consistent findings, where most all the results for an individual are significant in the same direction, or that there are 5 significant results, and one neutral result (although this method is by no means perfect, and different criteria could be applied to interpret the data).

Using these criteria, the analyses of RT laterality showed that SI 1, 2, 3 and 6 had significantly slower RT in contralateral than ipsilateral space, and that SI 5 showed the opposite profile (slower RT in ipsilateral than contralateral space. For the analyses of MV laterality, SI 1, 2, 3, 4 and 8 had significantly slower MV in contralateral than ipsilateral space, with SI 1, 2 and 3 showing consistent findings for the RT and MV dependent variables. For CV, only SI 7 showed a lateralized effect with more variance for responses in contralateral than ipsilateral space. Taken together, we could interpret that only SI 1,2, and 3 showed consistent profiles of HN laterality impairments (3 from the 9 SI:HN+). Unfortunately, these findings and interpretations are not clearly comparable to the omissions results from the Broken Hearts OCS sub-test or the visual search TAP sub-test.

For the case analyses of distractors inhibition (difficult minus easy) and using the same criteria as those used for laterality, the analyses showed significant impairments for SI 4 with RT, SI 6 with MV and SI 3, 4, 7 and 9 with CV. Only SI 4 showed effects on two dependent variables (RT and CV). Interestingly, these data do not show consistency between the lateralisation contrasts and the inhibition contrasts, other than for SI 7 showing a laterality and inhibition effect for the dependent variable of CV. This may indicate that spatial attention impairments are independent of distractor inhibition impairments, though clearly more participants are needed to thoroughly understand this point.

In the second analyses of the current study, we provided concurrent validity and reliability results for the REASmash. The validation was tested by comparing all the SI on the REASmash and two standardized tests; the OCS broken hearts sub-test (Demeyere et al., 2015), and TAP visual search sub-test (Zimmermann & Fimm, 1995a). For omissions, the performance on the REASmash showed non-significant low correlation performance with the OCS broken heart sub-test and high correlation with the TAP visual search sub-test. The low correlation with OCS sub-test could likely be explained by the low rate of omissions in both tests. For RT, the performance on REASmash was moderately correlated with the performance on the TAP visual search sub-test. The test-retest reliability was excellent for the RT and CV measures, moderate for MV, and poor for omissions. One possible explanation for this poor correlation could be related to the healthy CI sub-group that performed the test-retest, that made few omissions. The absence of data likely caused the poor correlation. The minimal detectable change was established for future use to assess improvements (e.g. pre/post treatment). Absolute reliability was investigated through Bland-Altman plots, and the analyses showed that overall measures in the two testing sessions are interchangeable, with little to no systematic differences between them, suggesting that REASmash has a good absolute reliability. However, these findings obtained among the healthy CI should be confirmed with a larger sample of clinical population, giving a more accurate estimation of the inherent measurement error association with REASmash.

The findings related to the user experience of the SI showed that the REASmash provided an overall positive experience. Specifically, SI scored highest in the dimensions of perspicuity and attractiveness, indicating that REASmash was easy to understand and appealing. The SI also expressed a favourable impression of the serious game, finding it enjoyable and attractive, and they highly rated the stimulation, efficiency, and novelty dimensions, suggesting that the gameplay and environment provided by REASmash were perceived as fun and exciting. Amusement is not the crux of use of serious games in IVR for neuropsychology assessment. However, it is known to enhance adherence to clinical intervention that can sometimes be perceived as wearisome and tedious (Kato & de Klerk, 2017; Valladares-Rodríguez et al., 2016). Interactions with the virtual environments were reported to be efficient and fast. Naturalistic and direct hand interactions (i.e. interactions that do not rely on a peripheral joystick or keyboard) reduced the adverse symptoms of IVR (motion sickness), enhanced user engagement with the virtual experience and felicitated ecologically valid scenarios (Brade et al., 2018; Kourtesis et al., 2019). The SI also reported that the REASmash was creative and innovative, and that they felt a certain degree of control over their interactions with the environment. It is worth noting that while the SI were able to initiate and terminate the game at their convenience, they were unable to predict the occurrence or features of the stimuli presented during the gameplay. This incapacity to control the stimuli is primordial in the context of clinical assessment, where a randomization of the presentation of the stimuli in repeated administrations is essential to reduce learning effects (McCaffrey et al., 1993; McCaffrey & Westervelt, 1995). This SI user experience evaluation suggests that REASmash is a novel test that rouses the users' interest.

All the evidence above suggests that REASmash is has moderated validity, with room for improvement. It holds potential to be used in a clinical setting or implemented for research purposes. It achieves several criteria established by the National Academy of Neuropsychology and the American Academy of Clinical Neuropsychology, that need to be taken in consideration when developing new computerized neuropsychological assessment devices (Bauer et al., 2012). For example, it is essential that the new assessment devices abide by the same standards and conventions of psychometric test development. Here, we provided evidence regarding REASmash feasibility, validity and usability. Secondly, according to Bauer et al. (2012), it is important to clearly identify the users of the assessment devices. Here, we defined our users as post-stroke individuals, and we considered their needs and capacity limitations when developing the REASmash. This is reflected in the unimanual nature of the serious game, and the flexible parameter that allow configuration of which hand to play with. This allows controlled evaluation of the SI performance with their non-hemiparesis or hemiparesis limb, with hemiparesis and hemiplegia being common consequences of stroke (Broeks et al., 1999; Nakayama et al., 1994). This functionality allows for comparison of performance between the non-hemiparesis and hemiparesis limbs, and how hemiparesis interactions with the diagnosis of spatial and distractor inhibition cognition. Moreover, stroke can also cause language (alexia) impairments (Sinanović et al., 2011; Turkeltaub et al., 2014). We provided multi-modal written and verbal audio instructions to ensure that a larger stroke population could interact with REASmash. These instructions were available in two languages (French and English) but can easily be adapted to multiple languages. Another example of Bauer et al. (2012) criteria includes the use of reporting services, and data privacy and security. It is necessary for clinicians to follow APA and ethical guidelines regarding user anonymity, test scoring and interpretation, and record keeping (APA, 2007). The REASmash uses an anonymous identification system that protects the privacy of users. The test is also run offline, eliminating the possibility of digital perpetuators accessing the data. Furthermore, the REASmash provide a CSV file containing all the anonymised recorded data (i.e. response time, response accuracy, level number, type of distractors), which can be easily downloaded and stored in respect to APA (2007) record keeping guidelines.

The main limitation of the present study was the relatively low number of SI with HN that participated to the study (a consequence of the COVID19 pandemic). Future studies will include a larger sample of individuals with HN in order to confirm the validity and reliability of REASmash. Additionally, we would include a larger sample of individuals with hemiparesis and without HN to deepen the assessment and understanding of the distractors inhibition impairment, and determine whether spatial attention and distractor inhibition are related or independent deficits. This comparative experimental design could deepen the understanding of distractor inhibition impairment. The efficiency of REASmash should be tested on a different technology to insure there is no bias linked to IVR. For example, the REASmash could be used on non-immersive VR touch-screen tablets, particularly better suited for acute SI. The use of IVR technology demonstrated great efficacy, important clinical ecological validity, and acceptability from the SI tested in this study (Canini et al., 2014; Rabuffetti et al., 2002; Terruzzi et al., 2023). IVR provides a safe ecological environment where controlled and accurate assessments can be performed (Parsons, 2015; Rizzo et al., 2004). The possibility to combine these measures with eye tracking that is now available in most IVR devices could provide more sensitive and precise assessments of different sub-types of HN (Brouwer et al., 2022; Kaiser et al., 2022b). For example, it might be that SI:HN+ who show pre-target selection perseverations (i.e. where they re-fixate already searched distractors) might show spatial and distractor inhibition impairments, but SI:HN+ not showing perseverations with eye-tracking, only showing spatial attention impairments. More data is needed to investigate how distractor inhibition is associated to spatial attention in SI with HN.

In conclusion, despite improved understanding of cognitive processes and significant advancements in technology, most of the current procedures used in present-day clinical neuropsychology diagnosis have their roots in the late 19th to mid-20th century (Bilder & Reise, 2019; Howieson, 2019; Marcopulos & Łojek, 2019). These assessment procedures have long been criticized for being based on outdated paradigms and for their lack of validity (Grattan & Woodbury, 2017b; Kessels, 2019). Consequently, there is a pressing need for clinicians to incorporate technology into daily clinical routine, and address these limitations (Germine et al., 2019; Singh & Germine, 2021). The REASmash IVR serious game (Ajana et al., 2023) is based on the visual search paradigm by Treisman and Gelade (1980). It was designed to evaluate spatial attention and distractor inhibition impairments though response accuracy, response time and kinematic measures. In this paper, we have provided norms for REASmash and we demonstrated its validity, reliability, and user friendliness.

Chapter 5

Cognitive inhibition difficulties in individuals with hemiparesis: Evidence from an immersive virtual reality target-distractor salience contrast visual search serious game

Introduction: Stroke can result in various impairments that require multidisciplinary rehabilitation. For example, preserved cognitive executive functions predict motor recovery success. Despite knowing these links, the evaluation of executive function in hemiparesis patients remains underexplored. Here, we examined whether post-stroke individuals with upper limb hemiparesis (SI:HP) had cognitive inhibition difficulties using a new immersive virtual reality (IVR) serious game.

Methods: Twenty SI:HP with no known history of cognitive impairment and who were not undergoing any neuropsychological rehabilitation and fifteen age-matched healthy control individuals (CI) were recruited. They performed the 6-level serious game requiring responses to spatial target presented amongst 11, 17 and 23 distractors with high versus low target-distractors saliency contrasts. Responses were made with non-hemiparetic hand for SI:HP group and dominant hand for CI. Response time (RT), and kinematic variables were measured.

Results: The SI:HP group was slower and more variable than the CI group. All participants were slower and more variable when responding to the low compared to high target-distractors saliency conditions, and when responding to targets with increased numbers of distractors. A significant interaction between task saliency and distractor number showed slower and more variable responses with increased numbers of distractors in the low saliency condition, but not in the high saliency condition. Interactions involving group and saliency for RT and coefficient of variation of speed showed that SI:HP compared to CI group showed a greater difference in responses to low versus high saliency conditions.

Conclusion: These results demonstrated that relative to the CI group, the SI:HP group showed cognitive inhibition difficulties performing an IVR serious game. As cognition plays a fundamental role in motor recovery, these results suggest a need for systematic cognitive screening of post-stroke patients.

Reference: Ajana, K., Everard, G., Sorrentino, G., Lejeune, T., & Edwards, M. G. (2023). Cognitive inhibition difficulties in individuals with hemiparesis: Evidence from an immersive virtual reality target-distractor salience contrast visual search serious game.

1. Introduction

Stroke is a global health issue and the leading cause of disability worldwide (Avan & Hachinski, 2021; Duncan, 1994; Sacco et al., 2013). While spontaneous recovery of function typically occurs during the first weeks post-incident (Hatem et al., 2016; Kwakkel et al., 2006), performance deficits typically remain following the spontaneous recovery period, often leaving survivors with a combination of long-term cognitive and motor deficits (Jokinen et al., 2015; Mackay et al., 2004). These impairments typically result in social life participation difficulties, as well as limitations in daily-life activities such as preparing food or driving, thereby affecting overall quality of life for both the patients and their caregivers (Jaracz & Kozubski, 2003; Sreedharan et al., 2013). In order to address this issue, there is a pressing need to develop new rehabilitation strategies, as well as improve early detection of motor and/or cognitive impairments to further optimize intensive treatment programmes that enhance the chances of recovery (Cumming et al., 2013; Kwakkel et al., 2010; Poulin et al., 2012; Zucchella et al., 2014).

The prevalence rate of motor impairments following stroke is estimated to range from 83% to 90% (Bogousslavsky et al., 1988; Dutta et al., 2022; Herman et al., 1982; Lawrence et al., 2001), representing the most common post-stroke impairment. The impact on patient behaviour includes problems in gait, balance, and general physical ability, including arm and hand movements for object interactions (Bernhardt et al., 2015; Middleton et al., 2017; Verma et al., 2012). Currently, these latter motor impairments are evaluated using valid and reliable standardized measures of activity capacity (Prange-Lasonder et al., 2021). The Box and Block Test is recommended for outcome measures of unilateral gross motor dexterity, the Fugl-Meyer Assessment is recommended for outcomes measures of upper limb impairment, and the Action Research Arm Test is recommended for outcome measures of upper limb activity capacity (all with strong validity, reliability, and clinical usefulness) (Duncan et al., 1983; Fugl-Meyer et al., 1975; Lyle, 1981; Mathiowetz et al., 1985; Prange-Lasonder et al., 2021; Uswatte et al., 2005). New innovations in clinical evaluation of motor function allows for the inclusion of kinematic measures using new technology such as rehabilitation robots and interactive virtual reality (Burton et al., 2022; Dehem et al., 2019; Everard et al., 2022), bringing positive additional value to the current state-of-the-art

(Aguilera-Rubio et al., 2022; Balasubramanian et al., 2012; Henderson et al., 2007; Lei et al., 2019; Micera et al., 2020; Scott & Dukelow, 2011).

The prevalence of cognitive impairments following stroke is less well understood, ranging from 24% to 96% of stroke individuals showing cognitive impairment (Douiri et al., 2013; Gutiérrez Pérez et al., 2011). This large variance is caused by different types of cognitive deficits such as attention, executive functions, and speed processing (Jokinen et al., 2015; Laakso et al., 2019; Leśniak et al., 2008). Although the extent of these cognitive impairments varies across individuals with stroke, it is nevertheless clear that cognitive impairments are a major determinant of poor long-term recovery, including recovery from motor impairments (Shimada et al., 2018; VanGilder et al., 2020). In current clinical practice, paper-and-pencil tests are frequently used to screen the range of potential cognitive impairments, as well as provide more detailed evaluations of specific cognitive impairments, thereby determining specific cognitive impairments and their severity (Cullen et al., 2007; Woodford & George, 2007). Over the last 10-20 years, computerized tests have been developed to address weaknesses in paper-and-pencil test sensitivity, for example, using methods such as trial randomization and more precise response time measurements (Montedoro et al., 2018; Tyryshkin et al., 2014; Zimmermann & Fimm, 2004). Sensitive cognitive tests are particularly important for understanding the influence of cognition on motor function, particularly when the cognitive impairments are not obvious when interacting with the patient.

Traditionally, motor and cognitive post-stroke impairments have been studied, assessed and managed as two distinct issues (Chen et al., 2013; Langhorne et al., 2011). In research, patients with cognitive impairments are often excluded from studies investigating motor impairments or the efficacy of motor rehabilitation strategies (Everard et al., 2020). Further, in clinical practice, motor dysfunction seems to be routinely evaluated for all patients with stroke, whereas cognitive evaluations appear to be conducted on only a subset of patients based on clinician intuition (Einstad et al., 2021; Montero-Odasso et al., 2018). This latter issue may be explained by the fact that motor impairments are more visible with clear impairments to daily life function, whereas cognitive impairments are hidden and less obvious (e.g., deficits in inhibition). This separatist approach obscures the understanding of underlying cognitive processes implied in motor recovery.

Various studies have demonstrated the importance of cognition in motor performance. For example, a meta-analysis of studies investigating cognitive and upper limb functions reported an association between cognitive impairment (such as inhibition) and improvements in upper limb motor impairment (Mullick et al., 2015). Similarly, dual-task paradigms that increase cognitive load (reduce cognition) disrupts the efficiency of motor ability learning (Wulf et al., 2007). In individuals with stroke, research reports links between motor and cognitive impairments (Čengić et al., 2011; Lowrey et al., 2022; VanGilder et al., 2020; Verstraeten et al., 2016). For example, McDowd et al. (2003) showed that stroke-related attentional impairments predicted daily-life functioning. Verstraeten et al. (2020) reported evidence of correlations between motor and cognitive performance impairments in more than one hundred chronic post-stroke survivors. Finally, Lin et al. (2021) reported differences in motor recovery during rehabilitation for tests of Grip Strength (low cognitive load) relative to the Box and Blocks test (higher cognitive load). Using Voxel Lesion Symptom Mapping, they showed that motor impairment in the Box and Blocks test was associated with lesions that included the dorsal anterior insula; implicated in complex attentional (selection / inhibition) cognitive processes, whereas Grip Strength performance was associated to sensorimotor lesions, and not implicated in areas associated with cognition.

Together, these data underline the importance of understanding how cognitive impairments influence motor impairments and recovery processes. This literature shows the importance of a thorough assessment that includes both motor and cognitive tests as an essential first step to define post-stroke rehabilitation (Bourke et al., 2016; Kleim & Jones, 2008; McDonald et al., 2019; Schaefer & Schumacher, 2011). It seems fundamentally necessary to tailor interventions and rehabilitation programs to the patient's clinical status, that incorporate both cognitive and motor neurorehabilitation where necessary, to more efficiently drive recovery. For example, for the restoration of motor abilities, patients must relearn to perform complex motor skills (Hodges & Franks, 2000; Wulf & Weigelt, 1997). These relearning processes involve cognition (Singer et al., 1989; Tennant et al., 2004), particularly executive functions, such as selective attention and cognitive inhibition

(Barrett & Muzaffar, 2014; Hochstenbach & Mulder, 1999; McEwen et al., 2009). Impairments of selective attention and cognitive inhibition are common consequences of stroke, and known to have a direct association to poor motor performance, specifically on the paretic upper limb (D'Imperio et al., 2021; Kim et al., 2021; Nijboer et al., 2014). Yet, the impact of selective attention and inhibitory control dysfunction on upper limb hemiparesis remains under investigated in the literature.

To better understand links between selective attention and inhibitory control (non-spatial attention) and motor performance in patients with motor impairments, it is important to develop tests that can measure cognitive and motor responses within the same test. An immersive virtual reality serious game “REASmash” have recently been developed (*Ajana et al. 2023*) based on Feature Integration Theory (FIT) (Treisman & Gelade, 1980) and the research of Duncan and Humphreys (1989). The task involves the patient searching for a spatial target presented amongst distractors. When the target differs from the distractors by a single feature, the search is said to be conducted in *parallel*. Attention is divided between the target and the distractors, and the visual features of the distractors are automatically registered and inhibited at a pre-attentional level of processing (Treisman & Souther, 1985). In this situation, the target is said to ‘pop-out’ from the distractors due to their high salience contrast (e.g., a red target presented with blue distractors). However, if the target shares a conjunction of features with the distractors (e.g., a red target with blue distractors and red distractors of a different shape), the search is conducted in *serial* due to a low salience contrast. The visual features of the distractors are attentively inhibited during a successive serial search of the stimuli in order to find the target (Koshino, 2001; Treisman & Sato, 1990). During this *serial search*, response time to find the target increases with the increased number of distractors (causing increased distractors inhibition demands) (Poisson & Wilkinson, 1992; Wolfe et al., 1989). In contrast, increasing the numbers of distractors has no effect on *parallel search* (Huang & Pashler, 2005; Wolfe et al., 1989). In our serious game, we manipulated the saliency between the target and distractors (low vs high), as well as systematically manipulating the number of distractors displayed (11, 17 and 23). Participants made motor responses to the target by reaching and interacting within immersive virtual reality using a hand controller. This makes the test unique as it measures distractor inhibition using a motor response (whereas most cognitive tests involve pushing a button on a peripheral keyboard or button box).

The principal objective of this paper was to examine whether post-stroke individuals with upper limb hemiparesis have distractor inhibition attention deficits. We tested a group of post-stroke individuals with hemiparesis (SI:HP) and a group of mean age matched healthy control individuals (CI). Responses were made with the less-affected limb for SI to exclude confound motor-cognitive impairments in the hemiparesis limb. Therefore, any differences in performance between SI:HP and CI (dominant hand performance), specifically regarding the FIT would indicate distractor inhibition impairments. We hypothesised that: (1) mean response time (RT) and mean velocity (MV) will be slower, and coefficient of variation of speed (CV) will be higher for the SI:HP than CI groups. We also hypothesised that (2) RT and MV will be slower, and CV will be higher for finding the target in the low target-distractors saliency condition (serial search) than in the high target-distractors saliency condition (parallel search) due to increased attentional load. We additionally hypothesised interactions. Firstly (3) an interaction between saliency and distractor number showing that in the high target-distractors saliency condition (parallel search), RT, MV and CV will show no differences between the number of distractors, whereas in the low target-distractors saliency condition (serial search), RT, MV and CV will show significant differences with increased numbers of distractors, with more distractors increasing attentional load and reducing performance (taking more time to respond to the target / more variance in responses). Secondly, we hypothesised (4) an interaction between search saliency and group showing that the SI: HP relative to CI groups will show a greater difference in RT to find the target between the low salience (serial) relative to high salience (parallel) search conditions, demonstrating a specific impairment of cognitive inhibition for individuals with hemiparesis relative to aged-matched healthy individuals. If this effect is found, it will indicate that patients with hemiparesis have underlying cognitive inhibition difficulties that have not been identified during clinical diagnosis. We hypothesize similar effects for MV and CV, though we have no prior evidence to support this hypothesis.

2. Methods

2.1 Participants

An a priori power analysis was conducted using G*Power (version 3.1.9.7) (Faul et al., 2007) for sample size estimation based on data from (Ajana et al., 2023) (N = 58; CI). The effect size in Ajana et al., (2023)'s study was f = 0.67 (F (2,114) = 117.58), which can be considered as a large effect according to Cohen's criteria (Cohen, 1973; Richardson, 2011). With a significance criterion of $\alpha = .05$, and power = 0.80, the minimum sample size needed for the same effect size was N = 4 for a repeated measures ANOVA. As the present study contrasted SI:HP with CI groups, a sample size of N = 20 per group was considered adequate to compensate for additional variance in the patient sample.

We tested 20 SI:HP (7 females; 8 left-handed (*less affected*)) (Please note that this group is the same included in Chapter 4). and 20 CI (10 females, 1 left-handed) using convenience sampling (Please note that this group is distinct from the groups in Chapter 3 and 4). The SI:HP were aged between 47 and 80 years (M = 61, SD = 11), and were recruited from the physical medicine and rehabilitation department of the Cliniques universitaires Saint-Luc in Brussels. Clinicians (two occupational therapists, from Cliniques universitaires Saint-Luc in Brussels introduced our experiment to their patients that were meeting our inclusion criteria. If the patients expressed interest in participating to this study. An experimenter would meet with them, or would call them, to explain the objectives and procedure of the experiment. If they agree after this first meeting, an appointment is scheduled. The participants were selected using the following inclusion criteria: (1) presence of an ischemic or haemorrhagic first stroke, diagnosed by CT or magnetic resonance imaging; (2) presence of upper-limp hemiparesis clinically diagnosed and documented through a physical medicine evaluation report, and; (3) a good understanding of the task instructions. The exclusion criteria were: (1) uncorrected vision deficiencies and (2) the presence of other neurological conditions such as dementia or orthopaedic dysfunction that could influence upper extremity function. None of these individuals had a known history of cognitive impairment, and they were not following any neuropsychological assessment. According to their medical record, 5 of the SI:HP had a left hemisphere lesion causing a right hemiparesis, and at the time of testing, they were between 1.3- and 142.2-months post-onset (see Table 1). The CI were aged between 60 and 69 years (M = 63., SD = 2.5). They were included if they had (1) corrected-to-normal vision, and (2) a good understanding of the task instructions, and they were excluded if they had (1) another orthopaedic or neurological condition that may influence their movement/motor function. The Saint-Luc UCLouvain-Hospital Faculty Ethics Committee (reference number: 2015/10FEV/053) approved all the procedures prior to experimentation. All the participants volunteered to participate in the study, providing written informed consent before participation.

Table 1: The demographic characteristics of the post-stroke individuals with hemiparesis (SI: HP)

	Gender	Age	Handedness pre-stroke	Handedness post-stroke (less-effected limb)	Stroke site	Stroke type	NHISS Score	Months post-onset
SI:HP01	M	47	Right	Left	Left lenticulostriate intraparenchymal hematoma	Hemorrhagic	19	6,8
SI:HP02	F	62	Right	Right	Right sylvien fissure	Ischemic	11	19,6
SI:HP03	M	56	Right	Right	Right thalamus	Ischemic	3	1,3
SI:HP04	F	51	Right	Left	Left sylvien fissure	Ischemic	19	3,7
SI:HP05	M	62	Right	Right	Right internal capsule lacunar	Ischemic	5	17,6
SI:HP06	M	69	Right	Left	Left paramedian pontine	Ischemic	5	36
SI:HP07	M	46	Right	Left	Left sylvien fissure	Ischemic	10	22,4
SI:HP08	F	79	Right	Left	Left sylvien fissure	Ischemic	10	2,3
SI:HP09	M	73	Right	Right	Right sylvien fissure	Ischemic	---	1,6
SI:HP10	M	74	Right	Right	Right sylvien fissure	Ischemic	5	9,8
SI:HP11	M	61	Right	Right	Right superficial and deep sylvien fissure	Ischemic	20	5,5
SI:HP12	M	47	Right	Left	Left temporal	Ischemic	15	0,2
SI:HP13	F	56	Left	Right	Right internal capsule	Ischemic	8	3
SI:HP14	M	65	Right	Right	Right capsulo-lenticular territory	Ischemic	1	0,95
SI:HP15	F	72	Right	Right	Right sylvien fissure	Ischemic	14	146,2
SI:HP16	F	50	Right	Right	Right deep temporal	Hemorrhagic	---	48,2
SI:HP17	M	50	Right	Left	Left pontine	Hemorrhagic	---	39,9
SI:HP18	F	55	Left	Right	Right sylvien fissure	Ischemic	16	3,4
SI:HP19	M	69	Right	Right	Right frontoparietal intraparenchymal	Hemorrhagic	8	4,1
SI:HP20	M	80	Right	Left	Left corona radiata	Ischemic	1	3,6
Mean (SD)		61 (11)						18 (33)

F = Female, M = Male, SD = Standard Deviation, NHISS = National Institutes of Health Stroke Scale

**The NHISS scores of SI:HP09, SI:HP16, and SI:HP17could not be found in their medical records*

2.2 Materials, Stimuli and Experimental Design

As described in the Introduction, we used an immersive virtual reality visual search serious game manipulating target-distractors saliency for measuring spatial and distractors inhibition attention (Ajana et al. 2023). The ‘REASmash’ was created using Unity 2019.3 software (in C# language). The hardware consisted of an IVR headset (Oculus Quest 2) and one Oculus Quest motion controller. The experiment was monitored through a live stream from the Oculus App to a digital tablet (Huawei MediaPad T, model AGS2-W09). Participants sat on a chair with their feet on the ground, wearing the IVR headset. The SI:HP held the controller with their less-effected (post-stroke dominant) hand, and the CI held the controller with their dominant hand. They were then immersed into the virtual environment that consisted of a simulated cartoon-like garden, with a raised-bed garden patch composed of twenty-four molehills (a grid of six columns and four rows). The stimuli were stylized cartoon-like moles that appeared from the molehills (with animation). In each trial, one target mole was presented with several distractor moles. The target mole wore a red miner’s helmet, and the distractor moles wore a blue miner’s helmets, or red or blue helmets with horns (see *Figure 1*).

At the beginning of the serious game, written and oral instructions were presented, instructing the participants to respond to the target as fast as they could using a virtual hammer controlled with the Oculus motion controller. They were also instructed to not make responses to the distractor stimuli. The target and distractors stimuli appeared for 7000 milliseconds maximum. If the participant correctly responded to the target within the 7000 milliseconds, the trial was recorded as a success. If no response was made by the participant within the 7000 milliseconds, the REASmash automatically registered the trial as an omission (i.e. the participant failed to find the target-mole). If the participant responded to a distractor instead of the target, the REASmash automatically registered the trial as a failed response (i.e. the participant failed to find the correct mole). After each response type, the next trial was automatically initiated.

The REASmash serious game was composed of 6 levels, with each level consisting of 24 trials (i.e. the target mole appearing from each of the 24 molehills, randomly across the 24 trials). In the three first levels, the target appeared among 11, 17, and 23 distractor moles wearing blue miner’s helmets or blue helmets with horns. These trials represented low inhibition demands due to the high salience difference between the target (red) and distractors (blue). In the latter three levels, the target again appeared among 11, 17, and 23 distractor moles, but this time wearing either red helmets with horns or blue helmets with horns, representing high inhibition demands due to the low salience difference between the target and distractors. The distractors (blue miner’s helmets and blue helmets with horns versus red helmets with horns and blue helmets with horns) were close to equally distributed (i.e. 5+6 for 11 distractors; 11+12 for 23 distractors etc.) across the 6 levels. The distractors were pseudo-randomly placed within the columns of the grid so that for 1 target and 11 distractors, 2 stimuli were presented in each column, for 1 target and 17 distractors, 3 stimuli were presented in each column and for 1 target and 23 distractors, 4 stimuli were presented in each column. Within each column, the distractor position was randomised for each trial. The levels were blocked as the original intention for the serious game was to allow selection of levels with patients based on their likely ability to perform the task (i.e. for some patients, levels 1 and 4 with 11 distractors may be too easy, while for other patients, levels 3 and 6 with 23 distractors may be too difficult). In the present study, we used all 6 levels. All trials were randomised for each participant.

Before every trial, the participant had to fixate a central stimulus (measured with the Oculus head position) and place their virtual mallet response hand on a central starting position (both positioned along the sagittal axis of the participant). This consisted of simultaneously fixating a floating red cube with an eye illustration and placing the virtual hammer on a second red cube with a hammer illustration. The eye-cube was positioned at the level of the participant’s eyes, and the hammer-cube was at the level of the participant’s arm. Once the participant successfully placed their gaze and hand on the cubes, they turned green, and the trial was initiated. This procedure was carried out to ensure that the participants-initiated responses from a consistent starting position across all trails.

Figure 1: The target was a mole wearing a red miner's helmet. In the high target-distractors saliency condition, the distractor moles wore blue miner's helmets and blue helmets with horns. In the low target-distractors saliency condition, the distractor moles wore red helmets with horns and blue helmets with horns. In the two examples, the target is shown with 17

2.3 Procedure

The experiments were run in the Cliniques universitaires Saint-Luc hospital in Brussels and in a laboratory in the Psychological Sciences Research Institute of the University of Louvain. Each experiment lasted approximately 40 minutes, and always started with an information session where the participant received oral explanations and instructions regarding the experimental design, followed by their signing of a consent form to agree to participate to the study. Once consent was provided, the participant was seated comfortably on a chair, and the IVR headset and motion controller were placed on the participant. They were then immersed in the virtual environment of the REASmash. Instructions were displayed within the serious game, and a training session was initiated consisting of 10 trials, to confirm that the participants understood the instructions, and enhance the feeling of immersion. After the training session, the participants pushed a start button within the virtual environment to initiate the experiment (consisting of 6 levels of 24 randomized trials; 144 trials in total). After the participant completed each of the 6 levels, a break of 60 seconds was provided to reduce fatigue. The CI participants received a payment of 10 euros for their participation. All the participants completed the experiment.

2.4 Methods of data analysis

The data analyses were performed using mixed measures (repeated and between) ANOVA, run using SPSS 27.0 (IBM). All post-hoc analyses used Bonferroni correction. The independent variables were search task saliency (low vs high), number of distractors (11, 17 or 23 distractors) and group (SI:HP vs CI). The dependent variables were mean response time (RT, time between stimuli presentation and response with the virtual hammer to the target stimulus; measure in milliseconds), mean velocity (MV, distance covered by the virtual hammer divided by the response time; measures in meters per second), and coefficient of variation of speed (CV, standard deviation of the virtual hammer velocity divided by mean velocity, expressed in percentage).

From the total data set of the SI:HP group (i.e. 144 trials x 20 SI:HP; 2880 trials), 93 omissions trials and 94 error trials (distractor response) were removed (see Table 2). From the total data set of the CI group (2880 total trials), 16 omission trials and 31 error trials were removed. For both groups, no participants made abnormal response times (< 250ms). The analysis was performed on the remaining data of SI:HP and CI group

Table 2: The frequency of omissions and errors (/144 trials) made by SI:HP group. There were no abnormal responses for any participant. The omissions data showed no signs of lateral bias typically associated with hemineglect, strengthening the clinical decision that these patients were not evaluated by the neuropsychology clinic of the hospital. The targets presented within the garden grid (6 columns and 4 rows) were re-coded relative to hand so that targets presented in contralateral space corresponded to columns 1-3 and targets presented in ipsilateral space corresponded to columns 4-6 for SI:HP and CI using their right-hand (with the right-lesion SI:HP using their right non-hemiparetic limb). For left hand responses, contralateral space corresponded to columns 4-6 and targets presented in ipsilateral space corresponded to columns 1-3 (with left-lesion SI:HP using their left less-effected limb).

	Total Omissions (only in contralateral space)	Errors (responded to a distractor)
SI:HP01	0(0)	4
SI:HP02	9(4)	1
SI:HP03	1(1)	0
SI:HP04	2(1)	0
SI:HP05	6(2)	4
SI:HP06	1(1)	3
SI:HP07	0(0)	1
SI:HP08	18(10)	2
SI:HP09	1(0)	1
SI:HP10	10(3)	3
SI:HP11	1(0)	4
SI:HP12	6(3)	22
SI:HP13	4(1)	7
SI:HP14	2(1)	1
SI:HP15	0(0)	4
SI:HP16	0(0)	2
SI:HP17	1(0)	3
SI:HP18	17(13)	13
SI:HP19	1(0)	1
SI:HP20	13(7)	18

3. Results

The analysis of RT showed that there was a main effect of group, $F(1,38) = 16.57$, $p < 0.001$, $\eta^2 = 0.30$, with SI:HP being slower than CI (SI:HP: M = 2712.11, SD = 93.93; CI: M = 2171.41, SD = 93.93). The analysis also showed main effects of search task saliency and distractors. For search task, $F(1,38) = 347.34$, $p < 0.001$, $\eta^2 = 0.90$, RT was significantly slower in the low compared to high target-distractors saliency condition (Low: M = 3011.93, SD = 85.90; High: 1871.59, SD = 57.58). For distractors, $F(2,76) = 74.38$, $p < 0.001$, $\eta^2 = 0.66$, RT was significantly slowed when the number of distractors increased, with significant differences between a target presented with 11 distractors, compared to 17 or 23 distractors, and between 17 and 23 distractors, (M = 2272.82, SD = 64.18; M = 2445.80, SD = 70.35; M = 2606.65, SD = 70.10, for 11, 17, and 23 distractors). As hypothesized, there was a significant interaction between search task saliency and distractors, F (2,76) = 71.97, $p < 0.001$, $\eta^2 = 0.65$ (*Figure 2a*). Separated ANOVAs were run for each search task. This showed that the effect of distractors was not significant for high target-distractors saliency stimuli (levels 1-3), F (2,76) = 2.06, p = 0.13, $\eta^2 = 0.05$, but that there was a significant distractor effect for low target-distractors saliency stimuli, F (2,76) = 79.96, $p < 0.001$, $\eta^2 = 0.68$. A Bonferroni post hoc analysis showed that mean RT significantly slowed as a function of increased number of distractors for low target-distractor saliency contrasts (with significant differences between each distractor set) (M = 2691.81, SD = 84.15; M = 3007.05, SD = 91.18; M = 3336.92, SD = 96.66, for 11, 17 & 23 distractors respectively).

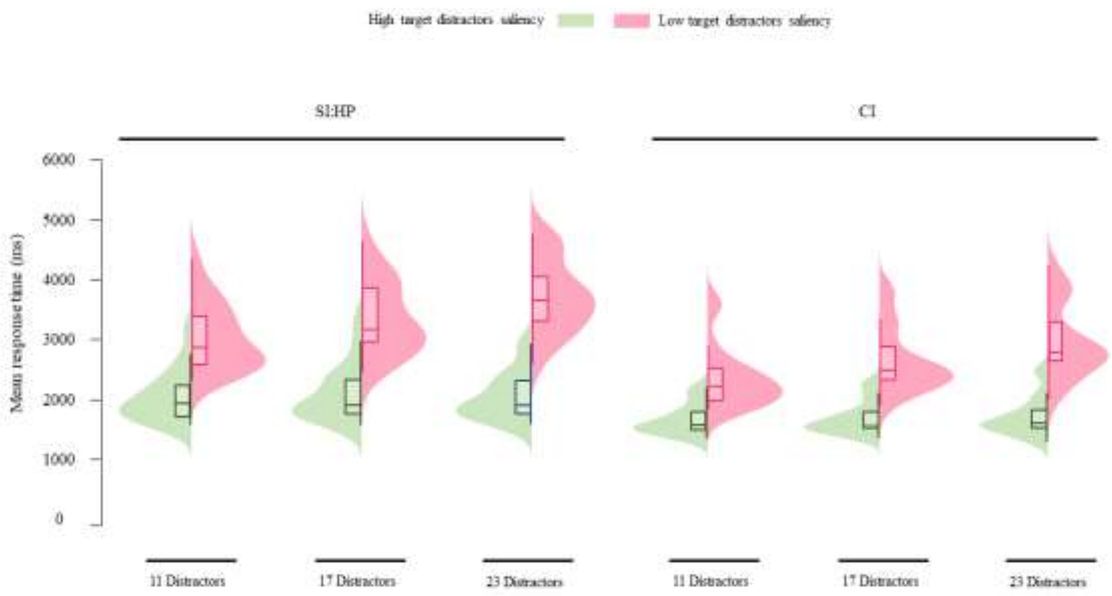


Figure 2a: Violin plots with boxplots illustrating high and low target-distractors saliency conditions with 11, 17, and 23 distractors and SI:HP and CI groups for (a) mean response time (milliseconds),

There was also a significant interaction between search task saliency and group, $F(1,38) = 7.50$, $p < 0.001$, $\eta^2 = 0.16$ (*Figure 3*). Separate ANOVAs were run for each search task. This showed that the effect of group was significant for both sets of stimuli (high target-distractor salience contrasts: levels 1-3, $F(1,38) = 10.50$, $p < 0.001$, $\eta^2 = 0.22$, and low target-distractor salience contrasts: levels 4-6, $F(1,38) = 17.00$, $p < 0.001$, $\eta^2 = 0.31$). The alternative post-hoc analysis of the interaction was made by separating the ANOVA by group. This showed significant differences for search task saliency in both the SI:HP, $F(1,19) = 219.97$, $p < 0.001$, $\eta^2 = 0.92$, and CI groups, $F(1,19) = 131.45$, $p < 0.001$, $\eta^2 = 0.87$, with mean RT significantly slower for responses made to targets in the low compared to high target-distractor salience condition for both groups (SI: HP: *Low:* M = 3366.09, SD = 121.48; *High:* M = 2058.12, SD = 81.42 – CI*: Low:* 2657.77, SD = 121.48; *High*: M = 1685.05, SD = 81.43). To understand the interaction effect more clearly, we ran a third post hoc analysis that re-analysed the data by subtracting mean RT for target search to the high from low target-distractors saliency contrasts (i.e. low-high=inhibition cost; with the positive time illustrating the relative cost of inhibition and eliminating the speed differences observed between participant groups). This analysis showed a main effect of group, $F(1, 38) = 7.50$, $p < 0.001$, $\eta^2 = 0.16$ (SI:HP: M = 1307.96, SD = 86.53; CI: M = 972.71, SD = 86.53), demonstrating that the SI:HP compared to CI groups showed a bigger difference between high and low target-distractor salience contrasts. The interaction between distractors and group was not significant, $F(2,76) = 0.10$, $p = 0.91$, $\eta^2 = 0.00$, and the triple interaction between search task, distractors and groups was not significant, $F(2, 76) = 0.73$, $p = 0.48$, $\eta^2 = 0.02$.

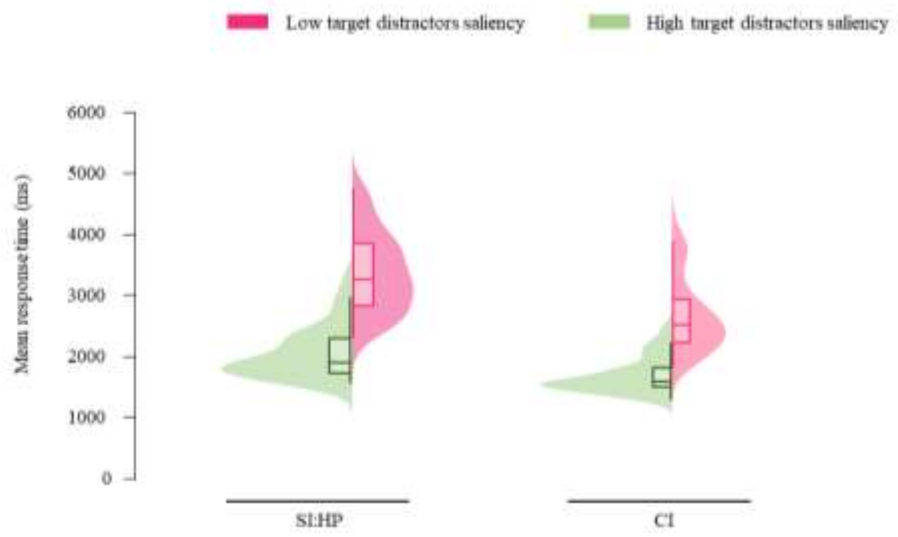


Figure 3: Violin plots with boxplots illustrating mean response time (milliseconds) to high target-distractors saliency (low inhibition demands) and low target-distractors saliency conditions (high inhibition demands) in SI:HP and CI groups. The figure shows that the difference between high and low target-distractor saliency was greater for the SI:HP than CI.

The analysis of MV showed that there was a main effect of group, $F(1,38) = 7.43$, $p < 0.001$, $\eta^2 = 0.16$, with SI:HP making slower actions than CI (SI: HP: $M = 0.36$, $SD = 0.02$; CI: $M = 0.43$, $SD = 0.02$). The analysis also showed main effects of search task saliency and distractors. For search task, $F(1,38) = 181.64$, $p < 0.001$, $\eta^2 = 0.83$, MV was significantly faster to targets presented in high target-distractors saliency ($M = 0.45$, $SD = 0.01$) than in low target-distractors saliency conditions ($M = 0.33$, $SD = 0.01$). For distractors, $F(2,76) = 20.66$, $p < 0.001$, $\eta^2 = 0.35$, MV significantly decreased when the number of distractors increased (i.e. responses slowed), with significant differences between a target presented with 11 distractors, compared to 17 or 23 distractors, and between 17 and 23 distractors, ($M = 0.41$, $SD = 0.01$; $M = 0.39$, $SD = 0.01$; $M = 0.38$, $SD = 0.01$, for 11, 17, and 23 distractors). As hypothesized, there was a significant interaction between search task saliency and distractors, $F(2,76) = 15.68$, $p < 0.001$, $\eta^2 = 0.29$ (*Figure 2b*). Separated ANOVAs were run for each search task. This showed that the effect of distractors was not significant for high target-distractors saliency, $F(2,76) = 1.69$, $p = 0.19$, $\eta^2 = 0.04$, but it was significant for low target-distractors saliency conditions, $F(2,76) = 25.35$, $p < 0.001$, $\eta^2 = 0.4$. A Bonferroni post hoc analysis showed that mean MV was significantly decreased when the number of distractors increased (i.e.

responses slowed), (M = 0.36, SD = 0.01; M = 0.33, SD = 0.01; M = 0.31, SD = 0.01, for 11, 17, and 23 distractors). There were no interactions between search task saliency and group, $F(1,38) = 0.02$, $p = 0.89$, $\eta^2 = 0.00$, distractors and group, $F(2,76) = 0.66$, $p = 0.52$, $\eta^2 = 0.02$, and search task saliency, distractors and group, $F(2,76) = 0.13$, $p = 0.87$, $\eta^2 = 0.00$.

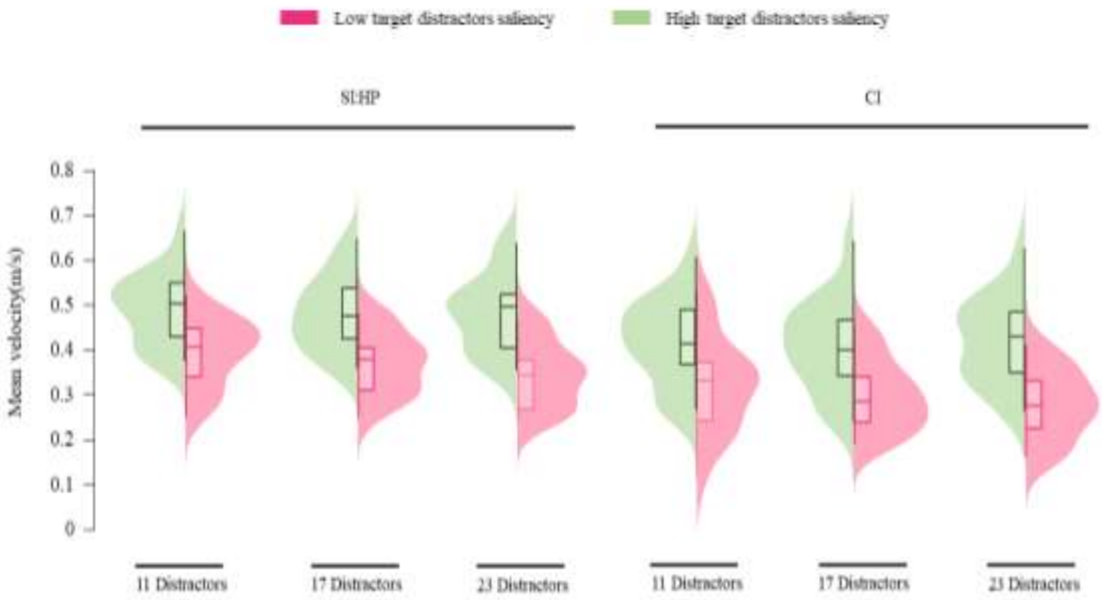


Figure 2b: Violin plots with boxplots illustrating high and low target-distractors saliency conditions with 11, 17, and 23 distractors and SI:HP and CI groups for mean velocity (m/s).

The analysis of CV showed that there was also main effects of search task and distractors. For search task, $F(1,38) = 49.26$, $p < 0.001$, $\eta^2 = 0.56$, CV was significantly higher in the low target-distractors saliency (M = 1.71, SD = 0.07) than high target-distractors saliency conditions (M = 1.43, SD = 0.05). For distractors, $F(2,76) = 14.86$, $p < 0.001$, $\eta^2 = 0.28$, CV significantly increased with the number of distractors increasing (M = 1.51, SD = 0.06; M = 1.56, SD = 0.06; M = 1.62, SD = 0.06, for 11, 17, and 23 distractors). However, there was no main effect of group, $F(1,38) = 3.9$, $p = 0.056$, $\eta^2 = 0.09$. As for RT and MV, the analysis showed a significant interaction between search task saliency and distractors, $F(2,76) = 22.61$, $p < 0.001$, $\eta^2 = 0.37$ (*Figure 2c*). Separated ANOVAs were run for each search task. This showed that the effect of distractors was not significant for high target-distractors saliency, $F(2,76) = 0.25$, $p = 0.78$, $\eta^2 = 0.00$, but was significant for low target-distractors saliency conditions, F (2,76) = 25.84, $p < 0.001$, $\eta^2 = 0.40$. A Bonferroni post hoc analysis showed that mean CV was significantly increased when the number of distractors increased (M = 1.59, SD = 0.07; M = 1.70, SD = 0.08; M = 1.83, SD = 0.08, for 11, 17, and 23 distractors).

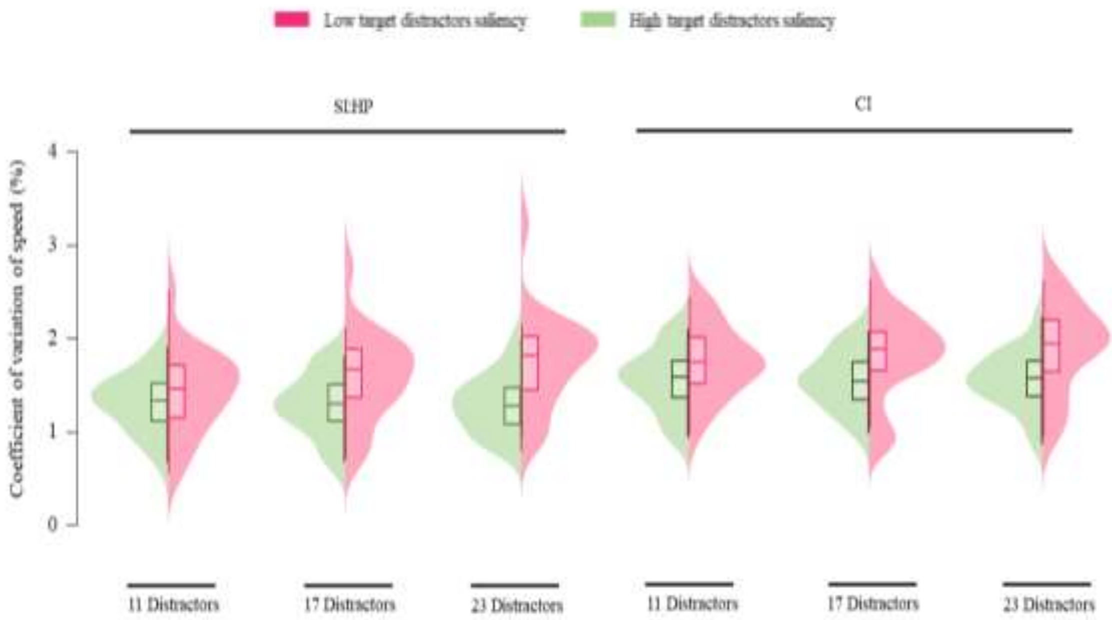


Figure 2c: Violin plots with boxplots illustrating high and low target-distractors saliency conditions with 11, 17, and 23 distractors and SI:HP and CI groups for coefficient of variation of speed (%)

The analyses also showed a significant three-way interaction between search task saliency, distractors and group, F (2,76) = 3.65, $p < 0.001$, $\eta^2 = 0.09$. Separated ANOVA were run for each search task saliency. This showed that the interaction between search task and distractors was significant for SI: HP, F (2,38) = 18.49, $p < 0.001$, $\eta^2 = 0.49$, and for CI, F (2,38) = 5.24, $p < 0.001$, $\eta^2 = 0.2$. An alternative post hoc analysis, was performed for each group and search task. This showed that in high target distractors saliency, there was no effect of distractors for CI, F (2,38) = 0.007, p = 0.99, $\eta^2 = 0.00$ and SI:HN, F (2,38) = 0.38, p = 0.69, $\eta^2 = 0.02$. However, in low target distractors saliency, there was a significant effect of distractors in CI, F (2,38) = 6.09, $p < 0.001$, $\eta^2 = 0.24$, and SI:HN, F (2,38) = 21.25, $p < 0.001$, $\eta^2 = 0.53$. As in RT analysis, we run a third post hoc analysis that re-analysed the data by subtracting mean CV for target search to the high from low target-distractors saliency contrasts. This showed that there was no group effect, F (1,38) = 0.20, p = 0.66, $\eta^2 = 0.00$.

4. Discussion

The main objective of this paper was to investigate the cognitive inhibition difficulties of post-stroke individuals with hemiparesis. We tested a group of post-stroke individuals with hemiparesis and a group of age-matched controls using an immersive virtual reality serious game based on Feature Integration Theory (FIT) (Treisman & Gelade, 1980). Our findings supported our hypotheses and the state-of-the-art, firstly showing that the group of individuals with hemiparesis made slower responses than age matched controls (RT and MV), and they were more variable (CV) (hypothesis 1). Secondly our results demonstrated that both participant groups showed the predicted effects associated with FIT. Specifically, both groups of participants were slower (RT and MV) and made more variable responses (CV) to find the target, when presented with low target-distractors saliency stimuli (levels 4-6; high inhibition demands) in comparison to high target-distractors saliency stimuli (levels 1-3; low inhibition demands), and participants response time to find the target was significantly slowed / move variable with increasing numbers of distractors, specifically in the low target-distractors saliency condition (levels 4-6), but not in the high target-distractors saliency condition (levels 1-3) (hypotheses 2 and 3). Contrasts between the patient groups and the FIT allowed us to demonstrate new findings showing that SI:HP compared to CI group were particularly slowed with low target-distractors saliency stimuli (levels 4-6; high inhibition demands) in comparison to high target-distractors saliency stimuli (levels 1-3; low inhibition demands), suggesting that the SI:HP group could have difficulties in cognitive inhibition compared to CI group.

In addition to replicating the effects reported in the literature, our research showed an interaction effect between search task and group for RT and search task, distractors and group for CV, providing new evidence that the SI:HP group were particularly slowed / more variable relative to the CI group for the low compared to high target-distractors saliency conditions (hypothesis 4). This was demonstrated by calculating the difference between responses to the low compared to high target-distractors saliency conditions (allowing to control between group speed / variance differences), showing that RT / CV differences were greater for the SI:HP group relative to the CI group. This finding is interesting for two reasons. Firstly, the selected HPI group were believed to have no cognitive impairment, and therefore did not benefit from an early neuropsychological assessment and received no cognitive neurorehabilitation. Secondly, based on existing literature, we can predict that patients with hemiparesis may show impairment of inhibitory executive function cognition in addition to motor hemiparesis that may interfere with hemiparesis rehabilitation.

The finding that inhibition executive function mediates the efficacy of recovery is perhaps not surprising when one considers the role of cognition in motor learning (Chan et al., 2006; Kitago & Krakauer, 2013; Patten et al., 2006). Several studies have highlighted the role of cognition in improving motor function (Aprile et al., 2021; Fregni & Pascual-Leone, 2006; Lincoln et al., 1989; Matthews et al., 2016; Mercier et al., 2001; Paolucci et al., 1996; Tatemichi et al., 1994). For example, Hummel et al. (2002) used electroencephalography (EEG) in a motor learning task where participants had to respond to cues with specific finger movements that they learned during a training session. While performing the task, EEG analyses clearly showed increased alpha oscillations in the sensorimotor areas typically engaged in primary motor inhibition of volitional learned motor movements. This finding was reinforced by the absence of these oscillations in patients with dystonia of the hand (Hummel et al., 2002). Similarly, Mooney et al. (2020) used transcranial magnetic stimulation (TMS) with a post-stroke upper limb paresis individuals compared to a healthy group. Participants were trained on a sequential visuomotor isometric wrist extension task. Their results showed that ipsilesional corticomotor excitability did not increase after skill acquisition in clinical population who successfully exhibited acquisition and retention skills, but their general performance was lower than the healthy group. This indicates an inhibition network within the primary motor cortex that is important to motor learning (Mooney et al., 2020). These studies are examples of the many studies that underlines the implication of inhibition in motor recovery (Coxon et al., 2007; Dora et al., 2021; Ridding et al., 1995; Schlaghecken & Eimer, 2002; Shadmehr & Holcomb, 1999; Toro et al., 2000).

From the present study, it is clear that we can repeat the call by Nys et al. (2005) that all individuals with stroke should undergo routine cognitive assessment. There are two solutions to facilitate this objective. Firstly, it could be that all individuals with stroke receive a rapid cognitive screening test, such as the recent test developed by Demeyere et al. (2015). The Oxford Cognitive screen is a valid and usable short cognitive screening tool that has been specifically developed for the post-stroke population. It is an inclusive tool that covers the different cognitive domains usually impaired after a stroke (e.g., attention, language, memory), can be completed in 15-20 min, and is available in different languages (Demeyere et al., 2021; Demeyere et al., 2015; Demeyere et al., 2019). Individuals showing cognitive impairments demonstrated by these screening tools should receive additional cognitive assessment, and furthermore, the rehabilitation programme should include cognitive neurorehabilitation. A second approach would be to develop motor assessments / rehabilitation that co-evaluate / co-rehabilitate cognition. The REASmash serious game, presented in this paper is a cognitive test involving direct motor responses to the target stimuli, and could be adapted to measure upper limb motor function as well as cognitive inhibition as demonstrated in the present paper. Alternatively, tests such as the box and block test could be adapted to contain non-response distractors that compete for attention with target stimuli, requiring inhibition. These combined tests could be presented to patients to offer multiple motor and cognitive assessments within the same test. Furthermore, serious game assessments could be modified to create rehabilitation serious games that exercise motor and cognitive responses (Dehem et al., 2019; Kaiser et al., 2022b; Montedoro et al., 2018).

In conclusion, in the present paper we show that a group of post-stroke individuals with hemiparesis had difficulties in distractors inhibition in an IVR serious game relative to a CI group. These data add to the existing literature showing an association between cognitive and motor functions, as well as highlighting the importance of cognitive assessment in stroke individuals with hemiparesis. Currently, cognitive impairments are not routinely assessed, and these unevaluated cognitive impairments may have severe consequences on overall recovery success. Therefore, we call for healthcare professionals and decision-makers to implement interventions embedding cognitive screening and neuropsychological evaluations for all stroke patients, and we also call for the researchers to be mindful of the integrative relation between cognitive and motor systems when developing new assessment tools for post-stroke individuals.

Chapter 6

General discussion

Technological advancements cause significant shifts in the development of neuropsychological assessment (Parsey & Schmitter-Edgecombe, 2013). In this context, the development of IVR in neuropsychological assessment has emerged as a promising solution to overcome the limitations of traditional paper and pencil assessment methods, that currently remain prevalent in clinic practice (Bilder, 2011; Neguț et al., 2016; Parsons, 2016). Noteworthy advantages offered by IVR lies in its ability to provide ecologically and valid testing environments, enabling more efficient and accurate measurements of complex cognitive functioning (Rizzo et al., 2004; Schultheis et al., 2002).

The aim of this PhD thesis was to use IVR to develop advances in neuropsychological assessments, that will bring benefits to clinical neurorehabilitation, as well as provide new understanding of post-stroke impairments in hemineglect (and hemiparesis). We developed two novel IVR serious games, drawing upon distinct theorical approaches, with the objective of providing sensitive measures for a comprehensive assessment of hemineglect (Chapters 2 and 3). The Peach test of Chapter 2 brought several novel innovations, including the development of a test in an ecologically relevant environment, and the ability to contrast peripersonal and extrapersonal spaces. The REASmash of Chapter 3 also brought several novel innovations, with the ability to measure spatial and distractor inhibition attention, with direct responses to stimuli allowing for omission, response time and action kinematic measures. In Chapter 4, an evaluation of the psychometric properties was conducted to validate the new developed IVR serious game. Then in Chapter 5, the prevalence of cognitive impairments among post-stroke individuals was investigated using the newly developed serious game.

In this General Discussion (Chapter 6), a summary of each empirical chapter will be provided, including a discussion of their limitations. Then, the two main objectives of this thesis will be discussed in light of the current state-of-the art, highlighting the specific contributions made by this research thesis. Finally, a reflection on future prospective and potential directions will be presented.

1. Summary of the thesis

In Chapter 2, we presented a newly developed serious game in IVR. This was named the Peach test as the test involved searching for a peach. It aimed to simultaneously assess spatial search in contra- versus ipsi-lateral space and peri- versus extra-personal space. The assessment involved immersing participants in a realistic three-dimensional virtual kitchen simulation, where they were instructed to perform a search task on a table within the kitchen. Participants were asked to locate a Peach target, presented among other fruits and vegetables distractors. We integrated avatars into the test to assess if that avatars would automatically trigger perspective shifts. Additionally, we manipulated whether the friendliness of the avatar would mediate perspective shifts (the presence of a "friendly avatar", a "non-friendly avatar", or in the absence of the avatar, with the three avatar conditions randomized).

The first objective of this Chapter 2 was to investigate the feasibility and user experience of the Peach test. To achieve this, we firstly tested sixty healthy controls on the Peach test. We demonstrated that there was no laterality effect, no proximity, and no avatar effect. As we have exposed in the *Discussion* of Chapter 2, this absence of the avatar effect, particularity in interaction with proximity, was not in line with the current literature (Freundlieb et al., 2017; Samson et al., 2010). Secondly, we tested a group of post-stroke individuals (with and without) hemineglect and a group of age-matched controls. We showed that post-stroke individuals were slower than the controls, but that they did not exhibit any lateralized bias. This laterality null effect was explained by the clinical status of the participants, who did not show any hemineglect when they were evaluated on standardized tests (i.e. the Apples test (Bickerton et al., 2011)). The data showed a proximity effect, with post-stroke individuals being slower in extra- compared to peri-personal space. However, there was no avatar effect, and no interaction with laterality and proximity, therefore not supporting our hypothesis that the avatar presence would lead to a shift in perspective taking, as proposed in the literature (Becchio et al., 2013; Della Sala et al., 2004). An explanation of the absence of avatar effect may be related to the fixation task. This required the participant to fixate a red basket that appeared before each trial, turning green after fixation and initiating the trial. The basket was positioned on the horizontal plane, level with the table. As a result, the participants' gaze was attracted away from the avatars positioned in front of them within the virtual kitchen. This absence of visual engagement with the avatars could potentially explain the absence of any noticeable effect. Furthermore, one could perhaps wonder if the richness of the virtual environment could cause an attentional overload, distracting participants from the avatar. Studies investigating perspective taking have used virtual environments and virtual avatars, and findings avatar effects on perspective (Müsseler et al., 2022; Surtees et al., 2013). It could be interesting in future studies to examine the impact of a virtual environment on perspective taking by manipulating the richness of this environment (e.g., an environment with no features vs an environment with features). Finally, in the user experience evaluation, post-stroke individuals expressed a general positive impression on Peach test. These findings indicated that the Peach test was user-friendly and easily understandable, making it enjoyable to use. Furthermore, these findings endorsed the use of IVR with post-stroke individuals, suggesting that they may be receptive to incorporating such technology to their treatment plan.

In Chapter 3, we developed and evaluated the feasibility of a second serious game in IVR. The test consisted of 6 levels of search tasks that assessed spatial attention and distractor inhibition (non-spatial attention). Participants were immersed in a simulation of a garden environment, in front a garden patch containing 24 molehills. From these molehills, moles wearing different helmets appeared. The participants were required to hit on a target mole wearing a red miner’s helmet as fast as they could with a virtual hammer held in their hand (and controlled by the IVR hand controller). In the first three levels, the target mole appeared with 11, 17, then 23 moles wearing blue helmets, with half being miner’s helmets and the others being helmets with horns. In the latter three levels, the target mole appeared with 11, 17, and 23 moles wearing blue miner’s helmets and red helmets with horns. The development of this serious game was based on the well-known visual search paradigm proposed by (Treisman & Gelade, 1980). This paradigm suggests that visual search is based on two processes. An automatic pre-attentive process involving *parallel* search, where the target is distinct from distractors by a single feature. This search was modelled in the first three levels of the serious game (single feature search levels). These levels were contrasted to a more effortful inhibition demand process involving a serial search. Here, the distractors differed from the target by a conjunction of features (three levels of feature conjunction search) (Duncan & Humphreys, 1989; Treisman & Gelade, 1980). The use of IVR allowed us to measure response time, and action kinematic measures, and create an amusing test scenario narrative.

The aim of this Chapter 3 was to evaluate the feasibility of the test, and whether our serious game would replicate previous findings based on simple stimuli. In addition, we examined the serial and parallel visual search effect on action kinematic measures (i.e., mean velocity and coefficient of variance of speed). We tested sixty healthy individuals who were instructed to perform the serious game with their dominant hand. Our results were in line with our hypothesis. The participants were slower (response time and mean velocity), and they showed higher action variance to the target presented in the last three levels (*feature conjunction search*), than in the first three levels (*single feature search*). They were also slower (response time and mean velocity) and showed high action variance with increasing numbers of distractors. When analysing the interaction between the two search types involved in the six levels and the number of distractors, we demonstrated that performance (i.e., response time, action velocity and variance) in the first three levels (*singe feature search*) were not modulated by the number of distractors. However, performance was significantly impacted by the increasing numbers of distractors in the last three levels (*conjunction feature search*), with RT and MV increasing and CV decreasing with increased distractor number (11, 17 and 23 distractors). Regarding the laterality effect, as predicted, the participants did not show a difference in response time to a target presented in the contra- compared to ipsi-lateral space. However, their action velocity was slower and variance higher when the target was presented in the ipsi-lateral space compared to when it was presented in the contra-lateral space.

Chapter 4 was an extension of Chapter 3, with the aim of further evaluating the newly developed REASmash IVR serious game. The objective was to assess its psychometric properties and user experience. We replicated the findings of Chapter 2 with a new group of healthy controls. Based on their performance, we established norms against which we compared the results of nine post-stroke individuals previously diagnosed with hemineglect. This normative analysis yielded significant effects for combinations of the independent variables.

Interestingly, there appeared to be little correspondence between spatial and distractor inhibition variables. However, studies based on more robust statistical analysis and a larger sample of acute post-stroke individuals with hemineglect are needed to verify these results.

We tested the validity of REASmash by comparing the performance of a group post-stroke individuals (with and without hemineglect) to their performance on two standardized tests (i.e. OCS Broken hearts sub-test (Demeyere et al., 2015), and TAP visual search sub-test (Zimmermann & Fimm, 2004)). The analysis showed a non-significant correlation for omission asymmetry, explained by low rate of omissions in REASmash and the two standardized tests. The analyses also showed a significant moderate correlation between the REASmash RT and OCS omissions sub-test. We also analysed the reliability with a sub-sample of the control group, which demonstrated excellent results for response time and coefficient of variation, and moderate results for mean velocity. However, the results for omissions were poor, likely caused by the low rate of omissions. We computed the minimal detectable change for future use, and investigated absolute reliability using Bland-Altman plots, suggesting that the measures across the two testing sessions were interchangeable. Although these results were positive, we proposed that a larger sample of post-stroke individuals is needed to improve the validity and reliability results. Finally, we evaluated the user experience of REASmash with the post-stroke individuals. The results suggested an overall positive impression. The post-stroke individuals seemed to enjoy REASmash and find it clear to understand and interact with. To conclude, the REASmash offers a new possibility to assess spatial attention and non-spatial attention (i.e. distractors inhibition) simultaneously in a motivating fun environment, with precise and standardised measures of response time, response accuracy, and action kinematics.

In Chapter 5, we used REASmash to investigated whether post-stroke individuals with upper limb hemiparesis had non-spatial attention (i.e. distractor inhibition) impairments. For this, we tested a group of post-stroke individuals with hemiparesis and a group of age-matched healthy controls. We hypothesized that the results would replicate the visual search paradigm (Ajana et al., 2023; Treisman & Gelade, 1980). Additionally, we predicted an interaction between groups and search levels, with post-stroke individuals compared to controls individuals expected to exhibit a larger disparity in response time in feature conjunction search than in single feature search. The results followed our hypotheses, demonstrated by a replication of the visual search paradigm effects (Treisman & Gelade, 1980), and that post-stroke individuals relative to control individuals were slower (response time and action velocity), and showed higher action variance to the target presented in the last three levels (*feature conjunction search*), compared the first three levels (*single feature search*). Moreover, the performance of the participants was impacted by increasing numbers of distractors, specifically in the three last levels (*feature conjunction search*), compared to the three first levels (*single feature search).* An analysis of contrasts between the performance of the two groups demonstrated that post-stroke individuals were particularly slower than controls. This finding suggested a non-spatial attention (i.e. distractors inhibition) impairment in a group of post-stroke individuals who were not diagnosed with cognitive impairments. This study provides evidence that post-stroke individuals without overt cognitive impairments and with no clinical evaluation of cognition can experience cognitive impairments that are subtle, but can have a significant impact on the everyday-life functioning.

To sum up, the focus of this thesis was the development of IVR serious games for neuropsychological assessment. In Chapter 2, we introduced a new serious game based on a new approach for the assessment of HN. Although the results did not support our predictions (specifically, the presence of avatar had no influence on perspective taking in HN), this study showed an excellent IVR usability. Chapters 3, 4 and 5 were centred around the second serious game, evaluating feasibility (Chapter 3), validity, reliability and user experience (Chapter 4) and an investigation of distractor inhibition within post-stroke individuals with hemiparesis (Chapter 5).

2. Objectives of the thesis

2.1 Enhancing the quality of neuropsychological assessment

As exposed in Chapter 1 (General Introduction) of this thesis, neuropsychology assessment is adapting to technological transformation. Today, this technological progress is expected to address the limitations of the traditional neuropsychological paper and pencil tests. These testes have been criticized for their lack of sensitivity in detecting the complexity of cognitive functioning in the real-world (Horowitz et al., 2019; Treviño et al., 2021). Furthermore, they have shown poor ecological validity and reliability (Howieson, 2019), and some tests lack theorical conceptualisation or are based on out-dated paradigms (Kessels, 2019; Parsons, 2016). In addition, these tests have been criticized for their perceived monotony and lack of engagement, leading to the notion that they are tedious (Cerrato & Ponticorvo, 2017).

In this thesis, we developed two IVR serious games. They were based on distinct theoretical models. In Chapter 2, we developed the Peach test, which offers an assessment of spatial attention in the contra- versus ipsi-lateral space, and in peri- versus extra-personal space. Although other aspects of the test did not work as predicted (i.e. the manipulation of avatars), it should be noted that the spatial assessment brings novelty to neuropsychology assessment. Notably, the capacity to systematically contrast peri- and extra-personal spaces for the evaluation of lateralized spatial attention. Traditional paper-and-pencil tests, commonly used in the assessment of spatial attention, are mostly limited to responses made in peri-personal space (Grattan & Woodbury, 2017a; Plummer et al., 2003). This constraint extends to the applications of IVR in HN assessment, all which evaluate responses to stimuli presented in the peri-personal space (e.g., (Jannink et al., 2009; Kim et al., 2011; Knobel et al., 2020)). Very few studies have investigated the effects of hemineglect to stimuli presented in extra-personal space (e.g., (Kim et al., 2010; Ogourtsova et al., 2018)). To our knowledge, there is only one study using IVR that proposes a systematic evaluation of responses to stimuli presented in both the peri- and extra-personal spaces (Perez-Marcos et al., 2023). This IVR-assessment test consists of four visual search tasks implemented in a forest simulation. Users of the test are requested to find different targets at three different distance ranges from their viewpoint. They tested their multi-level test with a group of healthy individuals and reported test feasibility and usability (Perez-Marcos et al., 2023).

In Chapter 3, we developed the REASmash that allows the evaluation of spatial and non-spatial attention (i.e. distractors inhibition). It involved a search task requiring a direct-action response to the stimuli, allowing us to measure response accuracy, response time, and action kinematics (Omowonuola et al., 2022; Wilson & Soranzo, 2015). These measures will provide a deeper understanding of the cognitive behaviour of the users, as well as increase diagnosis sensitivity. Both the Peach test and the REASmash were designed to be engaging, featuring a fun scenario that was set in familiar three-dimensional environments (i.e. a kitchen and a garden). The efficacy of serious games has been proven, as they offer challenging and fun gameplay experiences that encourages and motivates the users to perform at their best (Jenkins et al., 2009; Shute & Rahimi, 2017).

Across this thesis, we evaluated user experience using the User Experience Questionnaire (Laugwitz et al., 2008a). We showed that participants had an overall positive experience using both the Peach test and REASmash serious. These results could be considered as evidence that post-stroke individuals had good acceptance of IVR serious games (Morelli et al., 2022; Rose et al., 2018; Specht et al., 2021). In both of our serious games, the perspicuity dimension received the highest score. This dimension refers to how clear the serious game appears and how easily one can comprehend the objectives and functioning (Laugwitz et al., 2008a). It is related to general usability, or the “pragmatic” quality of the serious game, which addresses the users need for control and security over their interactions with an interface (Hassenzahl, 2001).

When we created the serious games, we considered usability. In both games, a simple storyline was developed. This was introduced using clear multimodal instructions (oral and written). This meets Bastien and Scapin (1993) ergonomic criteria guidance, that requires setting up a means to orient and instruct users throughout their interactions with the interface. Minimal actions were required to interact with the interface, and these actions were consistent throughout the game. Users were only required to use one button to interact with the interface, and perform two actions (i.e., the fixation task before each trial, and then during the trial, to find the target). This met brevity and consistency ergonomic criteria of Bastien and Scapin (1993). They respectively refer to the goal of limiting the number of action steps, and providing coherent and stable commands and procedures in the interface (Bastien & Scapin, 1993). Another design strategy implemented to ensure good serious games usability was related to the multimodal feedback received through the game to validate action responses (e.g., change in colour for the fixation task). This is in line with the immediate feedback ergonomic criteria of Bastien and Scapin (1993), which concerns a system capacity to provide fast and appropriate responses to user actions.

The user experience evaluation of both serious games presented in this thesis yielded a relatively low score for dependability (low compared to the other dimensions). Dependability refers to the predictability of interactions and a sense of control over them (Laugwitz et al., 2008a). It is considered as a usability criterion. Bastien and Scapin (1993) suggest that in order to achieve efficient and effective interactions, users should always be in control of a system (e.g., being able to interrupt, pause and/or continue). This control existed within our serious games. However, the experimental context, in which they were evaluated, they could not use actions. Future research could explore these interactions and determine whether increased user control has consequences for diagnostic accuracy. Using a comprehensive user and game experience protocols allow users' to evaluate the usability and playfulness of serious games, and should be systematically evaluated for all test developments.

Chapters 3 and 4 provided feasibility and validity results for the REASmash. These studies evaluated the psychometric properties of the test and established standardized quality. This vital step ensures the comparability and reliability of REASmash. A validation process is important as it enhances the accuracy and usefulness of new tests contributing to the improvement of neuropsychological assessment, leading to increased understanding of patient conditions, and more informed decision-making regarding the treatment plans (Barr, 2001; Franzen, 2013).

The results for the evaluation of validity and reliability in this thesis could be improved. We evaluated the concurrent validity of REASmash and showed correlation, but as explained in the discussion of Chapter 4, this effect could be related to the absence of omissions data. Future studies should reinvestigate this psychometric component with a larger sample of participants with chronic hemineglect. Our results also showed good reliability. We used the test-retest method on four variable measurements (RT, MV, CV, and omissions), and obtained an ICC = 0.02 – 0.86 (the lowest ICC was for omission, and highest was for RT). It has been shown that neuropsychology tests with good to high test-retest reliability typically range by ICC = 0.70 – 0.90 (Bird et al., 2003). It is important to show a good test-retest reliability as it indicates that the test has minimal measurements error related to random variance (Anastasi & Urbina, 1997). This increases the likelihood of obtaining the same scores over multiple administrations of the test, supporting use as longitudinal measure of cognitive performance (Morrison et al., 2015; Sherman et al., 2011). Future studies should investigate reliability with a large sample of cognitively impaired individuals.

In this thesis, the sensitivity and specificity of the serious game was not investigated. Future studies, should examine these factors to ensure that the tests can accurately discriminate individuals with impairment from the individuals without impairment (Lezak, 1995; Urbina, 2014). Sensitivity and specificity depend on the cut-off value above or below which the test defines the diagnostic criteria (the individual succeeds the test versus they fail the test). They are computed as follows: sensitivity = number of true positives (individuals with an impairment who fail the test) / (number of true positives + number of false negatives; control individuals who fail the test); and specificity = number of true negatives (controls who succeed the test) / (number of true negatives + number of false positives; controls who fail the test) (Chu, 1999; Swift et al., 2020). For a test to be accurate, it needs to show high sensitivity and specificity. High sensitivity in a test can be obtained when the number of false negatives is low.
It is primordial to correctly identify individuals with impairment (here, post-stroke). As discussed in Chapter 5, undiagnosed cognitive impairments may have heavy consequences on the efficacy of recovery. When decreasing the number of false positives, a high specificity can be reached. This ensures that a test is not going to identify individuals without impairment as if they do have an impairment (Glaros & Kline, 1988).

While it is desirable to have high sensitivity and specificity in a test, there is a statistically trade-off between the two that results in one increasing when the other decreases (Chu, 1999). In the context of post-stroke neuropsychological assessment, setting up a low threshold for positive test results (i.e., maximizing sensitivity), could result in identifying a large sample of cases that include false positives. This means that it is less likely to miss a case with an impairment. However, individuals without the impairment might be wrongfully diagnosed.

2.2 New insights into the understanding of post-stroke cognitive impairments

Stroke leads to a range of complex impairments affecting cognitive, sensorial, and motor functioning (Leśniak et al., 2008; Robert Teasell & Hussein, 2016). Cognitive functioning impairments post-stroke can be diverse and vary in severity (Danovska & Peychinska, 2012; Vakhnina et al., 2009). They require a thorough assessment that lead to effective treatment plans. Failure to perform detailed assessments can have serious repercussions on recovery and every-day life functioning (Cumming et al., 2013; Mercier et al., 2001).

Spatial attention functioning is considered one of the most affected cognitive processes post-stroke (Hyndman & Ashburn, 2003; Hyndman et al., 2008; Stapleton et al., 2001). Impairments in spatial attention can lead to the development of a complex syndrome known as hemineglect (Heilman et al., 1994). It is typically characterized within an egocentric frame of reference, whereby the spatial location of a stimulus is coded relative to oneself (Calvanio et al., 1987; Driver & Pouget, 2000). However, when another person is present, a shift in this frame of reference can occur (Kampis & Southgate, 2020; Zaehle et al., 2007). This shift prompts a spontaneous perspective-taking process, allowing for the representation of stimuli from the other person's viewpoint (Tversky & Hard, 2009). In Chapter 2, we investigated this shift of frame of reference in a group of healthy controls and a group of post-stroke individuals. The participants performed the Peach test in three randomized conditions, where they had to interact with two avatars. Our findings were not conclusive and did not support our hypotheses. More testing is needed to understand if the presence of an avatar can provoke a change in perspective. Despite this null finding, as discussed above, we demonstrated that the IVR Peach test brings value in providing an experimental tool to investigate complex real-world peri- and extra-personal lateralized target search interactions.

Stroke can result in subtle impairments that may be less apparent and easily overlooked, leading to potential underdiagnosis (Montero-Odasso et al., 2018). Currently, the more noticeable and visible impairments that follow from a stroke, such as motor or speech difficulties, frequently receive immediate attention, in comparison to hidden cognitive impairments, such as distractor inhibition (Einstad et al., 2021). In Chapter 5, we used the REASmash to examine the presence of distractor inhibition impairments in post-stroke individuals with hemiparesis, who had not been diagnosed with any cognitive impairment. Our analysis revealed that these post-stroke individuals may have distractor inhibition impairments. These results contribute to the abundant literature that suggests an association between cognitive and motor functioning. As cognitive functioning plays a fundamental role in motor recovery, diagnosis of inhibition function is likely important for planning neurorehabilitation (Chan et al., 2006; Hummel et al., 2002; Mooney et al., 2020). In Chapter 4, we emphasized the significance of a systematic screening for cognitive impairments and subsequent comprehensive neuropsychological assessment following a stroke. This recommended procedure aims to minimize the risk of overlooking cognitive impairments, that can have a substantial impact on rehabilitation outcomes and social integration. By implementing a thorough evaluation process, healthcare professionals can ensure early detection and appropriate management of cognitive impairments, thereby enhancing the overall effectiveness of rehabilitation and promoting better social inclusion for stroke survivors.

To conclude, we developed two novel IVR serious games, the Peach test and the REASmash, for neuropsychological assessment. These serious games were developed to address some of the limitations of traditional paper and pencil assessment tests. As part of our research, we conducted a validation study for the REASmash, with the objective of evaluating its psychometric properties. The purpose of this validation process was to enhance the accuracy and reliability of the assessment measurements provided by REASmash. In the following section, we will explore the potential advancements of IVR serious games.

3. Limitations and perspectives of the thesis

This thesis is a contribution to the advancement of neuropsychological assessment and understanding of post-stroke cognitive impairments. By using IVR, serious games, and theoretical conceptualisation, we developed two novel IVR serious games. These tests assess specific components of cognitive impairments through the measure of response accuracy, response time, and action kinematic measures.

We investigated the feasibility and validity of these newly developed IVR serious games with a group of control individuals and post-stroke individuals. The size and composition of the post-stroke samples could be considered as the major limitation of this thesis. Indeed, we could only obtain a limited sample of post-stroke individuals, none showing current hemineglect on standard clinical tests. This was problematic insofar that it impacted the statistical power and size effect. Future studies should include a large sample of post-stroke individuals that show hemineglect at the time of testing. This is needed to validate the IVR-based serious games presented here.

Newly developed tests based on technological advances may bring many advantages to neuropsychological assessment practices, but they must prove their validity and reliability, as these psychometric components are fundamental to establish their clinical relevance (Barr, 2001; Howieson, 2019; Sherman et al., 2011). Moreover, they should include demographic adjusted norms that could yield adequate diagnosis (Diaz-Orueta et al., 2020). Here, we presented norms for REASmash, but they need to be pooled from a larger demographically diverse sample (Strauss et al., 2006).

Another limitation of the thesis is related to the ecological validity. We proposed new tests in rich virtual environments. However, we did not investigate the ecological validity of these tests. It would be important in future studies to examine this by testing the similarity between these tests and a real-world setting that require the same functions of the tests. This approach to ecological validity is termed verisimilitude, and it refers to the likeliness between the requirements of a tests and a real-world environment (Chaytor & Schmitter-Edgecombe, 2004; Franzen & Wilhelm, 1996).

Statistical analysis performed in this thesis was another limitation in this thesis. Repeated measures analysis of variance was perfomed on datasets, from which outliers were removed, using a normal distribution method. While this confidence interval method to remove outliers is an acceptable practice in the field, it is possible that better statistical methods exist for contrasting clinical participants with control participants. Future studies should concider the use of alternative statistics. For example, linear mixed models could be used after logarithmic transfarmation if data show non-normal distributions. This method is less sensitive to missing data (Krueger & Tian, 2004; Meert et al., 2010; Schober & Vetter, 2021) and perhaps more appropriate for the present data.

An additional limitation in this thesis could be related to the technology. Neuropsychological assessment can benefit greatly from IVR, as presented in the General Introduction (Chapter 1). However, the limited field of view of current IVR technology may constrain the effectiveness and accuracy of spatial search tasks (Kruijff et al., 2018; Ragan et al., 2015). It has been shown that reduced field of view leads reduces error rate (i.e., more participants successfully find the target) (Butkiewicz & Stevens, 2020; Cao et al., 2008; Grinyer & Teather, 2022). This factor could compromise the sensitivity of IVR-based search tasks used for the diagnosis of hemineglect, insofar as these tasks may fail to differentiate between individuals with a spatial attention impairment from controls.

While engaging with both of the serious games presented, individuals were interacting with the dynamic environment through the performance of upper limb movements. Therefore, the extraction of action kinematics provided valuable insights and sensitive measures to characterize cognitive impairments. Similarly, other behavioural and physiological sensors could be integrated to VR systems to further enhance the effectiveness of these tests, such as eye tracking. By combining multiple assessment modalities, more comprehensive and precise data can be gathered to explain the cognitive functioning. Eye tracking is recognized as a reliable and established technique for studying cognition (Burch et al., 2015; Kiefer et al., 2017). By analysing visual attention and gaze patterns, eye tracking offers valuable insights into cognitive processes (Duchowski et al., 2000). The progress made on small and high-quality camera technology, developed initially for devices like smartphones, made it possible to integrate eye tracking into IVR headsets

(Anderson et al., 2023; Clay et al., 2019). In fact, several headsets with integrated eye trackers are already commercially available (e.g. TC Vive Pro Eye, PlayStation®VR2, Pico Neo 3 Pro Eye). This integrative technology allows efficient and precise monitoring of gaze dynamics and cognitive functioning during free-viewing of naturalistic environments (Lutz et al., 2017; Meißner et al., 2019).

There is a growing body of research interested in the applications of eye trackers integrated to IVR for neuropsychological assessment (Kaiser et al., 2022b; Pettersson et al., 2018). Notably, a study conducted by Hougaard et al. (2021) examined the potential use of eye tracking integrated to IVR in assessing hemineglect across different body midlines (i.e. egocentric midlines of body, head, and eyes, and allocentric midlines of objects). They have demonstrated that the measures captured through this integrative technology, notably gaze-asymmetry, have the potential to detect sensitive sub-types of hemineglect (Hougaard et al., 2021).

The combination of electroencephalography (EEG) and IVR, also offer exciting possibilities for enhancing the quality of neuropsychological assessment and advancing the understanding of cognitive processes (Muñoz et al., 2022; Pezzetta et al., 2023; Tan et al., 2021). EEG allows non-invasive, real-time measurement of brain activity with high temporal resolution (Ladouce et al., 2021). EEG is a well-established neuroimaging research method which has been extensively applied to the study of neurological conditions in clinical settings (Askamp & van Putten, 2014; Jaiswal et al., 2010; Lau-Zhu et al., 2019; Saj et al., 2021). The signals recorded by surface EEG reflect the firing of large neuronal populations. The temporal, spectral and spatial features of this data has shown to provide insightful information about the cognitive processes associated with cognitive (dys)functions. The main pitfalls of EEG (and other neuroimaging research methods) lie in their reliance on the acquisition of multiple trials (implying the presentation of artificial stimuli through computerized paradigms and the performance of prototypical responses by the participants) to reach sufficient signal-to-noise ratio and ensure the interpretability of the data. As a consequence, the application of neuroimaging techniques to study everyday-life behaviours and gain insight on embodied aspects of human cognition has been hindered. The recording of brain activity during the performance of an IVR assessment task, however, holds great promises to address the aforementioned issues. Indeed, IVR, while simulating a scenario relatively close to a day-to-day activity, provides a semi-structured experimental paradigm upon which researchers have complete control and access to precise information regarding experimental events which is a non-trivial requirement for the extraction and analysis of EEG data. Applied to hemineglect research, this joint approach could lead to novel insights into cognitive behaviour. By combining EEG with IVR, the assessment process can be automated and refined. These physiological measures can inform the system of the user cognitive state and alter adaptively the environment to probe cognitive processes more precisely. Moreover, such a closed-loop design could provide the users with real-time feedback that could be displayed or expressed under various forms within the virtual environment. This integration not only enhances repeatability but also provides the advantages of real-time monitoring and analysis for a more efficient and accurate neuropsychological assessment.(Khalaf et al., 2018; Wen et al., 2018). It can be argued that the combination of engaging tasks taking place in immersive environments whose aspects adapt to the individuals’ performance, cognitive and physical states while providing feedback has important potential for the design of effective assessment and rehabilitation approaches for post-stroke cognitive impairments.

Building upon this thesis, future research projects will aim to enhance REASmash by integrating it into a headset equipped with an eye tracker. This integration is intended to delve deeper into the cognitive behaviour of post-stroke individuals. By incorporating measures such as response accuracy, response time, action kinematics, as well as head and gaze tracking, we aim to gain a comprehensive understanding of their cognitive functioning and performance.

Conclusion

In conclusion, the field of neuropsychological assessment have been encountering various obstacles related to technology, psychometrics, and conceptual aspects. Researchers and clinicians are actively working to overcome these challenges, as they acknowledge the importance of a sensitive and accurate assessment. Indeed, neglecting this step can have serious consequences on individuals' recovery and social integration.

The objective of this thesis is to make a meaningful contribution to the ongoing efforts directed towards the improvement of neuropsychological assessment quality. Additionally, we aimed to bring new insights to the understanding of post-stroke cognitive impairments. Firstly, we proposed a serious game in IVR, developed for the assessment of hemineglect in contra- versus ipsi-lateral spaces and in peri- versus extra-personal spaces. This serious game was also developed to investigate the effect of perspective taking on the ego-centric frame of reference in hemineglect. Then, we introduced a second serious game in IVR developed for the assessment of spatial and non-spatial attention, that have been examined on a psychometric level against a group chronic post-stroke individuals and healthy controls. Finally, we showed the usefulness of the latter serious game, by using it to enlarge the understanding of cognitive impairments post-stroke.

This thesis provided evidence of the valuable role that IVR and serious game can fulfil in addressing the limitations of current neuropsychological assessment approaches. It also highlighted the significance of a development process based on a theoretical conceptualization. However, it is important to acknowledge that this alone may not be enough for neuropsychological assessment to reach its maximum efficiency potential.

In fact, a noticeable gap exists within the field of neuropsychology between scientific developments and their practical implementation in clinical settings. To bridge this gap, it is essential to establish an open and effective dialogue between clinicians and researchers/tests developers fostering collaboration to create and apply meaningful approaches for assessment. Moreover, it is important to include clinicians, individuals with cognitive impairments and their caregivers in the developments of new technological tests, in order to ensure that the design of these devices are not only innovative but also practical and user-friendly, ultimately enhancing their usability and usefulness in real-world situations.

References

Aam, S., Einstad, M. S., Munthe-Kaas, R., Lydersen, S., Ihle-Hansen, H., Knapskog, A. B., Ellekjær, H., Seljeseth, Y., & Saltvedt, I. (2020). Post-stroke Cognitive Impairment-Impact of Follow-Up Time and Stroke Subtype on Severity and Cognitive Profile: The Nor-COAST Study. *Front Neurol*, *11*, 699. https://doi.org/10.3389/fneur.2020.00699

Abbasi, G. A., Jagaveeran, M., Goh, Y.-N., & Tariq, B. (2021). The impact of type of content use on smartphone addiction and academic performance: Physical activity as moderator. *Technology in Society*, *64*, 101521. https://doi.org/https://doi.org/10.1016/j.techsoc.2020.101521

Adams, R. J., Lichter, M. D., Ellington, A., White, M., Armstead, K., Patrie, J. T., & Diamond, P. T. (2017). Virtual activities of daily living for recovery of upper extremity motor function. *IEEE transactions on neural systems and rehabilitation engineering*, *26*(1), 252-260.

Aglioti, S., Smania, N., Barbieri, C., & Corbetta, M. (1997). Influence of stimulus salience and attentional demands on visual search patterns in hemispatial neglect. *Brain and cognition*, *34*(3), 388-403.

Aguilera-Rubio, Á., Alguacil-Diego, I. M., Mallo-López, A., & Cuesta-Gómez, A. (2022). Use of the Leap Motion Controller® System in the Rehabilitation of the Upper Limb in Stroke. A Systematic Review. *Journal of Stroke and Cerebrovascular Diseases*, *31*(1), 106174. https://doi.org/https://doi.org/10.1016/j.jstrokecerebrovasdis.2021.106174

Aimola, L., Schindler, I., Simone, A. M., & Venneri, A. (2012). Near and far space neglect: task sensitivity and anatomical substrates. *Neuropsychologia*, *50*(6), 1115-1123.

Ajana, K., Everard, G., Lejeune, T., & Edwards, M. G. (2023). A feature and conjunction visual search immersive virtual reality serious game for measuring spatial and distractor inhibition attention using response time and action kinematics. *Journal of Clinical and Experimental Neuropsychology*, 1-12. https://doi.org/10.1080/13803395.2023.2218571

Alam, A. (2021). Possibilities and apprehensions in the landscape of artificial intelligence in education. 2021 International Conference on Computational Intelligence and Computing Applications (ICCICA),

Alankus, G., Lazar, A., May, M., & Kelleher, C. (2010). Towards customizable games for stroke rehabilitation. Proceedings of the SIGCHI conference on human factors in computing systems,

Allain, P., Foloppe, D. A., Besnard, J., Yamaguchi, T., Etcharry-Bouyx, F., Le Gall, D., Nolin, P., & Richard, P. (2014). Detecting everyday action deficits in Alzheimer’s disease using a nonimmersive virtual

reality kitchen. *Journal of the International Neuropsychological Society*, *20*(5), 468-477.
Allison, T., Puce, A., & McCarthy, G. (2000). Social perception from visual cues: role of the STS region. *Trends in Cognitive Sciences*, *4*(7), 267-278. https://doi.org/https://doi.org/10.1016/S1364-6613(00)01501-1
Alqahtani, A. S., Daghestani, L. F., & Ibrahim, L. F. (2017). Environments and system types of virtual reality technology in STEM: A survey. *International Journal of Advanced Computer Science and Applications (IJACSA)*, *8*(6).
Alt Murphy, M., & Häger, C. K. (2015). Kinematic analysis of the upper extremity after stroke–how far have we reached and what have we grasped? *Physical Therapy Reviews*, *20*(3), 137-155.
An, K.-N. (1984). Kinematic analysis of human movement. *Annals of Biomedical Engineering*, *12*, 585-597.
Anastasi, A., & Urbina, S. (1997). *Psychological testing*. Prentice Hall/Pearson Education.
Anderson, B., Mennemeier, M., & Chatterjee, A. (2000). Variability not ability: another basis for performance decrements in neglect. *Neuropsychologia*, *38*(6), 785-796. https://doi.org/https://doi.org/10.1016/S0028-3932(99)00137-2
Anderson, N. C., Bischof, W. F., & Kingstone, A. (2023). Eye Tracking in Virtual Reality. In (pp. 1-28). Springer Berlin Heidelberg. https://doi.org/10.1007/7854_2022_409
Anthes, C., García-Hernández, R. J., Wiedemann, M., & Kranzlmüller, D. (2016). State of the art of virtual reality technology. 2016 IEEE aerospace conference,
APA. (2007). Record keeping guidelines. *The American Psychologist*, *62*(9), 993-1004.
Aprile, I., Guardati, G., Cipollini, V., Papadopoulou, D., Monteleone, S., Redolfi, A., Garattini, R., Sacella, G., Noro, F., & Galeri, S. (2021). Influence of cognitive impairment on the recovery of subjects with subacute stroke undergoing upper limb robotic rehabilitation. *Brain Sciences*, *11*(5), 587.
Arguin, M., Joanette, Y., & Cavanagh, P. (1993). Visual search for feature and conjunction targets with an attention deficit. *Journal of cognitive neuroscience*, *5*(4), 436-452.
Arlati, S., Keijsers, N., Paolini, G., Ferrigno, G., & Sacco, M. (2022). Kinematics of aimed movements in ecological immersive virtual reality: a comparative study with real world. *Virtual Reality*, *26*(3), 885-901. https://doi.org/10.1007/s10055-021-00603-5
Armstrong, C. M., Reger, G. M., Edwards, J., Rizzo, A. A., Courtney, C. G., & Parsons, T. D. (2013). Validity of the Virtual Reality Stroop Task (VRST) in active duty military [Article]. *Journal of Clinical and Experimental Neuropsychology*, *35*(2), 113-123. https://doi.org/10.1080/13803395.2012.740002
Askamp, J., & van Putten, M. J. (2014). Mobile EEG in epilepsy. *International journal of psychophysiology*, *91*(1), 30-35.

Avan, A., & Hachinski, V. (2021). Stroke and dementia, leading causes of neurological disability and death, potential for prevention. *Alzheimer's & Dementia*, *17*(6), 1072-1076.
Azouvi, P. (1996). Functional consequences and awareness of unilateral neglect: study of an evaluation scale. *Neuropsychological rehabilitation*, *6*(2), 133-150.
Azouvi, P. (2017). The ecological assessment of unilateral neglect. *Annals of Physical and Rehabilitation Medicine*, *60*(3), 186-190. https://doi.org/https://doi.org/10.1016/j.rehab.2015.12.005
Azouvi, P., Samuel, C., Louis-Dreyfus, A., Bernati, T., Bartolomeo, P., Beis, J., Chokron, S., Leclercq, M., Marchal, F., & Martin, Y. (2002). Sensitivity of clinical and behavioural tests of spatial neglect after right hemisphere stroke. *Journal of Neurology, Neurosurgery & Psychiatry*, *73*(2), 160-166.
Bailey, M. J., Riddoch, M. J., & Crome, P. (2000). Evaluation of a test battery for hemineglect in elderly stroke patients for use by therapists in clinical practice. *NeuroRehabilitation*, *14*(3), 139-150.
Bailey, M. J., Riddoch, M. J., & Crome, P. (2004). Test–retest stability of three tests for unilateral visual neglect in patients with stroke: Star Cancellation, Line Bisection, and the Baking Tray Task. *Neuropsychological rehabilitation*, *14*(4), 403-419.
Balasubramanian, S., Colombo, R., Sterpi, I., Sanguineti, V., & Burdet, E. (2012). Robotic assessment of upper limb motor function after stroke. *American journal of physical medicine & rehabilitation*, *91*(11), S255-S269.
Barker-Collo, S. L., Feigin, V. L., Lawes, C. M. M., Parag, V., & Senior, H. (2010). Attention Deficits After Incident Stroke in the Acute Period: Frequency Across Types of Attention and Relationships to Patient Characteristics and Functional Outcomes. *Topics in Stroke Rehabilitation*, *17*(6), 463-476. https://doi.org/10.1310/tsr1706-463
Barnard, D. (2019). Degrees of freedom (DoF): 3-DoF vs 6-DoF for VR headset selection. *Consulté le Avril*, *11*, 2021.
Barr, W. B. (2001). Methodologic Issues in Neuropsychological Testing. *J Athl Train*, *36*(3), 297-302.
Barrett, A. M., Buxbaum, L. J., Coslett, H. B., Edwards, E., Heilman, K. M., Hillis, A. E., Milberg, W. P., & Robertson, I. H. (2006). Cognitive rehabilitation interventions for neglect and related disorders: moving from bench to bedside in stroke patients. *Journal of cognitive neuroscience*, *18*(7), 1223-1236.
Barrett, A. M., & Muzaffar, T. (2014). Spatial cognitive rehabilitation and motor recovery after stroke. *Curr Opin Neurol*, *27*(6), 653-658. https://doi.org/10.1097/wco.0000000000000148
Bartolomeo, P. (2021). Visual and motor neglect: Clinical and neurocognitive aspects. *Revue Neurologique*, *177*(6), 619-626. https://doi.org/https://doi.org/10.1016/j.neurol.2020.09.003
Bartolomeo, P., Bachoud-Lévi, A.-C., Azouvi, P., & Chokron, S. (2005). Time to imagine space: a chronometric exploration of representational neglect. *Neuropsychologia*, *43*(9), 1249-1257.

https://doi.org/https://doi.org/10.1016/j.neuropsychologia.2004.12.013
Bartolomeo, P., & Chokron, S. (2002a). Can we change our vantage point to explore imaginal neglect? *Behavioral and Brain Sciences*, *25*(2), 184-185. https://doi.org/10.1017/S0140525X02240042
Bartolomeo, P., & Chokron, S. (2002b). Orienting of attention in left unilateral neglect. *Neuroscience & Biobehavioral Reviews*, *26*(2), 217-234. https://doi.org/https://doi.org/10.1016/S0149-7634(01)00065-3
Basagni, B., De Tanti, A., Damora, A., Abbruzzese, L., Varalta, V., Antonucci, G., Bickerton, W. L., Smania, N., & Mancuso, M. (2017). The assessment of hemineglect syndrome with cancellation tasks: a comparison between the Bells test and the Apples test. *Neurological Sciences*, *38*, 2171-2176.
Bashiri, A., Ghazisaeedi, M., & Shahmoradi, L. (2017). The opportunities of virtual reality in the rehabilitation of children with attention deficit hyperactivity disorder: a literature review. *Korean J Pediatr*, *60*(11), 337-343. https://doi.org/10.3345/kjp.2017.60.11.337
Bastien, C., & Scapin, D. (1993). *Ergonomic criteria for the evaluation of human-computer interfaces* Inria].
Bauer, R. M., Iverson, G. L., Cernich, A. N., Binder, L. M., Ruff, R. M., & Naugle, R. I. (2012). Computerized neuropsychological assessment devices: joint position paper of the American Academy of Clinical Neuropsychology and the National Academy of Neuropsychology. *The Clinical Neuropsychologist*, *26*(2), 177-196.
Beauvisage, T. (2009). Computer usage in daily life. Proceedings of the SIGCHI conference on Human Factors in Computing Systems,
Becchio, C., Del Giudice, M., Dal Monte, O., Latini-Corazzini, L., & Pia, L. (2013). In your place: neuropsychological evidence for altercentric remapping in embodied perspective taking. *Soc Cogn Affect Neurosci*, *8*(2), 165-170. https://doi.org/10.1093/scan/nsr083
Behrmann, M., & Moscovitch, M. (1994). Object-centered neglect in patients with unilateral neglect: Effects of left-right coordinates of objects. *Journal of cognitive neuroscience*, *6*(1), 1-16.
Bell, I. H., Nicholas, J., Alvarez-Jimenez, M., Thompson, A., & Valmaggia, L. (2020). Virtual reality as a clinical tool in mental health research and practice *Dialogues Clin Neurosci*, *22*(2), 169-177. https://doi.org/10.31887/DCNS.2020.22.2/lvalmaggia
Bennett, T. L. (2001). Neuropsychological evaluation in rehabilitation planning and evaluation of functional skills. *Archives of Clinical Neuropsychology*, *16*(3), 237-253.
Berg, E. A. (1948). A simple objective technique for measuring flexibility in thinking. *The Journal of general psychology*, *39*(1), 15-22.
Bergeron, B. (2006). Developing Serious Games. Charles River Media. *Inc, Hingham, MA*.
Bernhardt, J., Langhorne, P., Lindley, R. I., Thrift, A. G., Ellery, F., Collier, J., Churilov, L., Moodie, M., Dewey, H., & Donnan, G. (2015). Efficacy and safety of very early mobilisation within 24 h of stroke

onset (AVERT): a randomised controlled trial. *Lancet*, *386*(9988), 46-55.
Bevilacqua, R., Maranesi, E., Riccardi, G. R., Di Donna, V., Pelliccioni, P., Luzi, R., Lattanzio, F., & Pelliccioni, G. (2019). Non-immersive virtual reality for rehabilitation of the older people: A systematic review into efficacy and effectiveness [Review]. *Journal of Clinical Medicine*, *8*(11). https://doi.org/10.3390/jcm8111882
Bickerton, W. L., Samson, D., Williamson, J., & Humphreys, G. W. (2011). Separating forms of neglect using the Apples Test: validation and functional prediction in chronic and acute stroke. *Neuropsychology*, *25*(5), 567.
Bigler, E. D. (1994). Neuroimaging and neuropsychological assessment. *Cognitive assessment: A multidisciplinary perspective*, 1-34.
Bigler, E. D. (2017). Structural neuroimaging in neuropsychology: History and contemporary applications. *Neuropsychology*, *31*(8), 934.
Bilder, R. M. (2011). Neuropsychology 3.0: Evidence-based science and practice. *Journal of the International Neuropsychological Society*, *17*(1), 7-13.
Bilder, R. M., & Reise, S. P. (2019). Neuropsychological tests of the future: How do we get there from here? *Clin Neuropsychol*, *33*(2), 220-245. https://doi.org/10.1080/13854046.2018.1521993
Biocca, F. (1992). Communication within virtual reality: Creating a space for research. *Journal of communication*, *42*, 5-5.
Bird, C. M., Papadopoulou, K., Ricciardelli, P., Rossor, M. N., & Cipolotti, L. (2003). Test-retest reliability, practice effects and reliable change indices for the recognition memory test. *British Journal of Clinical Psychology*, *42*(4), 407-425.
Bisiach, E., & Luzzatti, C. (1978). Unilateral neglect of representational space. *Cortex*, *14*(1), 129-133.
Bisiach, E., Pattini, P., Rusconi, M. L., Ricci, R., & Bernardini, B. (1997). Unilateral neglect and space constancy during passive locomotion. *Cortex*, *33*(2), 313-322.
Bisiach, E., Perani, D., Vallar, G., & Berti, A. (1986). Unilateral neglect: personal and extra-personal. *Neuropsychologia*, *24*(6), 759-767.
Bjoertomt, O., Cowey, A., & Walsh, V. (2002). Spatial neglect in near and far space investigated by repetitive transcranial magnetic stimulation. *Brain*, *125*(9), 2012-2022.
Bland, J. M., & Altman, D. (1986). Statistical methods for assessing agreement between two methods of clinical measurement. *The Lancet*, *327*(8476), 307-310.
Boehme, A. K., Esenwa, C., & Elkind, M. S. (2017). Stroke Risk Factors, Genetics, and Prevention. *Circ Res*, *120*(3), 472-495. https://doi.org/10.1161/circresaha.116.308398
Bogousslavsky, J., Van Melle, G., & Regli, F. (1988). The Lausanne Stroke Registry: analysis of 1,000 consecutive patients with first stroke. *Stroke*, *19*(9), 1083-1092.

Bohil, C. J., Alicea, B., & Biocca, F. A. (2011). Virtual reality in neuroscience research and therapy. *Nature Reviews Neuroscience*, *12*(12), 752-762. https://doi.org/10.1038/nrn3122

Boone, A. E., Wolf, T. J., & Engsberg, J. R. (2019). Combining virtual reality motor rehabilitation with cognitive strategy use in chronic stroke. *The American Journal of Occupational Therapy*, *73*(4), 7304345020p7304345021-7304345020p7304345029.

Borghesi, F., Mancuso, V., Pedroli, E., & Cipresso, P. (2022). From virtual reality to 360 videos: Upgrade or downgrade? The multidimensional healthcare VR technology. In *Handbook of research on implementing digital reality and interactive technologies to achieve society 5.0* (pp. 549-572). IGI Global.

Borgnis, F., Baglio, F., Pedroli, E., Rossetto, F., Isernia, S., Uccellatore, L., Riva, G., & Cipresso, P. (2021). EXecutive-functions innovative tool (EXIT 360°): A usability and user experience study of an original 360°-based assessment instrument. *Sensors*, *21*(17), 5867.

Borgnis, F., Baglio, F., Pedroli, E., Rossetto, F., Uccellatore, L., Oliveira, J. A. G., Riva, G., & Cipresso, P. (2022). Available Virtual Reality-Based Tools for Executive Functions: A Systematic Review [Systematic Review]. *Frontiers in Psychology*, *13*. https://doi.org/10.3389/fpsyg.2022.833136

Bourke, T. C., Lowrey, C. R., Dukelow, S. P., Bagg, S. D., Norman, K. E., & Scott, S. H. (2016). A robot-based behavioural task to quantify impairments in rapid motor decisions and actions after stroke. *Journal of neuroengineering and rehabilitation*, *13*(1), 91. https://doi.org/10.1186/s12984-016-0201-2

Bowen, McKenna, K., & Tallis, R. C. (1999). Reasons for variability in the reported rate of occurrence of unilateral spatial neglect after stroke. *Stroke*, *30*(6), 1196-1202. https://doi.org/10.1161/01.str.30.6.1196

Brade, J., Dudczig, M., & Klimant, P. (2018). Using virtual prototyping technologies to evaluate human-machine-interaction concepts. aw&I Conference,

Brainin, M., Tuomilehto, J., Heiss, W. D., Bornstein, N. M., Bath, P. M., Teuschl, Y., Richard, E., Guekht, A., Quinn, T., & Group, P. S. C. S. (2015). Post-stroke cognitive decline: an update and perspectives for clinical research. *European journal of neurology*, *22*(2), 229-e216.

Bravo, G., & Potvin, L. (1991). Estimating the reliability of continuous measures with Cronbach's alpha or the intraclass correlation coefficient: toward the integration of two traditions. *Journal of clinical epidemiology*, *44*(4-5), 381-390.

Broeks, J., Lankhorst, G., Rumping, K., & Prevo, A. (1999). The long-term outcome of arm function after stroke: results of a follow-up study. *Disability and Rehabilitation*, *21*(8), 357-364.

Broeren, J., Samuelsson, H., Stibrant-Sunnerhagen, K., Blomstrand, C., & Rydmark, M. (2007). Neglect assessment as an application of virtual reality. *Acta Neurologica Scandinavica*, *116*(3), 157-163. https://doi.org/https://doi.org/10.1111/j.1600-0404.2007.00821.x

Brooks, B. L., Strauss, E., Sherman, E., Iverson, G. L., & Slick, D. J. (2009). Developments in neuropsychological assessment: Refining psychometric and clinical interpretive methods. *Canadian Psychology/Psychologie Canadienne*, *50*(3), 196.

Brouwer, V. H. E. W., Stuit, S., Hoogerbrugge, A., Ten Brink, A. F., Gosselt, I. K., Van der Stigchel, S., & Nijboer, T. C. W. (2022). Applying machine learning to dissociate between stroke patients and healthy controls using eye movement features obtained from a virtual reality task. *Heliyon*, *8*(4), e09207. https://doi.org/https://doi.org/10.1016/j.heliyon.2022.e09207

Brown, T., Nauman Vogel, E., Adler, S., Bohon, C., Bullock, K., Nameth, K., Riva, G., Safer, D. L., & Runfola, C. D. (2020). Bringing Virtual Reality From Clinical Trials to Clinical Practice for the Treatment of Eating Disorders: An Example Using Virtual Reality Cue Exposure Therapy. *J Med Internet Res*, *22*(4), e16386. https://doi.org/10.2196/16386

Bukowski, H., & Samson, D. (2016). Can emotions influence level-1 visual perspective taking? *Cognitive neuroscience*, *7*(1-4), 182-191.

Burch, M., Blascheck, T., Kurzhals, K., Pflüger, H., Raschke, M., Weiskopf, D., & Pfeiffer, T. (2015). Eye Tracking Visualization. Eurographics (Tutorials),

Burgess, P. W., Alderman, N., Forbes, C., Costello, A., LAURE, M. C., Dawson, D. R., Anderson, N. D., Gilbert, S. J., Dumontheil, I., & Channon, S. (2006). The case for the development and use of "ecologically valid" measures of executive function in experimental and clinical neuropsychology. *Journal of the International Neuropsychological Society*, *12*(2), 194-209.

Burke, J. W., McNeill, M., Charles, D. K., Morrow, P. J., Crosbie, J. H., & McDonough, S. M. (2009). Optimising engagement for stroke rehabilitation using serious games. *The Visual Computer*, *25*(12), 1085-1099.

Burton, Q., Lejeune, T., Dehem, S., Lebrun, N., Ajana, K., Edwards, M. G., & Everard, G. (2022). Performing a shortened version of the Action Research Arm Test in immersive virtual reality to assess post-stroke upper limb activity. *Journal of neuroengineering and rehabilitation*, *19*(1), 1-12.

Butkiewicz, T., & Stevens, A. H. (2020). Evaluation of the effects of field-of-view in augmented reality for marine navigation. Optical Architectures for Displays and Sensing in Augmented, Virtual, and Mixed Reality (AR, VR, MR),

Butler, B. C., Eskes, G. A., & Vandorpe, R. A. (2004). Gradients of detection in neglect: comparison of peripersonal and extrapersonal space. *Neuropsychologia*, *42*(3), 346-358. https://doi.org/https://doi.org/10.1016/j.neuropsychologia.2003.08.008

Buttussi, F., & Chittaro, L. (2017). Effects of different types of virtual reality display on presence and learning in a safety training scenario.

IEEE transactions on visualization and computer graphics, *24*(2), 1063-1076.
Buxbaum, Ferraro, M., Veramonti, T., Farne, A., Whyte, J., Ladavas, E., Frassinetti, F., & Coslett, H. (2004). Hemispatial neglect: Subtypes, neuroanatomy, and disability. *Neurology*, *62*(5), 749-756.
Caggiano, P., Beschin, N., & Cocchini, G. (2014). Personal neglect following unilateral right and left brain damage. *Procedia-Social and Behavioral Sciences*, *140*, 164-167.
Calamia, M., Markon, K., & Tranel, D. (2013). The robust reliability of neuropsychological measures: Meta-analyses of test–retest correlations. *The Clinical Neuropsychologist*, *27*(7), 1077-1105.
Calvanio, R., Petrone, P. N., & Levine, D. N. (1987). Left visual spatial neglect is both environment-centered and body-centered. *Neurology*, *37*(7), 1179-1179.
Camara, W. J., Nathan, J. S., & Puente, A. E. (2000). Psychological test usage: Implications in professional psychology. *Professional Psychology: Research and Practice, 31*(2), 141.
Campbell, Z., Zakzanis, K. K., Jovanovski, D., Joordens, S., Mraz, R., & Graham, S. J. (2009). Utilizing virtual reality to improve the ecological validity of clinical neuropsychology: an FMRI case study elucidating the neural basis of planning by comparing the Tower of London with a three-dimensional navigation task. *Applied neuropsychology*, *16*(4), 295-306.
Canini, M., Battista, P., Della Rosa, P. A., Catricalà, E., Salvatore, C., Gilardi, M. C., & Castiglioni, I. (2014). Computerized neuropsychological assessment in aging: testing efficacy and clinical ecology of different interfaces. *Computational and mathematical methods in medicine, 2014*.
Cao, X., Li, J. J., & Balakrishnan, R. (2008). Peephole pointing: modeling acquisition of dynamically revealed targets. Proceedings of the SIGCHI conference on human factors in computing systems,
Capitani, E. (1997). Normative data and neuropsychological assessment. Common problems in clinical practice and research. *Neuropsychological Rehabilitation*, *7*(4), 295-310.
Carlo, G., Allen, J. B., & Buhman, D. C. (1999). Facilitating and disinhibiting prosocial behaviors: The nonlinear interaction of trait perspective taking and trait personal distress on volunteering. *Basic and Applied Social Psychology*, *21*(3), 189-197.
Casaletto, K. B., & Heaton, R. K. (2017). Neuropsychological assessment: Past and future. *Journal of the International Neuropsychological Society*, *23*(9-10), 778-790.
Castiello, U. (1996). Grasping a fruit: selection for action. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(3), 582.
Cavallo, A., Ansuini, C., Capozzi, F., Tversky, B., & Becchio, C. (2017). When Far Becomes Near:Perspective Taking Induces Social Remapping of Spatial Relations. *Psychological science*, *28*(1), 69-79. https://doi.org/10.1177/0956797616672464

Cavedoni, S., Chirico, A., Pedroli, E., Cipresso, P., & Riva, G. (2020). Digital biomarkers for the early detection of mild cognitive impairment: artificial intelligence meets virtual reality. *Frontiers in Human Neuroscience*, *14*, 245.
Cavedoni, S., Cipresso, P., Mancuso, V., Bruni, F., & Pedroli, E. (2022). Virtual reality for the assessment and rehabilitation of neglect: where are we now? A 6-year review update. *Virtual Reality*, *26*(4), 1663-1704.
Čengić, L., Vuletić, V., Karlić, M., Dikanović, M., & Demarin, V. (2011). Motor and cognitive impairment after stroke. *Acta Clinica Croatica*, *50*(4), 463-467.
Cerrato, A., & Ponticorvo, M. (2017). Enhancing neuropsychological testing with gamification and tangible interfaces: The baking tray task. Biomedical Applications Based on Natural and Artificial Computing: International Work-Conference on the Interplay Between Natural and Artificial Computation, IWINAC 2017, Corunna, Spain, June 19-23, 2017, Proceedings, Part II,
Chan, D. Y., Chan, C. C., & Au, D. K. (2006). Motor relearning programme for stroke patients: a randomized controlled trial. *Clin Rehabil*, *20*(3), 191-200. https://doi.org/10.1191/0269215506cr930oa
Chang, S. W., & Abrams, R. A. (2004). Hand movements deviate toward distracters in the absence of response competition. *Journal of General Psychology*, *131*(4), 328-344.
Chang, T. P., Sherman, J. M., & Gerard, J. M. (2019). Overview of serious gaming and virtual reality. *Healthcare simulation research: a practical guide*, 29-38.
Charter, R. A. (1996). Revisiting the standard errors of measurement, estimate, and prediction and their application to test scores. *Perceptual and Motor Skills*, *82*(3_suppl), 1139-1144.
Chatterjee, A., Thompson, K. A., & Ricci, R. (1999). Quantitative analysis of cancellation tasks in neglect. *Cortex*, *35*(2), 253-262.
Chaytor, N., & Schmitter-Edgecombe, M. (2003). The ecological validity of neuropsychological tests: A review of the literature on everyday cognitive skills. *Neuropsychology Review*, *13*, 181-197.
Chaytor, N., & Schmitter-Edgecombe, M. (2004). The Ecological Validity of Neuropsychological Tests: A Review of the Literature on Everyday Cognitive Skills. *Neuropsychology Review*, *13*, 181-197. https://doi.org/10.1023/B:NERV.0000009483.91468.fb
Chechlacz, M., Humphreys, G., & Cazzoli, D. (2016). Spatial and non-spatial aspects of visual attention: Interactive cognitive mechanisms and neural underpinnings. *Neuropsychologia*, *92*.
Checketts, M., Mancuso, M., Fordell, H., Chen, P., Hreha, K., Eskes, G. A., Vuilleumier, P., Vail, A., & Bowen, A. (2021). Current clinical practice in the screening and diagnosis of spatial neglect post-stroke: Findings from a multidisciplinary international survey. *Neuropsychological rehabilitation*, *31*(9), 1495-1526.

Chen, C., Leys, D., & Esquenazi, A. (2013). The interaction between neuropsychological and motor deficits in patients after stroke. *Neurology*, *80*(3 Supplement 2), S27-S34.
Chen, P., Chen, C. C., Hreha, K., Goedert, K. M., & Barrett, A. M. (2015). Kessler Foundation Neglect Assessment Process Uniquely Measures Spatial Neglect During Activities of Daily Living. *Archives of Physical Medicine and Rehabilitation*, *96*(5), 869-876.e861. https://doi.org/https://doi.org/10.1016/j.apmr.2014.10.023
Chokron, S. (2003). Right parietal lesions, unilateral spatial neglect, and the egocentric frame of reference. *NeuroImage*, *20*, S75-S81. https://doi.org/https://doi.org/10.1016/j.neuroimage.2003.09.002
Chu, K. (1999). An introduction to sensitivity, specificity, predictive values and likelihood ratios. *Emergency Medicine*, *11*(3), 175-181.
Chun, M. M. (2000). Contextual cueing of visual attention. *Trends in Cognitive Sciences*, *4*(5), 170-178.
Chun, M. M., & Jiang, Y. (1998). Contextual cueing: Implicit learning and memory of visual context guides spatial attention. *Cognitive psychology*, *36*(1), 28-71.
Clay, V., König, P., & König, S. (2019). Eye Tracking in Virtual Reality. *J Eye Mov Res*, *12*(1). https://doi.org/10.16910/jemr.12.1.3
Coelho, C., Tichon, J., Hine, T. J., Wallis, G., & Riva, G. (2006). Media presence and inner presence: the sense of presence in virtual reality technologies. *From communication to presence: Cognition, emotions and culture towards the ultimate communicative experience*, *11*, 25-45.
Cohen, J. (1973). Eta-squared and partial eta-squared in fixed factor ANOVA designs. *Educational and psychological measurement*, *33*(1), 107-112.
Cole, G. G., Atkinson, M., Le, A. T., & Smith, D. T. (2016). Do humans spontaneously take the perspective of others? *Acta psychologica*, *164*, 165-168.
Cole, G. G., & Millett, A. C. (2019). The closing of the theory of mind: A critique of perspective-taking. *Psychonomic bulletin & review*, *26*(6), 1787-1802. https://doi.org/10.3758/s13423-019-01657-y
Collie, A., Darby, D., & Maruff, P. (2001). Computerised cognitive assessment of athletes with sports related head injury. *British journal of sports medicine*, *35*(5), 297-302.
Collie, A., & Maruff, P. (2003). Computerised neuropsychological testing. *British journal of sports medicine*, *37*(1), 2-2.
Corbetta, & Shulman. (2011). Spatial neglect and attention networks. *Annual review of neuroscience*, *34*, 569-599.
Corbetta, M., Kincade, M. J., Lewis, C., Snyder, A. Z., & Sapir, A. (2005). Neural basis and recovery of spatial attention deficits in spatial neglect. *Nature neuroscience*, *8*(11), 1603-1610.
Costa, L. (1983). Clinical neuropsychology: A discipline in evolution. *Journal of Clinical Neuropsychology*, *5*(1), 1-11. https://doi.org/10.1080/01688638308401147

Coulthard, E., Rudd, A., & Husain, M. (2008). Motor neglect associated with loss of action inhibition. *Journal of Neurology, Neurosurgery & Psychiatry*, *79*(12), 1401-1404. https://doi.org/10.1136/jnnp.2007.140715

Coupland, A. P., Thapar, A., Qureshi, M. I., Jenkins, H., & Davies, A. H. (2017). The definition of stroke. *Journal of the Royal Society of Medicine*, *110*(1), 9-12.

Coxon, J. P., Stinear, C. M., & Byblow, W. D. (2007). Selective inhibition of movement. *J Neurophysiol*, *97*(3), 2480-2489. https://doi.org/10.1152/jn.01284.2006

Crawford, J. R., Garthwaite, P. H., & Gault, C. B. (2007). Estimating the percentage of the population with abnormally low scores (or abnormally large score differences) on standardized neuropsychological test batteries: a generic method with applications. *Neuropsychology*, *21*(4), 419.

Cullen, B., O'Neill, B., Evans, J. J., Coen, R. F., & Lawlor, B. A. (2007). A review of screening tests for cognitive impairment. *J Neurol Neurosurg Psychiatry*, *78*(8), 790-799. https://doi.org/10.1136/jnnp.2006.095414

Cumming, T. B., Marshall, R. S., & Lazar, R. M. (2013). Stroke, cognitive deficits, and rehabilitation: still an incomplete picture. *International Journal of Stroke*, *8*(1), 38-45.

D'Imperio, D., Romeo, Z., Maistrello, L., Durgoni, E., Della Pietà, C., De Filippo De Grazia, M., Meneghello, F., Turolla, A., & Zorzi, M. (2021). Sensorimotor, Attentional, and Neuroanatomical Predictors of Upper Limb Motor Deficits and Rehabilitation Outcome after Stroke. *Neural Plast*, *2021*, 8845685. https://doi.org/10.1155/2021/8845685

Dale, C. L., Simpson, G. V., Foxe, J. J., Luks, T. L., & Worden, M. S. (2008). ERP correlates of anticipatory attention: spatial and non-spatial specificity and relation to subsequent selective attention. *Experimental Brain Research*, *188*(1), 45-62. https://doi.org/10.1007/s00221-008-1338-4

Damasio, A. R. (1992). Aphasia. *New England Journal of Medicine*, *326*(8), 531-539.

Danovska, M., & Peychinska, D. (2012). Post-stroke cognitive impairment–phenomenology and prognostic factors. *Journal of IMAB–Annual Proceeding Scientific Papers*, *18*(3), 290-297.

Daugherty, J. C., Puente, A. E., Fasfous, A. F., Hidalgo-Ruzzante, N., & Pérez-Garcia, M. (2017). Diagnostic mistakes of culturally diverse individuals when using North American neuropsychological tests. *Applied Neuropsychology: Adult*, *24*(1), 16-22.

De Zubicaray, G. (2006). Neuroimaging and Clinical Neuropsychological Practice.

Dehem, S., Gilliaux, M., Stoquart, G., Detrembleur, C., Jacquemin, G., Palumbo, S., Frederick, A., & Lejeune, T. (2019). Effectiveness of upper-limb robotic-assisted therapy in the early rehabilitation phase after stroke: a single-blind, randomised, controlled trial. *Annals of Physical and Rehabilitation Medicine*, *62*(5), 313-320.

Della Sala, S., Logie, R. H., Beschin, N., & Denis, M. (2004). Preserved visuo-spatial transformations in representational neglect. *Neuropsychologia*, *42*(10), 1358-1364.

Demeyere, N., & Gillebert, C. R. (2019). Ego-and allocentric visuospatial neglect: Dissociations, prevalence, and laterality in acute stroke. *Neuropsychology*, *33*(4), 490.

Demeyere, N., Haupt, M., Webb, S. S., Strobel, L., Milosevich, E. T., Moore, M. J., Wright, H., Finke, K., & Duta, M. D. (2021). Introducing the tablet-based Oxford Cognitive Screen-Plus (OCS-Plus) as an assessment tool for subtle cognitive impairments. *Scientific reports*, *11*(1), 8000. https://doi.org/10.1038/s41598-021-87287-8

Demeyere, N., Riddoch, M. J., Slavkova, E. D., Bickerton, W.-L., & Humphreys, G. W. (2015). The Oxford Cognitive Screen (OCS): validation of a stroke-specific short cognitive screening tool. *Psychological assessment*, *27*(3), 883.

Demeyere, N., Riddoch, M. J., Slavkova, E. D., Jones, K., Reckless, I., Mathieson, P., & Humphreys, G. W. (2016). Domain-specific versus generalized cognitive screening in acute stroke. *Journal of Neurology*, *263*(2), 306-315. https://doi.org/10.1007/s00415-015-7964-4

Demeyere, N., Sun, S., Milosevich, E., & Vancleef, K. (2019). Post-stroke cognition with the Oxford Cognitive Screen vs Montreal Cognitive Assessment: a multi-site randomized controlled study (OCS-CARE). *AMRC Open Research*, *1*, 12.

DeVore, B., Campbell, R., Kelly, P., & Harrison, D. (2017). Left Gaze Bias with Left Sensory Hemineglect Syndrome: Hallucinations and Hemispatial Neglect Following Right Middle Cerebral Artery Cerebrovascular Accident. *BAOJ Neurology*, *3*, 1-7.

Diamond, A. (2013). Executive functions. *Annual review of psychology*, *64*, 135-168.

Diaz-Orueta, U., Blanco-Campal, A., Lamar, M., Libon, D. J., & Burke, T. (2020). Marrying past and present neuropsychology: Is the future of the process-based approach technology-based? *Frontiers in Psychology*, *11*, 361.

Dikmen, S. S., Heaton, R. K., Grant, I., & Temkin, N. R. (1999). Test–retest reliability and practice effects of expanded Halstead–Reitan Neuropsychological Test Battery. *Journal of the International Neuropsychological Society*, *5*(4), 346-356.

Dionisio, J. D. N., III, W. G. B., & Gilbert, R. (2013). 3D virtual worlds and the metaverse: Current status and future possibilities. *ACM Computing Surveys (CSUR)*, *45*(3), 1-38.

Doğan, N. Ö. (2018). Bland-Altman analysis: A paradigm to understand correlation and agreement. *Turkish Journal of Emergency Medicine*, *18*(4), 139-141. https://doi.org/https://doi.org/10.1016/j.tjem.2018.09.001

Donders, J. (2020). The incremental value of neuropsychological assessment: A critical review. *The Clinical Neuropsychologist*, *34*(1), 56-87. https://doi.org/10.1080/13854046.2019.1575471
Dontje, M. L., Dall, P. M., Skelton, D. A., Gill, J. M. R., & Chastin, S. F. M. (2018). Reliability, minimal detectable change and responsiveness to change: Indicators to select the best method to measure sedentary behaviour in older adults in different study designs. *PLoS ONE*, *13*(4), e0195424. https://doi.org/10.1371/journal.pone.0195424
Dora, K., Suga, T., Tomoo, K., Sugimoto, T., Mok, E., Tsukamoto, H., Takada, S., Hashimoto, T., & Isaka, T. (2021). Similar improvements in cognitive inhibitory control following low-intensity resistance exercise with slow movement and tonic force generation and high-intensity resistance exercise in healthy young adults: a preliminary study. *The Journal of Physiological Sciences*, *71*(1), 22. https://doi.org/10.1186/s12576-021-00806-0
Douiri, Rudd, & Wolfe. (2013). Prevalence of poststroke cognitive impairment: South London Stroke Register 1995-2010. *Stroke*, *44*(1), 138-145. https://doi.org/10.1161/strokeaha.112.670844
Doumas, I., Everard, G., Dehem, S., & Lejeune, T. (2021a). Serious games for upper limb rehabilitation after stroke: a meta-analysis. *Journal of neuroengineering and rehabilitation*, *18*, 1-16.
Doumas, I., Everard, G., Dehem, S., & Lejeune, T. (2021b). Serious games for upper limb rehabilitation after stroke: a meta-analysis. *Journal of neuroengineering and rehabilitation*, *18*(1), 1-16.
Driver, J. (2001). A selective review of selective attention research from the past century. *British journal of psychology*, *92*(1), 53-78.
Driver, J., & Pouget, A. (2000). Object-centered visual neglect, or relative egocentric neglect? *Journal of cognitive neuroscience*, *12*(3), 542.
Dubbels, B. (2013). Gamification, serious games, ludic simulation, and other contentious categories. *International Journal of Gaming and Computer-Mediated Simulations (IJGCMS)*, *5*(2), 1-19.
Duchowski, A. T., Shivashankaraiah, V., Rawls, T., Gramopadhye, A. K., Melloy, B. J., & Kanki, B. (2000). *Binocular eye tracking in virtual reality for inspection training* Proceedings of the 2000 symposium on Eye tracking research & applications, Palm Beach Gardens, Florida, USA. https://doi.org/10.1145/355017.355031
Duncan, J. (1985). Visual search and visual attention. *Attention and performance XI*, *85*, 105.
Duncan, J., Bundesen, C., Olson, A., Humphreys, G., Chavda, S., & Shibuya, H. (1999). Systematic analysis of deficits in visual attention. *Journal of Experimental Psychology: General*, *128*(4), 450.
Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review*, *96*(3), 433.
Duncan, P. W. (1994). Stroke Disability. *Physical Therapy*, *74*(5), 399-407. https://doi.org/10.1093/ptj/74.5.399

Duncan, P. W., Propst, M., & Nelson, S. G. (1983). Reliability of the Fugl-Meyer assessment of sensorimotor recovery following cerebrovascular accident. *Physical Therapy*, *63*(10), 1606-1610.

Dutta, D., Sen, S., Aruchamy, S., & Mandal, S. (2022). Prevalence of post-stroke upper extremity paresis in developing countries and significance of m-Health for rehabilitation after stroke - A review. *Smart Health*, *23*, 100264. https://doi.org/https://doi.org/10.1016/j.smhl.2022.100264

Edwards, M., & Humphreys, G. (1999). Pointing and grasping in unilateral visual neglect: effectof on-line visual feedback in grasping. *Neuropsychologia*, *37*(8), 959-973.

Einstad, M. S., Saltvedt, I., Lydersen, S., Ursin, M. H., Munthe-Kaas, R., Ihle-Hansen, H., Knapskog, A.-B., Askim, T., Beyer, M. K., & Næss, H. (2021). Associations between post-stroke motor and cognitive function: a cross-sectional study. *BMC geriatrics*, *21*(1), 1-10.

Eisapour, M., Cao, S., & Boger, J. (2020). Participatory design and evaluation of virtual reality games to promote engagement in physical activity for people living with dementia. *Journal of rehabilitation and assistive technologies engineering*, *7*, 2055668320913770.

Eling, P. (2019). History of neuropsychological assessment. *A history of neuropsychology*, *44*, 164-178.

Elkind, M. S., & Sacco, R. L. (1998). Stroke risk factors and stroke prevention. Seminars in Neurology,

Erez, A. B.-H., Katz, N., Ring, H., & Soroker, N. (2009). Assessment of spatial neglect using computerised feature and conjunction visual search tasks. *Neuropsychological rehabilitation*, *19*(5), 677-695.

Esposito, E., Shekhtman, G., & Chen, P. (2021). Prevalence of spatial neglect post-stroke: A systematic review. *Annals of Physical and Rehabilitation Medicine*, *64*(5), 101459. https://doi.org/https://doi.org/10.1016/j.rehab.2020.10.010

Evald, L., Wilms, I., & Nordfang, M. (2021). Assessment of spatial neglect in clinical practice: A nationwide survey. *Neuropsychological rehabilitation*, *31*(9), 1374-1389.

Evans, J. J., Greenfield, E., Wilson, B. A., & Bateman, A. (2009). Walking and talking therapy: Improving cognitive–motor dual-tasking in neurological illness. *Journal of the international Neuropsychological society*, *15*(1), 112-120.

Everard, G., Otmane-Tolba, Y., Rosselli, Z., Pellissier, T., Ajana, K., Dehem, S., Auvinet, E., Edwards, M. G., Lebleu, J., & Lejeune, T. (2022). Concurrent validity of an immersive virtual reality version of the Box and Block Test to assess manual dexterity among patients with stroke. *Journal of neuroengineering and rehabilitation*, *19*(1), 1-11.

Everard, G. J., Ajana, K., Dehem, S. B., Stoquart, G. G., Edwards, M. G., & Lejeune, T. M. (2020). Is cognition considered in post-stroke upper limb robot-assisted therapy trials? A brief systematic review.

International Journal of Rehabilitation Research, *43*(3). https://journals.lww.com/intjrehabilres/Fulltext/2020/09000/Is_cognition_considered_in_post_stroke_upper_limb.2.aspx

Farah, M. J., Brunn, J. L., Wong, A. B., Wallace, M. A., & Carpenter, P. A. (1990). Frames of reference for allocating attention to space: Evidence from the neglect syndrome. *Neuropsychologia*, *28*(4), 335-347.

Faria, A. L., Cameirão, M. S., Couras, J. F., Aguiar, J. R., Costa, G. M., & Bermúdez i Badia, S. (2018). Combined cognitive-motor rehabilitation in virtual reality improves motor outcomes in chronic stroke–a pilot study. *Frontiers in psychology*, *9*, 854.

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G* Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior research methods*, *39*(2), 175-191.

Feigin, V. L., Stark, B. A., Johnson, C. O., Roth, G. A., Bisignano, C., Abady, G. G., Abbasifard, M., Abbasi-Kangevari, M., Abd-Allah, F., Abedi, V., Abualhasan, A., Abu-Rmeileh, N. M. E., Abushouk, A. I., Adebayo, O. M., Agarwal, G., Agasthi, P., Ahinkorah, B. O., Ahmad, S., Ahmadi, S., Ahmed Salih, Y., Aji, B., Akbarpour, S., Akinyemi, R. O., Al Hamad, H., Alahdab, F., Alif, S. M., Alipour, V., Aljunid, S. M., Almustanyir, S., Al-Raddadi, R. M., Al-Shahi Salman, R., Alvis-Guzman, N., Ancuceanu, R., Anderlini, D., Anderson, J. A., Ansar, A., Antonazzo, I. C., Arabloo, J., Ärnlöv, J., Artanti, K. D., Aryan, Z., Asgari, S., Ashraf, T., Athar, M., Atreya, A., Ausloos, M., Baig, A. A., Baltatu, O. C., Banach, M., Barboza, M. A., Barker-Collo, S. L., Bärnighausen, T. W., Barone, M. T. U., Basu, S., Bazmandegan, G., Beghi, E., Beheshti, M., Béjot, Y., Bell, A. W., Bennett, D. A., Bensenor, I. M., Bezabhe, W. M., Bezabih, Y. M., Bhagavathula, A. S., Bhardwaj, P., Bhattacharyya, K., Bijani, A., Bikbov, B., Birhanu, M. M., Boloor, A., Bonny, A., Brauer, M., Brenner, H., Bryazka, D., Butt, Z. A., Caetano dos Santos, F. L., Campos-Nonato, I. R., Cantu-Brito, C., Carrero, J. J., Castañeda-Orjuela, C. A., Catapano, A. L., Chakraborty, P. A., Charan, J., Choudhari, S. G., Chowdhury, E. K., Chu, D.-T., Chung, S.-C., Colozza, D., Costa, V. M., Costanzo, S., Criqui, M. H., Dadras, O., Dagnew, B., Dai, X., Dalal, K., Damasceno, A. A. M., D'Amico, E., Dandona, L., Dandona, R., Darega Gela, J., Davletov, K., De la Cruz-Góngora, V., Desai, R., Dhamnetiya, D., Dharmaratne, S. D., Dhimal, M. L., Dhimal, M., Diaz, D., Dichgans, M., Dokova, K., Doshi, R., Douiri, A., Duncan, B. B., Eftekharzadeh, S., Ekholuenetale, M., El Nahas, N., Elgendy, I. Y., Elhadi, M., El-Jaafary, S. I., Endres, M., Endries, A. Y., Erku, D. A., Faraon, E. J. A., Farooque, U., Farzadfar, F., Feroze, A. H., Filip, I., Fischer, F., Flood, D., Gad, M. M., Gaidhane, S., Ghanei Gheshlagh, R., Ghashghaee, A., Ghith, N., Ghozali, G., Ghozy, S., Gialluisi, A., Giampaoli, S., Gilani, S. A., Gill, P. S., Gnedovskaya, E. V., Golechha, M., Goulart, A. C., Guo, Y., Gupta, R., Gupta, V. B., Gupta, V. K., Gyanwali, P., Hafezi-Nejad, N., Hamidi, S., Hanif, A., Hankey, G. J., Hargono, A., Hashi, A., Hassan, T. S., Hassen, H. Y., Havmoeller, R. J., Hay, S. I., Hayat, K., Hegazy, M. I., Herteliu, C., Holla, R., Hostiuc, S., Househ, M., Huang, J., Humayun, A., Hwang, B.-F., Iacoviello, L., Iavicoli, I., Ibitoye, S. E., Ilesanmi, O. S., Ilic, I. M., Ilic, M. D., Iqbal, U., Irvani, S. S. N., Islam, S. M. S., Ismail, N. E., Iso, H., Isola, G., Iwagami, M., Jacob, L., Jain, V., Jang, S.-I., Jayapal, S. K., Jayaram, S., Jayawardena, R., Jeemon, P., Jha, R. P., Johnson, W. D., Jonas, J. B., Joseph, N., Jozwiak, J. J., Jürisson, M., Kalani, R., Kalhor, R., Kalkonde, Y., Kamath, A., Kamiab, Z., Kanchan, T., Kandel, H., Karch, A., Katoto, P. D. M. C., Kayode, G. A., Keshavarz, P., Khader, Y. S., Khan, E. A., Khan, I. A., Khan, M., Khan, M. A. B., Khatib, M. N., Khubchandani, J., Kim, G. R., Kim, M. S., Kim, Y. J., Kisa, A., Kisa, S., Kivimäki, M., Kolte, D., Koolivand, A., Koulmane Laxminarayana, S. L., Koyanagi, A., Krishan, K., Krishnamoorthy, V., Krishnamurthi, R. V., Kumar, G. A., Kusuma, D., La Vecchia, C., Lacey, B., Lak, H. M., Lallukka, T., Lasrado, S., Lavados, P. M., Leonardi, M., Li, B., Li, S., Lin, H., Lin, R.-T., Liu, X., Lo, W. D., Lorkowski, S., Lucchetti, G., Lutzky Saute, R., Magdy Abd El Razek, H., Magnani, F. G., Mahajan, P. B., Majeed, A., Makki, A., Malekzadeh, R., Malik, A. A., Manafi, N., Mansournia, M. A., Mantovani, L. G., Martini, S., Mazzaglia, G., Mehndiratta, M. M., Menezes, R. G., Meretoja, A., Mersha, A. G., Miao Jonasson, J., Miazgowski, B., Miazgowski, T., Michalek, I. M., Mirrakhimov, E. M., Mohammad, Y., Mohammadian-Hafshejani, A., Mohammed, S., Mokdad, A. H., Mokhayeri, Y., Molokhia, M., Moni, M. A., Montasir, A. A., Moradzadeh, R., Morawska, L., Morze, J., Muruet, W., Musa, K. I., Nagarajan, A. J., Naghavi, M., Narasimha Swamy, S., Nascimento, B. R., Negoi, R. I., Neupane Kandel, S., Nguyen, T. H., Norrving, B., Noubiap, J. J., Nwatah, V. E., Oancea, B., Odukoya, O. O., Olagunju, A. T., Orru, H., Owolabi, M. O., Padubidri, J. R., Pana, A., Parekh, T., Park, E.-C., Pashazadeh Kan, F., Pathak, M., Peres, M. F. P., Perianayagam, A., Pham, T.-M., Piradov, M. A., Podder, V., Polinder, S., Postma, M. J., Pourshams, A., Radfar, A., Rafiei, A., Raggi, A., Rahim, F., Rahimi-Movaghar, V., Rahman, M., Rahman, M. A., Rahmani, A. M., Rajai, N., Ranasinghe, P., Rao, C. R., Rao, S. J., Rathi, P., Rawaf, D. L., Rawaf, S., Reitsma, M. B., Renjith, V., Renzaho, A. M. N., Rezapour, A., Rodriguez, J. A. B., Roever, L., Romoli, M., Rynkiewicz, A., Sacco, S., Sadeghi, M., Saeedi Moghaddam, S., Sahebkar, A., Saif-Ur-Rahman, K. M., Salah, R., Samaei, M., Samy, A. M., Santos, I. S., Santric-Milicevic, M. M., Sarrafzadegan, N., Sathian, B., Sattin, D., Schiavolin, S., Schlaich, M. P., Schmidt, M. I., Schutte, A. E., Sepanlou, S. G., Seylani, A., Sha, F., Shahabi, S., Shaikh, M. A., Shannawaz, M., Shawon, M. S. R., Sheikh, A., Sheikhbahaei, S., Shibuya, K., Siabani, S., Silva, D. A. S., Singh, J. A., Singh, J. K., Skryabin, V. Y., Skryabina, A. A., Sobaih, B. H., Stortecky, S., Stranges, S., Tadesse, E. G., Tarigan, I. U., Temsah, M.-H., Teuschl, Y., Thrift, A. G., Tonelli, M., Tovani-Palone, M. R., Tran, B. X., Tripathi, M., Tsegaye, G. W., Ullah, A., Unim, B., Unnikrishnan, B., Vakilian, A., Valadan Tahbaz, S., Vasankari, T. J., Venketasubramanian, N., Vervoort, D., Vo, B., Volovici, V., Vosoughi, K., Vu, G. T., Vu, L. G., Wafa, H. A., Waheed, Y., Wang, Y., Wijeratne, T., Winkler, A. S., Wolfe, C. D. A., Woodward, M., Wu, J. H., Wulf Hanson, S., Xu, X., Yadav, L., Yadollahpour, A., Yahyazadeh Jabbari, S. H., Yamagishi, K., Yatsuya, H., Yonemoto, N., Yu, C., Yunusa, I., Zaman, M. S., Zaman, S. B., Zamanian, M., Zand, R., Zandifar, A., Zastrozhin, M. S., Zastrozhina, A., Zhang, Y., Zhang, Z.-J., Zhong, C., Zuniga, Y. M. H., & Murray, C. J. L. (2021). Global, regional, and national burden of stroke and its risk factors, 1990–2019: a systematic analysis for the Global Burden of Disease Study 2019. *The Lancet Neurology*, *20*(10), 795-820. https://doi.org/https://doi.org/10.1016/S1474-4422(21)00252-0

Feng, Z., González, V. A., Amor, R., Lovreglio, R., & Cabrera-Guerrero, G. (2018). Immersive virtual reality serious games for evacuation training and research: A systematic literature review. *Computers & Education*, *127*, 252-266. https://doi.org/https://doi.org/10.1016/j.compedu.2018.09.002

Fernández, A. L., & Evans, J. (2022). *Understanding cross-cultural neuropsychology: Science, testing, and challenges*. Routledge.

Fernandez Montenegro, J. M., & Argyriou, V. (2017). Cognitive evaluation for the diagnosis of Alzheimer's disease based on Turing Test and Virtual Environments. *Physiology & Behavior*, *173*, 42-51. https://doi.org/https://doi.org/10.1016/j.physbeh.2017.01.034

Fichman, H. C., Uehara, E., & dos Santos, C. F. (2014). New technologies in assessment and neuropsychological rehabilitation. *Temas em Psicologia*, *22*(3), 539-553.

Fischer, M. H., & Adam, J. J. (2001). Distractor effects on pointing: The role of spatial layout. *Experimental Brain Research*, *136*(4), 507-513.

Fisk, J., & Goodale, M. (1985). The organization of eye and limb movements during unrestricted reaching to targets in contralateral and ipsilateral visual space. *Experimental brain research*, *60*(1), 159-178.

Fordell, H., Bodin, K., Bucht, G., & Malm, J. (2011). A virtual reality test battery for assessment and screening of spatial neglect [Article]. *Acta Neurologica Scandinavica*, *123*(3), 167-174. https://doi.org/10.1111/j.1600-0404.2010.01390.x

Franzen, M. D. (2013). *Reliability and validity in neuropsychological assessment*. Springer Science & Business Media.

Franzen, M. D., & Wilhelm, K. L. (1996). Conceptual foundations of ecological validity in neuropsychological assessment.

Fregni, F., & Pascual-Leone, A. (2006). Hand motor recovery after stroke: tuning the orchestra to improve hand motor function. *Cognitive and Behavioral Neurology*, *19*(1), 21-33.

Freundlieb, M., Sebanz, N., & Kovács, Á. M. (2017). Out of your sight, out of my mind: Knowledge about another person's visual access modulates spontaneous visuospatial perspective-taking. *Journal of Experimental Psychology: Human Perception and Performance*, *43*(6), 1065.

Friedman, P. J. (1990). Spatial neglect in acute stroke: the line bisection test. *Journal of Rehabilitation Medicine*, *22*(2), 101-106.

Friedman, P. J. (1991). Clock drawing in acute stroke. *Age Ageing*, *20*(2), 140-145. https://doi.org/10.1093/ageing/20.2.140

Frith, U., & Frith, C. (2010). The social brain: allowing humans to boldly go where no other species has been. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *365*(1537), 165-176.

Fugl-Meyer, A. R., Jääskö, L., Leyman, I., Olsson, S., & Steglind, S. (1975). A method for evaluation of physical performance. *Scand J Rehabil Med*, *7*(1), 13-31.

Furlanetto, T., Cavallo, A., Manera, V., Tversky, B., & Becchio, C. (2013). Through your eyes: incongruence of gaze and action increases spontaneous perspective taking. *Frontiers in Human Neuroscience*, *7*, 455.

Gandhi, R. D., & Patel, D. S. (2018). Virtual reality–opportunities and challenges. *Virtual Reality*, *5*(01), 2714-2724.

Garre-Olmo, J., Faúndez-Zanuy, M., López-de-Ipiña, K., Calvó-Perxas, L., & Turró-Garriga, O. (2017). Kinematic and Pressure Features of Handwriting and Drawing: Preliminary Results Between Patients with Mild Cognitive Impairment, Alzheimer Disease and Healthy Controls. *Curr Alzheimer Res*, *14*(9), 960-968. https://doi.org/10.2174/1567205014666170309120708

Garrett, B., Taverner, T., Gromala, D., Tao, G., Cordingley, E., & Sun, C. (2018). Virtual reality clinical research: promises and challenges. *JMIR serious games*, *6*(4), e10839.

Gauthier, L., Dehaut, F., & Joanette, Y. (1989). The bells test: a quantitative and qualitative test for visual neglect. *International journal of clinical neuropsychology*, *11*(2), 49-54.

Germine, L., Reinecke, K., & Chaytor, N. S. (2019). Digital neuropsychology: Challenges and opportunities at the intersection of science and software. *The Clinical Neuropsychologist*, *33*(2), 271-286. https://doi.org/10.1080/13854046.2018.1535662

Giovannetti, T., Yamaguchi, T., Roll, E., Harada, T., Rycroft, S. S., Divers, R., Hulswit, J., Tan, C. C., Matchanova, A., & Ham, L. (2019). The Virtual Kitchen Challenge: preliminary data from a novel virtual reality test of mild difficulties in everyday functioning. *Aging, Neuropsychology, and Cognition*, *26*(6), 823-841.

Glaros, A. G., & Kline, R. B. (1988). Understanding the accuracy of tests with cutting scores: The sensitivity, specificity, and predictive value model. *Journal of Clinical Psychology*, *44*(6), 1013-1023.

Golden, C. J., & Freshwater, S. M. (2001). Luria-Nebraska neuropsychological battery. *Understanding psychological assessment*, 59-75.

Golisz, K. M. (1998). Dynamic assessment and multicontext treatment of unilateral neglect. *Topics in Stroke Rehabilitation*, *5*(2), 11-28.
Gómez-Cáceres, B., Cano-López, I., Aliño, M., & Puig-Perez, S. (2022). Effectiveness of virtual reality-based neuropsychological interventions in improving cognitive functioning in patients with mild cognitive impairment: A systematic review and meta-analysis. *The Clinical Neuropsychologist*, 1-34. https://doi.org/10.1080/13854046.2022.2148283
Graafland, M., Schraagen, J. M., & Schijven, M. P. (2012). Systematic review of serious games for medical education and surgical skills training. *Journal of British Surgery*, *99*(10), 1322-1330.
Grattan, & Woodbury. (2017a). Do neglect assessments detect neglect differently? *The American journal of occupational therapy*, *71*(3), 7103190050p7103190051-7103190050p7103190059.
Grattan, & Woodbury. (2017b). Do Neglect Assessments Detect Neglect Differently? *Am J Occup Ther*, *71*(3), 7103190050p7103190051-7103190050p7103190059. https://doi.org/10.5014/ajot.2017.025015
Graves, R. E. (1997). The Legacy of the Wernicke-Lichtheim Model. *Journal of the History of the Neurosciences*, *6*(1), 3-20. https://doi.org/10.1080/09647049709525682
Grewe, P., Kohsik, A., Flentge, D., Dyck, E., Botsch, M., Winter, Y., Markowitsch, H. J., Bien, C. G., & Piefke, M. (2013). Learning real-life cognitive abilities in a novel 360-virtual reality supermarket: a neuropsychological study of healthy participants and patients with epilepsy. *Journal of neuroengineering and rehabilitation*, *10*, 1-15.
Grinyer, K., & Teather, R. J. (2022). Effects of field of view on dynamic out-of-view target search in virtual reality. 2022 IEEE Conference on Virtual Reality and 3D User Interfaces (VR),
Grysiewicz, R. A., Thomas, K., & Pandey, D. K. (2008). Epidemiology of Ischemic and Hemorrhagic Stroke: Incidence, Prevalence, Mortality, and Risk Factors. *Neurologic Clinics*, *26*(4), 871-895. https://doi.org/https://doi.org/10.1016/j.ncl.2008.07.003
Guariglia, C., Palermo, L., Piccardi, L., Iaria, G., & Incoccia, C. (2013). Neglecting the Left Side of a City Square but Not the Left Side of Its Clock: Prevalence and Characteristics of Representational Neglect. *PLoS ONE*, *8*(7), e67390. https://doi.org/10.1371/journal.pone.0067390
Guariglia, C., Piccardi, L., Iaria, G., Nico, D., & Pizzamiglio, L. (2005). Representational neglect and navigation in real space. *Neuropsychologia*, *43*(8), 1138-1143. https://doi.org/https://doi.org/10.1016/j.neuropsychologia.2004.11.021
Guilbert, A. (2022). Clinical assessment of unilateral spatial neglect dissociations and heterogeneities: A narrative synthesis. *Neuropsychology*.
Guilmette, T. J., Sweet, J. J., Hebben, N., Koltai, D., Mahone, E. M., Spiegler, B. J., Stucky, K., Westerveld, M., & Participants, C. (2020). American Academy of Clinical Neuropsychology consensus

conference statement on uniform labeling of performance test scores. *The Clinical Neuropsychologist*, *34*(3), 437-453.
Gunalp, P., Moossaian, T., & Hegarty, M. (2019). Spatial perspective taking: Effects of social, directional, and interactive cues. *Memory & Cognition*, *47*(5), 1031-1043. https://doi.org/10.3758/s13421-019-00910-y
Gutiérrez Pérez, C., Sävborg, M., Påhlman, U., Cederfeldt, M., Knopp, E., Nordlund, A., Åstrand, R., Wallin, A., Fröjd, K., & Wijk, H. (2011). High frequency of cognitive dysfunction before stroke among older people. *International journal of geriatric psychiatry*, *26*(6), 622-629.
Guttman, L. (1945). A basis for analyzing test-retest reliability. *Psychometrika*, *10*(4), 255-282.
Hamad, A., & Jia, B. (2022). How virtual reality technology has changed our lives: an overview of the current and potential applications and limitations. *International Journal of Environmental Research and Public Health*, *19*(18), 11278.
Hankey, G. J. (2017). Stroke. *Lancet*, *389*(10069), 641-654.
Hartlage, L. C., & DeFilippis, N. A. (1983). History of Neuropsychological Assessment. In C. J. Golden & P. J. Vicente (Eds.), *Foundations of Clinical Neuropsychology* (pp. 1-23). Springer US. https://doi.org/10.1007/978-1-4613-3679-2_1
Harvey, P. D. (2019). Domains of cognition and their assessment. *Dialogues in Clinical Neuroscience*, *21*(3), 227-237. https://doi.org/10.31887/DCNS.2019.21.3/pharvey
Hassenzahl, M. (2001). The effect of perceived hedonic quality on product appealingness. *International Journal of Human-Computer Interaction*, *13*(4), 481-499.
Hatem, Saussez, G., Della Faille, M., Prist, V., Zhang, X., Dispa, D., & Bleyenheuft, Y. (2016). Rehabilitation of motor function after stroke: a multiple systematic review focused on techniques to stimulate upper extremity recovery. *Frontiers in Human Neuroscience*, *10*, 442.
Havig, P., McIntire, J., & Geiselman, E. (2011). Virtual reality in a cave: limitations and the need for HMDs? Head-and helmet-mounted displays XVI: design and applications,
Heilman, K. M., Bowers, D., Valenstein, E., & Watson, R. T. (1987). Hemispace and hemispatial neglect. In *Advances in psychology* (Vol. 45, pp. 115-150). Elsevier.
Heilman, K. M., Bowers, D., Valenstein, E., & Watson, R. T. (1993). Disorders of visual attention. *Baillieres Clin Neurol*, *2*(2), 389-413.
Heilman, K. M., Schwartz, H. D., & Watson, R. T. (1978). Hypoarousal in patients with the neglect syndrome and emotional indifference. *Neurology*, *28*(3), 229-229.
Heilman, K. M., Valenstein, E., & Watson, R. T. (1984). Neglect and related disorders. Seminars in Neurology,
Heilman, K. M., Valenstein, E., & Watson, R. T. (1994). The what and how of neglect. *Neuropsychological rehabilitation*, *4*(2), 133-139. https://doi.org/10.1080/09602019408402270

Helmerhorst, H. H. J. F., Brage, S., Warren, J., Besson, H., & Ekelund, U. (2012). A systematic review of reliability and objective criterion-related validity of physical activity questionnaires. *International Journal of Behavioral Nutrition and Physical Activity*, *9*(1), 103. https://doi.org/10.1186/1479-5868-9-103

Henderson, A., Korner-Bitensky, N., & Levin, M. (2007). Virtual reality in stroke rehabilitation: a systematic review of its effectiveness for upper limb motor recovery. *Topics in stroke rehabilitation*, *14*(2), 52-61.

Herman, B., Leyten, A., Van Luijk, J., Frenken, C., Op de Coul, A., & Schulte, B. (1982). Epidemiology of stroke in Tilburg, the Netherlands. The population-based stroke incidence register: 2. Incidence, initial clinical picture and medical care, and three-week case fatality. *Stroke*, *13*(5), 629-634.

Hochstenbach, J., & Mulder, T. (1999). The role of neuropsychology in the relearning of motor skills following stroke. *The Cognitive, Emotional, and Behavioural Consequences of Stroke*.

Hodges, N. J., & Franks, I. M. (2000). Attention focusing instructions and coordination bias: Implications for learning a novel bimanual task. *Human Movement Science*, *19*(6), 843-867. https://doi.org/https://doi.org/10.1016/S0167-9457(01)00025-2

Holleman, G. A., Hooge, I. T. C., Kemner, C., & Hessels, R. S. (2020). The 'Real-World Approach' and Its Problems: A Critique of the Term Ecological Validity [Conceptual Analysis]. *Frontiers in Psychology*, *11*. https://doi.org/10.3389/fpsyg.2020.00721

Horowitz, T. S., Treviño, M., Gooch, I. M., & Duffy, K. A. (2019). Understanding the Profile of Cancer-Related Cognitive Impairments: A Critique of Meta-Analyses. *J Natl Cancer Inst*, *111*(10), 1009-1015. https://doi.org/10.1093/jnci/djz100

Horst, H. A. (2020). New media technologies in everyday life. In *Digital anthropology* (pp. 61-79). Routledge.

Hougaard, B. I., Knoche, H., Jensen, J., & Evald, L. (2021). Spatial neglect midline diagnostics from virtual reality and eye tracking in a free-viewing environment. *Frontiers in Psychology*, 5226.

Howieson, D. (2019). Current limitations of neuropsychological tests and assessment procedures. *The Clinical Neuropsychologist*, *33*(2), 200-208.

Howieson, D. B., & Lezak, M. D. (2008). The neuropsychological evaluation.

Huang, L., & Pashler, H. (2005). Attention capacity and task difficulty in visual search. *Cognition*, *94*(3), B101-B111.

Huang, M. P., & Alessi, N. E. (1998). Current limitations into the application of virtual reality to mental health research. *Studies in health technology and informatics*, 63-66.

Hummel, F., Andres, F., Altenmüller, E., Dichgans, J., & Gerloff, C. (2002). Inhibitory control of acquired motor programmes in the human brain. *Brain*, *125*(2), 404-420. https://doi.org/10.1093/brain/awf030

Husain, M. (2008). Hemineglect. *Scholarpedia*, *3*(2), 3681.

Husain, M., & Rorden, C. (2003). Non-spatially lateralized mechanisms in hemispatial neglect. *Nature Reviews Neuroscience*, *4*(1), 26-36.

Huygelier, H., & Gillebert, C. R. (2020). Quantifying egocentric spatial neglect with cancellation tasks: A theoretical validation. *Journal of neuropsychology*, *14*(1), 1-19.

Huygelier, H., Mattheus, E., Abeele, V. V., van Ee, R., & Gillebert, C. R. (2021). The Use of the Term Virtual Reality in Post-Stroke Rehabilitation: A Scoping Review and Commentary. *Psychol Belg*, *61*(1), 145-162. https://doi.org/10.5334/pb.1033

Huygelier, H., Schraepen, B., Lafosse, C., Vaes, N., Schillebeeckx, F., Michiels, K., Note, E., Vanden Abeele, V., van Ee, R., & Gillebert, C. R. (2022). An immersive virtual reality game to train spatial attention orientation after stroke: A feasibility study. *Applied Neuropsychology: Adult*, *29*(5), 915-935.

Hyndman, D., & Ashburn, A. (2003). People with stroke living in the community: Attention deficits, balance, ADL ability and falls. *Disability and rehabilitation*, *25*(15), 817-822.

Hyndman, D., Pickering, R. M., & Ashburn, A. (2008). The influence of attention deficits on functional recovery post stroke during the first 12 months after discharge from hospital. *Journal of Neurology, Neurosurgery & Psychiatry*, *79*(6), 656-663.

Jaillard, A., Naegele, B., Trabucco-Miguel, S., LeBas, J. F., & Hommel, M. (2009). Hidden dysfunctioning in subacute stroke. *Stroke*, *40*(7), 2473-2479.

Jaiswal, N., Ray, W., & Slobounov, S. (2010). Encoding of visual–spatial information in working memory requires more cerebral efforts than retrieval: Evidence from an EEG and virtual reality study. *Brain Research*, *1347*, 80-89. https://doi.org/https://doi.org/10.1016/j.brainres.2010.05.086

Jang, W., Shin, J.-H., Kim, M., & Kim, K. (2016). Human field of regard, field of view, and attention bias. *Computer Methods and Programs in Biomedicine*, *135*, 115-123. https://doi.org/https://doi.org/10.1016/j.cmpb.2016.07.026

Jannink, M. J., Aznar, M., de Kort, A. C., Van de Vis, W., Veltink, P., & van der Kooij, H. (2009). Assessment of visuospatial neglect in stroke patients using virtual reality: a pilot study. *International Journal of Rehabilitation Research*, *32*(4), 280-286.

Jaracz, K., & Kozubski, W. (2003). Quality of life in stroke patients. *Acta Neurologica Scandinavica*, *107*(5), 324-329.

Jenkins, H., Camper, B., Chisholm, A., & Grigsby, N. (2009). From serious games to serious gaming. In *Serious Games* (pp. 470-490). Routledge.

Jennett, C., Cox, A. L., Cairns, P., Dhoparee, S., Epps, A., Tijs, T., & Walton, A. (2008). Measuring and defining the experience of immersion in games. *International journal of human-computer studies*, *66*(9), 641-661.

Jin, R., Pilozzi, A., & Huang, X. (2020). Current cognition tests, potential virtual reality applications, and serious games in cognitive assessment and non-pharmacological therapy for neurocognitive disorders. *Journal of Clinical Medicine*, *9*(10), 3287.

Jokinen, H., Melkas, S., Ylikoski, R., Pohjasvaara, T., Kaste, M., Erkinjuntti, T., & Hietanen, M. (2015). Post-stroke cognitive impairment is common even after successful clinical recovery. *European Journal of Neurology*, *22*(9), 1288-1294.

Kaiser, A. P., Villadsen, K. W., Samani, A., Knoche, H., & Evald, L. (2022a). Virtual Reality and Eye-tracking Assessment and Treatment of Unilateral Spatial Neglect: Systematic Review and Future Prospect. *Frontiers in psychology*, 479.

Kaiser, A. P., Villadsen, K. W., Samani, A., Knoche, H., & Evald, L. (2022b). Virtual Reality and Eye-Tracking Assessment, and Treatment of Unilateral Spatial Neglect: Systematic Review and Future Prospects [Systematic Review]. *Frontiers in Psychology*, *13*. https://doi.org/10.3389/fpsyg.2022.787382

Kalantari, S., & Neo, J. R. J. (2020). Virtual environments for design research: Lessons learned from use of fully immersive virtual reality in interior design research. *Journal of Interior Design*, *45*(3), 27-42.

Kalantari, S., Rounds, J. D., Kan, J., Tripathi, V., & Cruz-Garza, J. G. (2021). Comparing physiological responses during cognitive tests in virtual environments vs. in identical real-world environments. *Scientific Reports*, *11*(1), 10227. https://doi.org/10.1038/s41598-021-89297-y

Kalawsky, R. S. (1996). Exploiting virtual reality techniques in education and training: Technological issues. *http://www. man. ac. uk/MVC/SIMA/vrtech/title. html*.

Kamphuis, C., Barsom, E., Schijven, M., & Christoph, N. (2014). Augmented reality in medical education? *Perspectives on medical education*, *3*, 300-311.

Kampis, D., & Southgate, V. (2020). Altercentric cognition: how others influence our cognitive processing. *Trends in Cognitive Sciences*, *24*(11), 945-959.

Kamtchum Tatuene, J., Allali, G., Saj, A., Bernati, T., Sztajzel, R., Pollak, P., & Momjian-Mayor, I. (2016). Incidence, Risk Factors and Anatomy of Peripersonal Visuospatial Neglect in Acute Stroke. *European Neurology*, *75*(3-4), 157-163. https://doi.org/10.1159/000444709

Kane, R. L. (1991). Standardized and flexible batteries in neuropsychology: An assessment update. *Neuropsychology Review*, *2*, 281-339.

Kane, R. L., & Kay, G. G. (1992). Computerized assessment in neuropsychology: a review of tests and test batteries. *Neuropsychology review*, *3*(1), 1-117.

Kaplan, R. F., Verfaellie, M., Meadows, M.-E., Caplan, L. R., Pessin, M. S., & DeWitt, L. D. (1991). Changing attentional demands in left hemispatial neglect. *Archives of Neurology*, *48*(12), 1263-1266.

Kardong-Edgren, S., Farra, S. L., Alinier, G., & Young, H. M. (2019). A Call to Unify Definitions of Virtual Reality. *Clinical Simulation in*

Nursing, *31*, 28-34. https://doi.org/https://doi.org/10.1016/j.ecns.2019.02.006
Karnath, H.-O. (2015). Spatial attention systems in spatial neglect. *Neuropsychologia*, *75*, 61-73. https://doi.org/https://doi.org/10.1016/j.neuropsychologia.2015.05.019
Karnath, H.-O., & Niemeier, M. (2002). Task-dependent differences in the exploratory behaviour of patients with spatial neglect. *Neuropsychologia*, *40*(9), 1577-1585.
Karnath, H., Niemeier, M., & Dichgans, J. (1998). Space exploration in neglect. *Brain: a journal of neurology*, *121*(12), 2357-2367.
Kato, P. M., & de Klerk, S. (2017). Serious games for assessment: Welcome to the jungle. *Journal of Applied Testing Technology*, *18*(S1), 1-6.
Kerkhoff, G. (2001). Spatial hemineglect in humans. *Progress in neurobiology*, *63*(1), 1-27.
Kessels. (2019). Improving precision in neuropsychological assessment: Bridging the gap between classic paper-and-pencil tests and paradigms from cognitive neuroscience. *The Clinical Neuropsychologist*, *33*(2), 357-368.
Kessels, R. P. (2019). Improving precision in neuropsychological assessment: Bridging the gap between classic paper-and-pencil tests and paradigms from cognitive neuroscience. *The Clinical Neuropsychologist*, *33*(2), 357-368.
Khalaf, A., Kersey, J., Eldeeb, S., Alankus, G., Grattan, E., Waterstram, L., Skidmore, E., & Akcakaya, M. (2018). EEG-based neglect assessment: A feasibility study. *Journal of Neuroscience Methods*, *303*, 169-177. https://doi.org/https://doi.org/10.1016/j.jneumeth.2018.03.019
Khan, Y., Xu, Z., & Stigant, M. (2003). Virtual reality for Neuropsychological diagnosis and rehabilitation: A Survey. Proceedings on Seventh International Conference on Information Visualization, 2003. IV 2003.,
Kiefer, P., Giannopoulos, I., Raubal, M., & Duchowski, A. (2017). Eye tracking for spatial research: Cognition, computation, challenges. *Spatial Cognition & Computation*, *17*(1-2), 1-19.
Kim. (2010). Assessment of post-stroke extrapersonal neglect using a three-dimensional immersive virtual street crossing program [Article]. *Acta Neurologica Scandinavica*, *121*(3), 171-177. https://doi.org/10.1111/j.1600-0404.2009.01194.x
Kim, D., Ku, J., Chang, W., Park, T., Lim, J., Han, K., Kim, I. Y., & Kim, S. (2010). Assessment of post-stroke extrapersonal neglect using a three-dimensional immersive virtual street crossing program. *Acta Neurologica Scandinavica*, *121*(3), 171-177.
Kim, H., Kim, H.-K., Kim, N., & Nam, C. S. (2021). Dual Task Effects on Speed and Accuracy During Cognitive and Upper Limb Motor Tasks in Adults With Stroke Hemiparesis. *Frontiers in human neuroscience*, *15*, 671541.

Kim, M.-S., & Cave, K. R. (1995). Spatial attention in visual search for features and feature conjunctions. *Psychological science*, *6*(6), 376-380.

Kim, Y. M., Chun, M. H., Yun, G. J., Song, Y. J., & Young, H. E. (2011). The effect of virtual reality training on unilateral spatial neglect in stroke patients. *Annals of rehabilitation medicine*, *35*(3), 309-315.

Kinsbourne, M. (1970). A model for the mechanism of unilateral neglect of space. *Transactions of the American Neurological Association*, *95*.

Kinsbourne, M. (1987). Mechanisms of unilateral neglect. In *Advances in psychology* (Vol. 45, pp. 69-86). Elsevier.

Kishishita, N., Kiyokawa, K., Orlosky, J., Mashita, T., Takemura, H., & Kruijff, E. (2014). Analysing the effects of a wide field of view augmented reality display on search performance in divided attention tasks. 2014 IEEE International Symposium on Mixed and Augmented Reality (ISMAR),

Kitago, T., & Krakauer, J. W. (2013). Motor learning principles for neurorehabilitation. *Handbook of clinical neurology*, *110*, 93-103.

Kleim, J. A., & Jones, T. A. (2008). Principles of experience-dependent neural plasticity: implications for rehabilitation after brain damage.

Knobel, S. E., Kaufmann, B. C., Gerber, S. M., Cazzoli, D., Müri, R. M., Nyffeler, T., & Nef, T. (2020). Immersive 3D virtual reality cancellation task for visual neglect assessment: a pilot study. *Frontiers in human neuroscience*, *14*, 180.

Knobel, S. E. J., Kaufmann, B. C., Gerber, S. M., Urwyler, P., Cazzoli, D., Müri, R. M., Nef, T., & Nyffeler, T. (2021). Development of a search task using immersive virtual reality: proof-of-concept study. *JMIR Serious Games*, *9*(3), e29182.

Koch, G., Oliveri, M., Cheeran, B., Ruge, D., Gerfo, E. L., Salerno, S., Torriero, S., Marconi, B., Mori, F., & Driver, J. (2008). Hyperexcitability of parietal-motor functional connections in the intact left-hemisphere of patients with neglect. *Brain*, *131*(12), 3147-3155.

Koo, T. K., & Li, M. Y. (2016). A guideline of selecting and reporting intraclass correlation coefficients for reliability research. *Journal of chiropractic medicine*, *15*(2), 155-163.

Koshino, H. (2001). Activation and inhibition of stimulus features in conjunction search. *Psychonomic bulletin & review*, *8*(2), 294-300.

Kothgassner, O. D., & Felnhofer, A. (2020). Does virtual reality help to cut the Gordian knot between ecological validity and experimental control? *Annals of the International Communication Association*, *44*(3), 210-218.

Kourtesis, P., Collina, S., Doumas, L. A. A., & MacPherson, S. E. (2019). Technological Competence Is a Pre-condition for Effective Implementation of Virtual Reality Head Mounted Displays in Human Neuroscience: A Technological Review and Meta-Analysis [Systematic Review]. *Frontiers in Human Neuroscience*, *13*. https://doi.org/10.3389/fnhum.2019.00342

Kourtesis, P., & MacPherson, S. E. (2021). How immersive virtual reality methods may meet the criteria of the National Academy of Neuropsychology and American Academy of Clinical Neuropsychology: A software review of the Virtual Reality Everyday Assessment Lab (VR-EAL). *Computers in Human Behavior Reports*, *4*, 100151. https://doi.org/https://doi.org/10.1016/j.chbr.2021.100151
Kovacs, F. M., Abraira, V., Royuela, A., Corcoll, J., Alegre, L., Tomás, M., Mir, M. A., Cano, A., Muriel, A., Zamora, J., Del Real, M. T., Gestoso, M., & Mufraggi, N. (2008). Minimum detectable and minimal clinically important changes for pain in patients with nonspecific neck pain. *BMC Musculoskelet Disord*, *9*, 43. https://doi.org/10.1186/1471-2474-9-43
Krath, J., Schürmann, L., & Von Korflesch, H. F. (2021). Revealing the theoretical basis of gamification: A systematic review and analysis of theory in research on gamification, serious games and game-based learning. *Computers in Human Behavior*, *125*, 106963.
Krauß, V., Boden, A., Oppermann, L., & Reiners, R. (2021). Current practices, challenges, and design implications for collaborative ar/vr application development. Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems,
Kristjánsson, Á., & Egeth, H. (2020). How feature integration theory integrated cognitive psychology, neurophysiology, and psychophysics. *Attention, Perception, & Psychophysics*, *82*(1), 7-23. https://doi.org/10.3758/s13414-019-01803-7
Krohn, S., Tromp, J., Quinque, E. M., Belger, J., Klotzsche, F., Rekers, S., Chojecki, P., de Mooij, J., Akbal, M., McCall, C., Villringer, A., Gaebler, M., Finke, C., & Thöne-Otto, A. (2020). Multidimensional Evaluation of Virtual Reality Paradigms in Clinical Neuropsychology: Application of the VR-Check Framework. *J Med Internet Res*, *22*(4), e16724. https://doi.org/10.2196/16724
Krueger, C., & Tian, L. (2004). A comparison of the general linear mixed model and repeated measures ANOVA using a dataset with multiple missing data points. *Biological research for nursing*, *6*(2), 151-157.
Kruijff, E., Orlosky, J., Kishishita, N., Trepkowski, C., & Kiyokawa, K. (2018). The influence of label design on search performance and noticeability in wide field of view augmented reality displays. *IEEE transactions on visualization and computer graphics*, *25*(9), 2821-2837.
Kwakkel, G., Kollen, B., & Twisk, J. (2006). Impact of time on improvement of outcome after stroke. *Stroke*, *37*(9), 2348-2353.
Kwakkel, G., Veerbeek, J. M., van Wegen, E. E., Nijland, R., Harmeling-van der Wel, B. C., & Dippel, D. W. (2010). Predictive value of the NIHSS for ADL outcome after ischemic hemispheric stroke: does timing of early assessment matter? *Journal of the Neurological Sciences*, *294*(1-2), 57-61.
Laakso, H., Hietanen, M., Melkas, S., Sibolt, G., Curtze, S., Virta, M., Ylikoski, R., Pohjasvaara, T., Kaste, M., & Erkinjuntti, T. (2019).

Executive function subdomains are associated with post-stroke functional outcome and permanent institutionalization. *European Journal of Neurology*, *26*(3), 546-552.
Ladavas, E. (1987). Is the hemispatial deficit produced by right parietal lobe damage associated with retinal or gravitational coordinates? *Brain*, *110*(1), 167-180.
Ladouce, S., Mustile, M., & Dehais, F. (2021). Capturing cognitive events embedded in the real-world using mobile EEG and Eye-Tracking. *bioRxiv*, 2021.2011. 2030.470560.
Lalkhen, A. G., & McCluskey, A. (2008). Clinical tests: sensitivity and specificity. *Continuing Education in Anaesthesia Critical Care & Pain*, *8*(6), 221-223. https://doi.org/10.1093/bjaceaccp/mkn041
Langhorne, P., Bernhardt, J., & Kwakkel, G. (2011). Stroke rehabilitation. *The Lancet*, *377*(9778), 1693-1702. https://doi.org/https://doi.org/10.1016/S0140-6736(11)60325-5
Laplane, D., & Degos, J. D. (1983). Motor neglect [Article]. *Journal of Neurology Neurosurgery and Psychiatry*, *46*(2), 152-158. https://doi.org/10.1136/jnnp.46.2.152
LaRocco, M. (2020). Developing the 'best practices' of virtual reality design: industry standards at the frontier of emerging media. *Journal of Visual Culture*, *19*(1), 96-111. https://doi.org/10.1177/1470412920906255
Lau-Zhu, A., Lau, M. P., & McLoughlin, G. (2019). Mobile EEG in research on neurodevelopmental disorders: Opportunities and challenges. *Developmental cognitive neuroscience*, *36*, 100635.
Laugwitz, B., Held, T., & Schrepp, M. (2008a). Construction and evaluation of a user experience questionnaire. Symposium of the Austrian HCI and usability engineering group,
Laugwitz, B., Held, T., & Schrepp, M. (2008b). Construction and evaluation of a user experience questionnaire. HCI and Usability for Education and Work: 4th Symposium of the Workgroup Human-Computer Interaction and Usability Engineering of the Austrian Computer Society, USAB 2008, Graz, Austria, November 20-21, 2008. Proceedings 4,
Lawrence, E. S., Coshall, C., Dundas, R., Stewart, J., Rudd, A. G., Howard, R., & Wolfe, C. D. (2001). Estimates of the prevalence of acute stroke impairments and disability in a multiethnic population. *Stroke*, *32*(6), 1279-1284.
Lee, P., Liu, C.-H., Fan, C.-W., Lu, C.-P., Lu, W.-S., & Hsieh, C.-L. (2013). The test–retest reliability and the minimal detectable change of the Purdue pegboard test in schizophrenia. *Journal of the Formosan Medical Association*, *112*(6), 332-337. https://doi.org/https://doi.org/10.1016/j.jfma.2012.02.023
Lei, C., Sunzi, K., Dai, F., Liu, X., Wang, Y., Zhang, B., He, L., & Ju, M. (2019). Effects of virtual reality rehabilitation training on gait and balance in patients with Parkinson's disease: a systematic review. *PLoS ONE*, *14*(11), e0224819.

Lemée, J.-M., Bernard, F., Ter Minassian, A., & Menei, P. (2018). Right hemisphere cognitive functions: from clinical and anatomical bases to brain mapping during awake craniotomy. Part II: neuropsychological tasks and brain mapping. *World neurosurgery*, *118*, 360-367.

Leposavić, I., Leposavić, L., & Šaula-Marojević, B. (2010). NEUROPSYCHOLOGICAL ASSESSMENT: COMPUTERIZES BATTERIES OR STANDARD TESTS. *Psychiatria Danubina*, *22*(2), 145-152.

Leśniak, M., Bak, T., Czepiel, W., Seniów, J., & Członkowska, A. (2008). Frequency and prognostic value of cognitive disorders in stroke patients. *Dementia and geriatric cognitive disorders*, *26*(4), 356-363.

Lezak, M. (1995). Neumpsychologicalassessment (3rd cd.). In: New York: Oxford.

Lezak, M. D. (2000). Nature, applications, and limitations of neuropsychological assessment following traumatic brain injury. In *International handbook of neuropsychological rehabilitation* (pp. 67-79). Springer.

Lezak, M. D., Howieson, D. B., Loring, D. W., & Fischer, J. S. (2004). *Neuropsychological assessment*. Oxford University Press, USA.

Li, L., Zeng, L., Lin, Z.-J., Cazzell, M., & Liu, H. (2015). Tutorial on use of intraclass correlation coefficients for assessing intertest reliability and its application in functional near-infrared spectroscopy–based brain imaging. *Journal of biomedical optics*, *20*(5), 050801-050801.

Libon, D. J., Baliga, G., Swenson, R., & Au, R. (2021). Digital Neuropsychological Assessment: New Technology for Measuring Subtle Neuropsychological Behavior. *Journal of Alzheimer's Disease*, *82*, 1-4. https://doi.org/10.3233/JAD-210513

Lin, D. J., Erler, K. S., Snider, S. B., Bonkhoff, A. K., DiCarlo, J. A., Lam, N., Ranford, J., Parlman, K., Cohen, A., Freeburn, J., Finklestein, S. P., Schwamm, L. H., Hochberg, L. R., & Cramer, S. C. (2021). Cognitive Demands Influence Upper Extremity Motor Performance During Recovery From Acute Stroke. *Neurology*, *96*(21), e2576-e2586. https://doi.org/10.1212/wnl.0000000000011992

Lincoln, N. B., Blackburn, M., Ellis, S., Jackson, J., Edmans, J., Nouri, F., Walrer, M., & Haworth, H. (1989). An investigation of factors affecting progress of patients on a stroke unit. *Journal of Neurology, Neurosurgery & Psychiatry*, *52*(4), 493-496.

Livari, N., Sharma, S., & Ventä-Olkkonen, L. (2020). Digital transformation of everyday life – How COVID-19 pandemic transformed the basic education of the young generation and why information management research should care? *International Journal of Information Management*, *55*, 102183. https://doi.org/https://doi.org/10.1016/j.ijinfomgt.2020.102183

Loetscher, T., Potter, K. J., Wong, D., & das Nair, R. (2019). Cognitive rehabilitation for attention deficits following stroke. *Cochrane Database of Systematic Reviews*(11).

Long, J. W., Masters, B., Sajjadi, P., Simons, C., & Masterson, T. D. (2023). The development of an immersive mixed-reality application to improve the ecological validity of eating and sensory behavior research. *Front Nutr*, *10*, 1170311. https://doi.org/10.3389/fnut.2023.1170311

Losier, B. J., & Klein, R. M. (2001). A review of the evidence for a disengage deficit following parietal lobe damage. *Neuroscience & Biobehavioral Reviews*, *25*(1), 1-13.

Lowrey, C. R., Dukelow, S. P., Bagg, S. D., Ritsma, B., & Scott, S. H. (2022). Impairments in Cognitive Control Using a Reverse Visually Guided Reaching Task Following Stroke. *Neurorehabil Neural Repair*, *36*(7), 449-460. https://doi.org/10.1177/15459683221100510

Lumsden, J., Edwards, E. A., Lawrence, N. S., Coyle, D., & Munafò, M. R. (2016). Gamification of Cognitive Assessment and Cognitive Training: A Systematic Review of Applications and Efficacy. *JMIR serious games*, *4*(2), e11. https://doi.org/10.2196/games.5888

Lutz, O. H.-M., Burmeister, C., dos Santos, L. F., Morkisch, N., Dohle, C., & Krüger, J. (2017). Application of head-mounted devices with eye-tracking in virtual reality therapy. *Current Directions in Biomedical Engineering*, *3*(1), 53-56.

Lyle, R. C. (1981). A performance test for assessment of upper limb function in physical rehabilitation treatment and research. *International Journal of Rehabilitation Research*, *4*(4), 483-492.

Ma, M., & Zheng, H. (2011). Virtual reality and serious games in healthcare. In *Advanced computational intelligence paradigms in healthcare 6. Virtual reality in psychotherapy, rehabilitation, and assessment* (pp. 169-192). Springer.

Mach, V., Valouch, J., Adámek, M., & Ševčík, J. (2019). Virtual reality–level of immersion within the crime investigation. MATEC Web of Conferences,

Mackay, J., Mensah, G. A., & Greenlund, K. (2004). *The atlas of heart disease and stroke*. World Health Organization.

Mainwaring, S. D., Tversky, B., Ohgishi, M., & Schiano, D. J. (2003). Descriptions of simple spatial scenes in English and Japanese. *Spatial cognition and computation*, *3*(1), 3-42.

Manly, T., Hawkins, K., Evans, J., Woldt, K., & Robertson, I. H. (2002). Rehabilitation of executive function: facilitation of effective goal management on complex tasks using periodic auditory alerts. *Neuropsychologia*, *40*(3), 271-281. https://doi.org/https://doi.org/10.1016/S0028-3932(01)00094-X

Mansfield, A., Inness, E. L., & McIlroy, W. E. (2018). Stroke. *Handb Clin Neurol*, *159*, 205-228. https://doi.org/10.1016/b978-0-444-63916-5.00013-6

Maramba, I., Chatterjee, A., & Newman, C. (2019). Methods of usability testing in the development of eHealth applications: A scoping review. *International Journal of Medical Informatics*, *126*, 95-104. https://doi.org/https://doi.org/10.1016/j.ijmedinf.2019.03.018

Marcopulos, B., & Łojek, E. (2019). Introduction to the special issue: Are modern neuropsychological assessment methods really “modern”? Reflections on the current neuropsychological test armamentarium. *The Clinical Neuropsychologist*, *33*(2), 187-199. https://doi.org/10.1080/13854046.2018.1560502

Marques-Costa, Simões, Almiro, Prieto, & Pinho. (2022). Integrating Technology in Neuropsychological Assessment. *European Psychologist*.

Marques-Costa, C., Simões, M. R., Almiro, P. A., Prieto, G., & Salomé Pinho, M. (2022). Integrating technology in neuropsychological assessment: A narrative review of the main obstacles, new developments, and potential issues in assessment through tablets. *European Psychologist*.

Martino Cinnera, A., Bisirri, A., Chioccia, I., Leone, E., Ciancarelli, I., Iosa, M., Morone, G., & Verna, V. (2022). Exploring the Potential of Immersive Virtual Reality in the Treatment of Unilateral Spatial Neglect Due to Stroke: A Comprehensive Systematic Review. *Brain Sciences*, *12*(11), 1589. https://www.mdpi.com/2076-3425/12/11/1589

Massetti, T., Da Silva, T. D., Crocetta, T. B., Guarnieri, R., De Freitas, B. L., Bianchi Lopes, P., Watson, S., Tonks, J., & de Mello Monteiro, C. B. (2018). The clinical utility of virtual reality in neurorehabilitation: a systematic review. *Journal of central nervous system disease*, *10*, 1179573518813541.

Mathiowetz, V., Volland, G., Kashman, N., & Weber, K. (1985). Adult norms for the Box and Block Test of manual dexterity. *The American journal of occupational therapy*, *39*(6), 386-391.

Matthews, M. J., Yusuf, M., Doyle, C., & Thompson, C. (2016). Quadrupedal movement training improves markers of cognition and joint repositioning. *Human Movement Science*, *47*, 70-80. https://doi.org/https://doi.org/10.1016/j.humov.2016.02.002

McCaffrey, R. J., Ortega, A., & Haase, R. F. (1993). Effects of repeated neuropsychological assessments. *Archives of Clinical Neuropsychology*, *8*(6), 519-524.

McCaffrey, R. J., & Westervelt, H. J. (1995). Issues associated with repeated neuropsychological assessments. *Neuropsychology Review*, *5*, 203-221.

McDonald, M. W., Black, S. E., Copland, D. A., Corbett, D., Dijkhuizen, R. M., Farr, T. D., Jeffers, M. S., Kalaria, R. N., Karayanidis, F., & Leff, A. P. (2019). Cognition in stroke rehabilitation and recovery research: Consensus-based core recommendations from the second Stroke Recovery and Rehabilitation Roundtable. *International Journal of Stroke*, *14*(8), 774-782.

McDowd, J. M., Filion, D. L., Pohl, P. S., Richards, L. G., & Stiers, W. (2003). Attentional Abilities and Functional Outcomes Following Stroke. *The Journals of Gerontology: Series B, 58*(1), P45-P53. https://doi.org/10.1093/geronb/58.1.P45

McEwen, S. E., Huijbregts, M. P., Ryan, J. D., & Polatajko, H. J. (2009). Cognitive strategy use to enhance motor skill acquisition post-stroke: a critical review. *Brain Injury*, *23*(4), 263-277.

McRae, M. (2005). Broca and beyond: A short history of localization in the brain. *History of Medicine Days*, *125*.

Meegan, D. V., & Tipper, S. P. (1999). Visual search and target-directed action. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(5), 1347.

Meert, G., Grégoire, J., & Noël, M.-P. (2010). Comparing the magnitude of two fractions with common components: Which representations are used by 10-and 12-year-olds? *Journal of Experimental Child Psychology*, *107*(3), 244-259.

Meißner, M., Pfeiffer, J., Pfeiffer, T., & Oppewal, H. (2019). Combining virtual reality and mobile eye tracking to provide a naturalistic experimental environment for shopper research. *Journal of Business Research*, *100*, 445-458.

Mellon, L., Brewer, L., Hall, P., Horgan, F., Williams, D., & Hickey, A. (2015). Cognitive impairment six months after ischaemic stroke: a profile from the ASPIRE-S study. *BMC neurology*, *15*(1), 1-9.

Men, L., Bryan-Kinns, N., Hassard, A. S., & Ma, Z. (2017). The impact of transitions on user experience in virtual reality. 2017 IEEE virtual reality (VR),

Menon, A., & Korner-Bitensky, N. (2004). Evaluating unilateral spatial neglect post stroke: working your way through the maze of assessment choices. *Topics in Stroke Rehabilitation*, *11*(3), 41-66.

Mercier, L., Audet, T., Hébert, R., Rochette, A., & Dubois, M.-F. (2001). Impact of motor, cognitive, and perceptual disorders on ability to perform activities of daily living after stroke. *Stroke*, *32*(11), 2602-2608.

Merten, T., Bossink, L., & Schmand, B. (2007). On the limits of effort testing: Symptom validity tests and severity of neurocognitive symptoms in nonlitigant patients. *Journal of Clinical and Experimental Neuropsychology*, *29*(3), 308-318.

Mesulam, M.-M. (1999). Spatial attention and neglect: parietal, frontal and cingulate contributions to the mental representation and attentional targeting of salient extrapersonal events. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, *354*(1387), 1325-1346.

Mezrar, S., & Bendella, F. (2022). A Systematic Review of Serious Games Relating to Cognitive Impairment and Dementia. *Journal of Digital Information Management*, *20*(1), 1-9.

Micera, S., Caleo, M., Chisari, C., Hummel, F. C., & Pedrocchi, A. (2020). Advanced Neurotechnologies for the Restoration of Motor Function. *Neuron*, *105*(4), 604-620. https://doi.org/https://doi.org/10.1016/j.neuron.2020.01.039

Middleton, A., Braun, C. H., Lewek, M. D., & Fritz, S. L. (2017). Balance impairment limits ability to increase walking speed in individuals with chronic stroke. *Disabil Rehabil*, *39*(5), 497-502. https://doi.org/10.3109/09638288.2016.1152603

Milgram, P., & Kishino, F. (1994). A taxonomy of mixed reality visual displays. *IEICE TRANSACTIONS on Information and Systems*, *77*(12), 1321-1329.

Miller, J. B., & Barr, W. B. (2017). The technology crisis in neuropsychology. *Archives of Clinical Neuropsychology*, *32*(5), 541-554.

Miller, M. R., Herrera, F., Jun, H., Landay, J. A., & Bailenson, J. N. (2020). Personal identifiability of user tracking data during observation of 360-degree VR video. *Scientific reports*, *10*(1), 1-10.

Milner, A. D., & McIntosh, R. D. (2005). The neurological basis of visual neglect. *Current opinion in neurology*, *18*(6), 748-753.

Mishra, S., Abbas, M., Jindal, K., Narayan, J., & Dwivedy, S. K. (2022). Artificial intelligence-based technological advancements in clinical healthcare applications: A systematic review. *Revolutions in Product Design for Healthcare: Advances in Product Design and Design Methods for Healthcare*, 207-227.

Miyake, A., & Friedman, N. P. (2012). The Nature and Organization of Individual Differences in Executive Functions: Four General Conclusions. *Current Directions in Psychological Science*, *21*(1), 8-14. https://doi.org/10.1177/0963721411429458

Mohr, J. P., Pessin, M. S., Finkelstein, S., Funkenstein, H. H., Duncan, G. W., & Davis, K. R. (1978). Broca aphasia: pathologic and clinical. *Neurology*, *28*(4), 311-311.

Mokkink, L. B., Terwee, C. B., Patrick, D. L., Alonso, J., Stratford, P. W., Knol, D. L., Bouter, L. M., & de Vet, H. C. (2010). The COSMIN checklist for assessing the methodological quality of studies on measurement properties of health status measurement instruments: an international Delphi study. *Qual Life Res*, *19*(4), 539-549. https://doi.org/10.1007/s11136-010-9606-8

Montedoro, V., Alsamour, M., Dehem, S., Lejeune, T., Dehez, B., & Edwards, M. G. (2018). Robot diagnosis test for egocentric and allocentric hemineglect. *Archives of Clinical Neuropsychology*, *34*(4), 481-494.

Montero-Odasso, M., Almeida, Q. J., Bherer, L., Burhan, A. M., Camicioli, R., Doyon, J., Fraser, S., Muir-Hunter, S., Li, K. Z. H., Liu-Ambrose, T., McIlroy, W., Middleton, L., Morais, J. A., Sakurai, R., Speechley, M., Vasudev, A., Beauchet, O., Hausdorff, J. M., Rosano, C., Studenski, S., Verghese, J., Gait, C., & Network, C. (2018). Consensus on Shared Measures of Mobility and Cognition: From the Canadian Consortium on Neurodegeneration in Aging (CCNA). *The Journals of Gerontology: Series A*, *74*(6), 897-909. https://doi.org/10.1093/gerona/gly148

Mooney, R. A., Cirillo, J., Stinear, C. M., & Byblow, W. D. (2020). Neurophysiology of motor skill learning in chronic stroke. *Clinical Neurophysiology*, *131*(4), 791-798. https://doi.org/https://doi.org/10.1016/j.clinph.2019.12.410

Morel, M., Bideau, B., Lardy, J., & Kulpa, R. (2015). Advantages and limitations of virtual reality for balance assessment and rehabilitation. *Neurophysiologie Clinique/Clinical Neurophysiology*, *45*(4), 315-326. https://doi.org/https://doi.org/10.1016/j.neucli.2015.09.007

Morelli, S., D'avenio, G., Rossi, M., & Grigioni, M. (2022). Investigating Virtual Reality technology acceptance by patients: preliminary results from a TAM-based model. *Annual Review of CyberTherapy and Telemedicine*, *20*, 103-107.

Morrison, G. E., Simone, C. M., Ng, N. F., & Hardy, J. L. (2015). Reliability and validity of the NeuroCognitive Performance Test, a web-based neuropsychological assessment [Technology Report]. *Frontiers in Psychology*, *6*. https://doi.org/10.3389/fpsyg.2015.01652

Mozer. (2002a). Frames of reference in unilateral neglect and visual perception: A computational perspective. *Psychological Review*, *109*, 156-185. https://doi.org/10.1037//0033-295X.109.1.156

Mozer. (2002b). Frames of reference in unilateral neglect and visual perception: a computational perspective. *Psychological Review*, *109*(1), 156.

Mubin, O., Alnajjar, F., Al Mahmud, A., Jishtu, N., & Alsinglawi, B. (2022). Exploring serious games for stroke rehabilitation: a scoping review. *Disability and Rehabilitation: Assistive Technology*, *17*(2), 159-165.

Mudgal, S. K., Sharma, S. K., Chaturvedi, J., & Sharma, A. (2020). Brain computer interface advancement in neurosciences: Applications and issues. *Interdisciplinary Neurosurgery*, *20*, 100694. https://doi.org/https://doi.org/10.1016/j.inat.2020.100694

Müller, H. J., & Mühlenen, A. v. (2000). Probing distractor inhibition in visual search: inhibition of return. *Journal of Experimental Psychology: Human Perception and Performance*, *26*(5), 1591.

Mullick, A. A., Subramanian, S. K., & Levin, M. F. (2015). Emerging evidence of the association between cognitive deficits and arm motor recovery after stroke: A meta-analysis. *Restorative Neurology and Neuroscience*, *33*, 389-403. https://doi.org/10.3233/RNN-150510

Muñoz, D., Barria, P., Cifuentes, C. A., Aguilar, R., Baleta, K., Azorín, J. M., & Múnera, M. (2022). EEG Evaluation in a Neuropsychological Intervention Program Based on Virtual Reality in Adults with Parkinson's Disease. *Biosensors*, *12*(9), 751.

Müsseler, J., von Salm-Hoogstraeten, S., & Böffel, C. (2022). Perspective Taking and Avatar-Self Merging [Review]. *Frontiers in Psychology*, *13*. https://doi.org/10.3389/fpsyg.2022.714464

Nakayama, H., Jørgensen, H. S., Raaschou, H. O., & Olsen, T. S. (1994). Recovery of upper extremity function in stroke patients: the Copenhagen Stroke Study. *Archives of Physical Medicine and Rehabilitation*, *75*(4), 394-398.

Neguț, A., Matu, S.-A., Sava, F. A., & David, D. (2016). Virtual reality measures in neuropsychological assessment: a meta-analytic review. *The Clinical Neuropsychologist*, *30*(2), 165-184.
Neppi-Mòdona, M., Savazzi, S., Ricci, R., Genero, R., Berruti, G., & Pepi, R. (2002). Unilateral neglect and perceptual parsing: a large-group study. *Neuropsychologia*, *40*(12), 1918-1929. https://doi.org/https://doi.org/10.1016/S0028-3932(02)00066-0
Nijboer, T. C., Kollen, B. J., & Kwakkel, G. (2014). The impact of recovery of visuo-spatial neglect on motor recovery of the upper paretic limb after stroke. *PLoS One*, *9*(6), e100584.
Nolin, P., Besnard, J., Allain, P., & Banville, F. (2019). Assessment and rehabilitation using virtual reality after stroke: A literature review. *Virtual reality for psychological and neurocognitive interventions*, 307-326.
North, M. M., & North, S. M. (2016). A comparative study of sense of presence of traditional virtual reality and immersive environments. *Australasian Journal of Information Systems*, *20*.
Nys, G., Van Zandvoort, M., De Kort, P., Van der Worp, H., Jansen, B., Algra, A., De Haan, E., & Kappelle, L. (2005). The prognostic value of domain-specific cognitive abilities in acute first-ever stroke. *Neurology*, *64*(5), 821-827.
Nys, G. M., van Zandvoort, M. J., de Kort, P. L., Jansen, B. P., de Haan, E. H., & Kappelle, L. J. (2007). Cognitive disorders in acute stroke: prevalence and clinical determinants. *Cerebrovasc Dis*, *23*(5-6), 408-416. https://doi.org/10.1159/000101464
Ogawa, H., Takeda, Y., & Yagi, A. (2002). Inhibitory tagging on randomly moving objects. *Psychological science*, *13*(2), 125-129.
Ogden, J. A. (1985). Anterior-posterior interhemispheric differences in the loci of lesions producing visual hemineglect. *Brain and cognition*, *4*(1), 59-75.
Ogourtsova, T., Archambault, P., Sangani, S., & Lamontagne, A. (2018). Ecological Virtual Reality Evaluation of Neglect Symptoms (EVENS): Effects of Virtual Scene Complexity in the Assessment of Poststroke Unilateral Spatial Neglect. *Neurorehabil Neural Repair*, *32*(1), 46-61. https://doi.org/10.1177/1545968317751677
Ogourtsova, T., Souza Silva, W., Archambault, P. S., & Lamontagne, A. (2017). Virtual reality treatment and assessments for post-stroke unilateral spatial neglect: a systematic literature review. *Neuropsychological Rehabilitation*, *27*(3), 409-454.
Ogura, K., Sugano, M., Takabatake, S., Naitoh, Y., & Nakaoka, K. (2019). VR application for visual field measurement of unilateral spatial neglect patients using eye tracking. 2019 IEEE International Conference on Healthcare Informatics (ICHI),
Olgers, T. J., bij de Weg, A. A., & Ter Maaten, J. C. (2021). Serious games for improving technical skills in medicine: scoping review. *JMIR serious games*, *9*(1), e24093.
Omowonuola, V., Ridgeway, Z., Vandeput, B., Yamashiro, Y., & Kher, S. (2022, 2022//). Virtual Reality and Motion Capture Training.

Proceedings of the Future Technologies Conference (FTC) 2021, Volume 3, Cham.
Ouellet, É., Boller, B., Corriveau-Lecavalier, N., Cloutier, S., & Belleville, S. (2018). The Virtual Shop: A new immersive virtual reality environment and scenario for the assessment of everyday memory. *Journal of Neuroscience Methods*, *303*, 126-135. https://doi.org/https://doi.org/10.1016/j.jneumeth.2018.03.010
Overend, T., Anderson, C., Sawant, A., Perryman, B., & Locking-Cusolito, H. (2010). Relative and absolute reliability of physical function measures in people with end-stage renal disease. *Physiother Can*, *62*(2), 122-128. https://doi.org/10.3138/physio.62.2.122
Paolucci, S., Antonucci, G., Gialloreti, L. E., Traballesi, M., Lubich, S., Pratesi, L., & Palombi, L. (1996). Predicting Stroke Inpatient Rehabilitation Outcome: The Prominent Role of Neuropsychological Disorders. *European Neurology*, *36*(6), 385-390. https://doi.org/10.1159/000117298
Parsey, C. M., & Schmitter-Edgecombe, M. (2013). Applications of Technology in Neuropsychological Assessment. *The Clinical Neuropsychologist*, *27*(8), 1328-1361. https://doi.org/10.1080/13854046.2013.834971
Parsons. (2011). Neuropsychological assessment using virtual environments: enhanced assessment technology for improved ecological validity. *Advanced computational intelligence paradigms in healthcare 6. Virtual reality in psychotherapy, rehabilitation, and assessment*, 271-289.
Parsons. (2015). Ecological validity in virtual reality-based neuropsychological assessment. In *Encyclopedia of Information Science and Technology, Third Edition* (pp. 1006-1015). IGI Global.
Parsons. (2016). Introduction. In T. D. Parsons (Ed.), *Clinical Neuropsychology and Technology: What's New and How We Can Use It* (pp. 3-10). Springer International Publishing. https://doi.org/10.1007/978-3-319-31075-6_1
Parsons, T., & Duffield, T. (2020). Paradigm Shift Toward Digital Neuropsychology and High-Dimensional Neuropsychological Assessments: Review. *J Med Internet Res*, *22*(12), e23777. https://doi.org/10.2196/23777
Parsons, T. D., McPherson, S., & Interrante, V. (2013). Enhancing neurocognitive assessment using immersive virtual reality. 2013 1st Workshop on Virtual and Augmented Assistive Technology (VAAT),
Parsons, T. D., & Reinebold, J. L. (2012). Adaptive virtual environments for neuropsychological assessment in serious games. *IEEE Transactions on Consumer Electronics*, *58*(2), 197-204.
Parsons, T. D., Silva, T. M., Pair, J., & Rizzo, A. A. (2008). Virtual environment for assessment of neurocognitive functioning: virtual reality cognitive performance assessment test. *Studies in Health Technology and Informatics*, *132*, 351.

Patten, C., Dozono, J., Schmidt, S. G., Jue, M. E., & Lum, P. S. (2006). Combined functional task practice and dynamic high intensity resistance training promotes recovery of upper-extremity motor function in post-stroke hemiparesis: a case study. *Journal of Neurologic Physical Therapy*, *30*(3), 99-115.

Pedersen, P., Jørgensen, H., Nakayama, H., Raaschou, H., & Olsen, T. (1997). Hemineglect in acute stroke--incidence and prognostic implications. The Copenhagen Stroke Study. *American journal of physical medicine & rehabilitation / Association of Academic Physiatrists*, *76*, 122-127.

Pedroli, E., Cipresso, P., Serino, S., Riva, G., & Albani, G. (2013). A virtual reality test for the assessment of cognitive deficits: usability and perspectives. 2013 7th International Conference on Pervasive Computing Technologies for Healthcare and Workshops,

Perez-Marcos, D., Ronchi, R., Giroux, A., Brenet, F., Serino, A., Tadi, T., & Blanke, O. (2023). An immersive virtual reality system for ecological assessment of peripersonal and extrapersonal unilateral spatial neglect. *J Neuroeng Rehabil*, *20*(1), 33. https://doi.org/10.1186/s12984-023-01156-1

Pérez, G., Sävborg, M., Påhlman, U., Cederfeldt, M., Knopp, E., Nordlund, A., Astrand, R., Wallin, A., Fröjd, K., Wijk, H., & Tarkowski, E. (2011). High frequency of cognitive dysfunction before stroke among older people. *Int J Geriatr Psychiatry*, *26*(6), 622-629. https://doi.org/10.1002/gps.2573

Pettersson, J., Albo, A., Eriksson, J., Larsson, P., Falkman, K., & Falkman, P. (2018). Cognitive ability evaluation using virtual reality and eye tracking. 2018 IEEE international conference on computational intelligence and virtual environments for measurement systems and applications (CIVEMSA),

Pezzetta, R., Ozkan, D., Era, V., Tieri, G., Zabberoni, S., Taglieri, S., Costa, A., Peppe, A., Caltagirone, C., & Aglioti, S. (2023). Combined EEG and immersive virtual reality unveil dopaminergic modulation of error monitoring in Parkinson’s Disease. *npj Parkinson's Disease*, *9*(1), 3.

Pieri, L., Tosi, G., & Romano, D. (2023). Virtual reality technology in neuropsychological testing: A systematic review. *Journal of neuropsychology*.

Pisella, L., & Mattingley, J. B. (2004). The contribution of spatial remapping impairments to unilateral visual neglect. *Neuroscience & Biobehavioral Reviews*, *28*(2), 181-200.

Pizzamiglio, L., Cappa, S., Vallar, G., Zoccolotti, P., Bottini, G., Ciurlil, P., Guariglia, C., & Antonucci, G. (1989). Visual neglect for far and near extra-personal space in humans. *Cortex*, *25*(3), 471-477.

Plotnik, M., Ben-Gal, O., Doniger, G. M., Gottlieb, A., Bahat, Y., Cohen, M., Kimel-Naor, S., Zeilig, G., & Beeri, M. S. (2021). Multimodal immersive trail making-virtual reality paradigm to study cognitive-motor interactions. *Journal of neuroengineering and rehabilitation*, *18*, 1-16.

Plotnik, M., Doniger, G. M., Bahat, Y., Gottleib, A., Gal, O. B., Arad, E., Kribus-Shmiel, L., Kimel-Naor, S., Zeilig, G., & Schnaider-Beeri, M. (2017). Immersive trail making: Construct validity of an ecological neuropsychological test. 2017 International Conference on Virtual Rehabilitation (ICVR),

Plummer, P., Morris, M. E., & Dunai, J. (2003). Assessment of Unilateral Neglect. *Physical Therapy*, *83*(8), 732-740. https://doi.org/10.1093/ptj/83.8.732

Poisson, M. E., & Wilkinson, F. (1992). Distractor ratio and grouping processes in visual conjunction search. *Perception*, *21*(1), 21-38.

Portney, L. G., & Watkins, M. P. (2009). *Foundations of clinical research: applications to practice* (Vol. 892). Pearson/Prentice Hall Upper Saddle River, NJ.

Posner, M. I., & DiGirolamo, G. J. (1998). Executive attention: Conflict, target detection, and cognitive control.

Posner, M. I., & Petersen, S. E. (1990). The attention system of the human brain. *Annual review of neuroscience*, *13*(1), 25-42.

Posner, M. I., Walker, J. A., Friedrich, F. J., & Rafal, R. D. (1984). Effects of parietal injury on covert orienting of attention. *Journal of neuroscience*, *4*(7), 1863-1874.

Pouget, A., & Driver, J. (1999). Visual neglect. *MIT Encyclopedia of Cognitive Sciences. MIT Press, Cambridge*, 869-871.

Poulin, V., Korner-Bitensky, N., Dawson, D. R., & Bherer, L. (2012). Efficacy of executive function interventions after stroke: a systematic review. *Top Stroke Rehabil*, *19*(2), 158-171. https://doi.org/10.1310/tsr1902-158

Pourmand, A., Davis, S., Lee, D., Barber, S., & Sikka, N. (2017). Emerging utility of virtual reality as a multidisciplinary tool in clinical medicine. *Games for Health Journal*, *6*(5), 263-270.

Prange-Lasonder, G. B., Alt Murphy, M., Lamers, I., Hughes, A.-M., Buurke, J. H., Feys, P., Keller, T., Klamroth-Marganska, V., Tarkka, I. M., & Timmermans, A. (2021). European evidence-based recommendations for clinical assessment of upper limb in neurorehabilitation (CAULIN): data synthesis from systematic reviews, clinical practice guidelines and expert consensus. *Journal of neuroengineering and rehabilitation*, *18*, 1-12.

Pratt, D. R., Zyda, M., & Kelleher, K. (1995). Virtual reality: in the mind of the beholder. *Computer*, *28*(07), 17-19.

Pratt, J., & Abrams, R. A. (1994). Action-centered inhibition: Effects of distractors on movement planning and execution. *Human Movement Science*, *13*(2), 245-254.

Prinzmetal, W. (1981). Principles of feature integration in visual perception. *Perception & Psychophysics*, *30*(4), 330-340.

Quest, M. (2023). *www.oculus.com*. https://www.oculus.com/experiences/quest/?utm_source=www.google.com&utm_medium=oculusredirect&locale=fr-fr&store=quest

Quinlan, P. T., & Humphreys, G. W. (1987). Visual search for targets defined by combinations of color, shape, and size: An examination

of the task constraints on feature and conjunction searches. *Perception & Psychophysics*, *41*(5), 455-472.
Rabin, L. A., Paolillo, E., & Barr, W. B. (2016). Stability in Test-Usage Practices of Clinical Neuropsychologists in the United States and Canada Over a 10-Year Period: A Follow-Up Survey of INS and NAN Members. *Archives of Clinical Neuropsychology*, *31*(3), 206-230. https://doi.org/10.1093/arclin/acw007
Rabuffetti, M., Ferrarin, M., Spadone, R., Pellegatta, D., Gentileschi, V., Vallar, G., & Pedotti, A. (2002). Touch-screen system for assessing visuo-motor exploratory skills in neuropsychological disorders of spatial cognition. *Medical and Biological Engineering and Computing*, *40*, 675-686.
Ragan, E. D., Bowman, D. A., Kopper, R., Stinson, C., Scerbo, S., & McMahan, R. P. (2015). Effects of field of view and visual complexity on virtual reality training effectiveness for a visual scanning task. *IEEE transactions on visualization and computer graphics*, *21*(7), 794-807.
Rand, D., Weiss, P. L., & Katz, N. (2009). Training multitasking in a virtual supermarket: A novel intervention after stroke. *The American Journal of Occupational Therapy*, *63*(5), 535-542.
Ratcliff, R., & McKoon, G. (2022). Can neuropsychological testing be improved with model-based approaches? *Trends in Cognitive Sciences*, *26*(11), 899-901. https://doi.org/https://doi.org/10.1016/j.tics.2022.08.015
Rengachary, J., d'Avossa, G., Sapir, A., Shulman, G. L., & Corbetta, M. (2009). Is the Posner Reaction Time Test More Accurate Than Clinical Tests in Detecting Left Neglect in Acute and Chronic Stroke? *Archives of Physical Medicine and Rehabilitation*, *90*(12), 2081-2088. https://doi.org/https://doi.org/10.1016/j.apmr.2009.07.014
Rengachary, J., He, B. J., Shulman, G. L., & Corbetta, M. (2011). A behavioral analysis of spatial neglect and its recovery after stroke. *Frontiers in Human Neuroscience*, *5*, 29.
Reynolds, C. R., & Mason, B. A. (2009). Measurement and statistical problems in neuropsychological assessment of children. In *Handbook of clinical child neuropsychology* (pp. 203-230). Springer.
Richardson, J. T. E. (2011). Eta squared and partial eta squared as measures of effect size in educational research. *Educational Research Review*, *6*(2), 135-147. https://doi.org/https://doi.org/10.1016/j.edurev.2010.12.001
Ridding, M., Sheean, G., Rothwell, J., Inzelberg, R., & Kujirai, T. (1995). Changes in the balance between motor cortical excitation and inhibition in focal, task specific dystonia. *Journal of Neurology, Neurosurgery & Psychiatry*, *59*(5), 493-498.
Riddoch, M. J., & Humphreys, G. W. (1987). Perceptual and action systems in unilateral visual neglect. In *Advances in psychology* (Vol. 45, pp. 151-181). Elsevier.

Ries, J. D., Echternach, J. L., Nof, L., & Gagnon Blodgett, M. (2009). Test-Retest Reliability and Minimal Detectable Change Scores for the Timed “Up & Go” Test, the Six-Minute Walk Test, and Gait Speed in People With Alzheimer Disease. *Physical Therapy*, *89*(6), 569-579. https://doi.org/10.2522/ptj.20080258

Rimmele, D. L., & Thomalla, G. (2022). [Long-term consequences of stroke]. *Bundesgesundheitsblatt Gesundheitsforschung Gesundheitsschutz*, *65*(4), 498-502. https://doi.org/10.1007/s00103-022-03505-2 (Langzeitfolgen von Schlaganfällen.)

Ritterfeld, U., Cody, M., & Vorderer, P. (2009). *Serious games: Mechanisms and effects*. Routledge.

Riva, G. (2009). Virtual reality: an experiential tool for clinical psychology. *British Journal of Guidance & Counselling*, *37*(3), 337-345.

Rizzo, A., & Koenig, S. T. (2017). Is clinical virtual reality ready for primetime? *Neuropsychology*, *31*(8), 877.

Rizzo, A. A., Bowerly, T., Buckwalter, J. G., Klimchuk, D., Mitura, R., & Parsons, T. D. (2009). A virtual reality scenario for all seasons: the virtual classroom. *Cns Spectrums*, *11*(1), 35-44.

Rizzo, A. A., & Buckwalter, J. G. (1997). Virtual reality and cognitive assessment and rehabilitation: the state of the art. *Virtual reality in neuro-psycho-physiology*, 123-145.

Rizzo, A. A., Schultheis, M., Kerns, K. A., & Mateer, C. (2004). Analysis of assets for virtual reality applications in neuropsychology. *Neuropsychological Rehabilitation*, *14*(1-2), 207-239. https://doi.org/10.1080/09602010343000183

Robert Teasell, M., & Hussein, N. (2016). Clinical consequences of stroke. *Evidence-Based Review of Stroke Rehabilitation*, 1-30.

Robertson, I. H. (2001). Do We Need the “Lateral” in Unilateral Neglect? Spatially Nonselective Attention Deficits in Unilateral Neglect and Their Implications for Rehabilitation. *NeuroImage*, *14*(1), S85-S90. https://doi.org/https://doi.org/10.1006/nimg.2001.0838

Robertson, I. H., Manly, T., Beschin, N., Daini, R., Haeske-Dewick, H., Hömberg, V., Jehkonen, M., Pizzamiglio, G., Shiel, A., & Weber, E. (1997). Auditory sustained attention is a marker of unilateral spatial neglect [Article]. *Neuropsychologia*, *35*(12), 1527-1532. https://doi.org/10.1016/S0028-3932(97)00084-5

Rode, Fourtassi, Pagliari, Pisella, & Rossetti. (2017). Complexity vs. unity in unilateral spatial neglect [Review]. *Revue Neurologique*, *173*(7-8), 440-450. https://doi.org/10.1016/j.neurol.2017.07.010

Rode, Pagliari, Huchon, Rossetti, & Pisella. (2017). Semiology of neglect: An update. *Annals of Physical and Rehabilitation Medicine*, *60*(3), 177-185. https://doi.org/https://doi.org/10.1016/j.rehab.2016.03.003

Rorden, C., Hjaltason, H., Fillmore, P., Fridriksson, J., Kjartansson, O., Magnusdottir, S., & Karnath, H.-O. (2012). Allocentric neglect strongly associated with egocentric neglect. *Neuropsychologia*, *50*(6), 1151-1157.

Rorden, C., & Karnath, H.-O. (2010). A simple measure of neglect severity. *Neuropsychologia*, *48*(9), 2758-2763.

Rose, T., Nam, C. S., & Chen, K. B. (2018). Immersion of virtual reality for rehabilitation-Review. *Applied ergonomics*, *69*, 153-161.

Rosenberg, L., Nygård, L., & Kottorp, A. (2009). Everyday technology use questionnaire: psychometric evaluation of a new assessment of competence in technology use. *OTJR: Occupation, Participation and Health*, *29*(2), 52-62.

Ruthenbeck, G. S., & Reynolds, K. J. (2015). Virtual reality for medical training: the state-of-the-art. *Journal of Simulation*, *9*(1), 16-26. https://doi.org/10.1057/jos.2014.14

Ryan, W. S., Cornick, J., Blascovich, J., & Bailenson, J. N. (2019). Virtual Reality: Whence, How and What For. In A. S. Rizzo & S. Bouchard (Eds.), *Virtual Reality for Psychological and Neurocognitive Interventions* (pp. 15-46). Springer New York. https://doi.org/10.1007/978-1-4939-9482-3_2

Sacco, R. L., Kasner, S. E., Broderick, J. P., Caplan, L. R., Connors, J., Culebras, A., Elkind, M. S., George, M. G., Hamdan, A. D., & Higashida, R. T. (2013). An updated definition of stroke for the 21st century: a statement for healthcare professionals from the American Heart Association/American Stroke Association. *Stroke*, *44*(7), 2064-2089.

Sachdev, P. S., Blacker, D., Blazer, D. G., Ganguli, M., Jeste, D. V., Paulsen, J. S., & Petersen, R. C. (2014). Classifying neurocognitive disorders: the DSM-5 approach. *Nature Reviews Neurology*, *10*(11), 634-642.

Saevarsson, S. (2013). Motor response deficits of unilateral neglect: assessment, therapy, and neuroanatomy. *Applied Neuropsychology: Adult*, *20*(4), 292-305.

Saj, A., Pierce, J. E., Ronchi, R., Ros, T., Thomasson, M., Bernati, T., Van De Ville, D., Serino, A., & Vuilleumier, P. (2021). Real-time fMRI and EEG neurofeedback: A perspective on applications for the rehabilitation of spatial neglect. *Annals of Physical and Rehabilitation Medicine*, *64*(5), 101561. https://doi.org/https://doi.org/10.1016/j.rehab.2021.101561

Sala, D., Logie, Beschin, & Denis. (2004). Preserved visuo-spatial transformations in representational neglect. *Neuropsychologia*, *42*(10), 1358-1364. https://doi.org/https://doi.org/10.1016/j.neuropsychologia.2004.02.011

Salvato, G., Sedda, A., & Bottini, G. (2014). In search of the disappeared half of it: 35 years of studies on representational neglect. *Neuropsychology*, *28*(5), 706.

Sampanis, D., & Riddoch, J. (2013). Motor Neglect and Future Directions for Research [Opinion]. *Frontiers in Human Neuroscience*, *7*. https://doi.org/10.3389/fnhum.2013.00110

Samson, D., Apperly, I. A., Braithwaite, J. J., Andrews, B. J., & Bodley Scott, S. E. (2010). Seeing it their way: evidence for rapid and involuntary computation of what other people see. *Journal of*

Experimental Psychology: Human Perception and Performance, *36*(5), 1255.
Samuelsson, H., Hjelmquist, E., Jensen, C., Ekholm, S., & Blomstrand, C. (1998). Nonlateralized attentional deficits: an important component behind persisting visuospatial neglect? *Journal of Clinical and Experimental Neuropsychology*, *20*(1), 73-88.
Santiesteban, I., Catmur, C., Hopkins, S. C., Bird, G., & Heyes, C. (2014). Avatars and arrows: Implicit mentalizing or domain-general processing? *Journal of Experimental Psychology: Human Perception and Performance*, *40*(3), 929.
Sauer, J., Sonderegger, A., & Schmutz, S. (2020). Usability, user experience and accessibility: towards an integrative model. *Ergonomics*, *63*(10), 1207-1220.
Sbordone, R. J. (2008). Ecological validity of neuropsychological testing: critical issues. *The neuropsychology handbook*, *367*, 394.
Schaefer, S., & Schumacher, V. (2011). The interplay between cognitive and motor functioning in healthy older adults: findings from dual-task studies and suggestions for intervention. *Gerontology*, *57*(3), 239-246. https://doi.org/10.1159/000322197
Schenkenberg, T., Bradford, D., & Ajax, E. (1980). Line bisection and unilateral visual neglect in patients with neurologic impairment. *Neurology*, *30*(5), 509-509.
Scherder, E., Dekker, W., & Eggermont, L. (2008). Higher-level hand motor function in aging and (preclinical) dementia: its relationship with (instrumental) activities of daily life--a mini-review. *Gerontology*, *54*(6), 333-341. https://doi.org/10.1159/000168203
Schlaghecken, F., & Eimer, M. (2002). Motor activation with and without inhibition: Evidence for a threshold mechanism in motor control. *Perception & Psychophysics*, *64*(1), 148-162.
Schmand, B. (2019). Why are neuropsychologists so reluctant to embrace modern assessment techniques? *The Clinical Neuropsychologist*, *33*(2), 209-219.
Schmuckler, M. (2001). What Is Ecological Validity? A Dimensional Analysis. *Infancy*, *2*. https://doi.org/10.1207/S15327078IN0204_02
Schober, P., & Vetter, T. R. (2021). Linear Mixed-Effects Models in Medical Research. *Anesthesia & Analgesia*, *132*(6). https://journals.lww.com/anesthesia-analgesia/fulltext/2021/06000/linear_mixed_effects_models_in_medical_research.13.aspx
Schrepp, M. (2015). User experience questionnaire handbook. *All you need to know to apply the UEQ successfully in your project*.
Schrepp, M. (2023). *UEQ-Online websites*. https://www.ueq-online.org/
Schrepp, M., Hinderks, A., & Thomaschewski, J. (2014). Applying the user experience questionnaire (UEQ) in different evaluation scenarios. Design, User Experience, and Usability. Theories, Methods, and Tools for Designing the User Experience: Third International Conference, DUXU 2014, Held as Part of HCI International 2014, Heraklion, Crete, Greece, June 22-27, 2014, Proceedings, Part I 3,

Schrepp, M., Thomaschewski, J. r., & Hinderks, A. (2017). Construction of a benchmark for the user experience questionnaire (UEQ).
Schultheis, M., & Rizzo, A. (2001). The application of virtual reality technology in rehabilitation. *Rehabilitation Psychology*, *46*, 296-311. https://doi.org/10.1037/0090-5550.46.3.296
Schultheis, M. T., Himelstein, J., & Rizzo, A. A. (2002). Virtual reality and neuropsychology: upgrading the current tools. *The Journal of head trauma rehabilitation*, *17*(5), 378-394.
Scott, S. H., & Dukelow, S. P. (2011). Potential of robots as next-generation technology for clinical assessment of neurological disorders and upper-limb therapy. *Journal of Rehabilitation Research & Development*, *48*(4).
Seo, K., Kim, J.-k., Oh, D. H., Ryu, H., & Choi, H. (2017). Virtual daily living test to screen for mild cognitive impairment using kinematic movement analysis. *PLoS ONE*, *12*(7), e0181883.
Servotte, J.-C., Goosse, M., Campbell, S. H., Dardenne, N., Pilote, B., Simoneau, I. L., Guillaume, M., Bragard, I., & Ghuysen, A. (2020). Virtual Reality Experience: Immersion, Sense of Presence, and Cybersickness. *Clinical Simulation in Nursing*, *38*, 35-43. https://doi.org/https://doi.org/10.1016/j.ecns.2019.09.006
Shadmehr, R., & Holcomb, H. H. (1999). Inhibitory control of competing motor memories. *Experimental Brain Research*, *126*, 235-251.
Shen, J., Xiang, H., Luna, J., Grishchenko, A., Patterson, J., Strouse, R. V., Roland, M., Lundine, J. P., Koterba, C. H., & Lever, K. (2020). Virtual reality–based executive function rehabilitation system for children with traumatic brain injury: design and usability study. *JMIR serious games*, *8*(3), e16947.
Shenal, B., Rhodes, R., Moore, T., Higgins, D., & Harrison, D. (2001). Quantitative electroencephalography (QEEG) and neuropsychological syndrome analysis. *Neuropsychology Review*, *11*, 31-44.
Sherman, E., Brooks, B., Iverson, G., Slick, D., & Strauss, E. (2011). Reliability and Validity in Neuropsychology. https://doi.org/10.1007/978-0-387-76978-3_30
Shiber, J. R., Fontane, E., & Adewale, A. (2010). Stroke registry: hemorrhagic vs ischemic strokes. *The American Journal of Emergency Medicine*, *28*(3), 331-333. https://doi.org/https://doi.org/10.1016/j.ajem.2008.10.026
Shimada, H., Makizako, H., Doi, T., Park, H., Tsutsumimoto, K., Verghese, J., & Suzuki, T. (2018). Effects of Combined Physical and Cognitive Exercises on Cognition and Mobility in Patients With Mild Cognitive Impairment: A Randomized Clinical Trial. *J Am Med Dir Assoc*, *19*(7), 584-591. https://doi.org/10.1016/j.jamda.2017.09.019
Shou, Y., Sellbom, M., & Chen, H.-F. (2022). 4.02 - Fundamentals of Measurement in Clinical Psychology. In G. J. G. Asmundson (Ed.), *Comprehensive Clinical Psychology (Second Edition)* (pp. 13-35). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-12-818697-8.00110-2

Shrout, P. E., & Fleiss, J. L. (1979). Intraclass correlations: uses in assessing rater reliability. *Psychological bulletin*, *86*(2), 420.
Shute, V. J., & Rahimi, S. (2017). Review of computer-based assessment for learning in elementary and secondary education. *Journal of Computer Assisted Learning*, *33*(1), 1-19.
Siekierka-Kleiser, E., Kleiser, R., Wohlschläger, A., Freund, H.-J., & Seitz, R. (2006). Quantitative assessment of recovery from motor hemineglect in acute stroke patients. *Cerebrovascular Diseases*, *21*(5-6), 307-314.
Sinanović, O., Mrkonjić, Z., Zukić, S., & Vidović, M. (2011). Post-stroke language disorders. *Acta Clinica Croatica*, *50*(1), 79-93.
Singer, R. N., DeFrancesco, C., & Randal, L. E. (1989). Effectiveness of a Global Learning Strategy Practiced in Different Contexts on Primary and Transfer Self-Paced Motor Tasks. *Journal of Sport and Exercise Psychology*, *11*(3), 290-303. https://doi.org/10.1123/jsep.11.3.290
Singh, S., & Germine, L. (2021). Technology meets tradition: a hybrid model for implementing digital tools in neuropsychology. *International Review of Psychiatry*, *33*(4), 382-393. https://doi.org/10.1080/09540261.2020.1835839
Sisk, C. A., Remington, R. W., & Jiang, Y. V. (2019). Mechanisms of contextual cueing: A tutorial review. *Attention, Perception, & Psychophysics*, *81*(8), 2571-2589. https://doi.org/10.3758/s13414-019-01832-2
Smania, N., Martini, M., Gambina, G., Tomelleri, G., Palamara, A., Natale, E., & Marzi, C. (1998). The spatial distribution of visual attention in hemineglect and extinction patients. *Brain: a journal of neurology*, *121*(9), 1759-1770.
Song, J.-H., & Nakayama, K. (2006). Role of focal attention on latencies and trajectories of visually guided manual pointing. *Journal of Vision*, *6*(9), 11-11.
Song, J.-H., & Nakayama, K. (2008). Target selection in visual search as revealed by movement trajectories. *Vision Research*, *48*(7), 853-861. https://doi.org/https://doi.org/10.1016/j.visres.2007.12.015
Southgate, V. (2020). Are infants altercentric? The other and the self in early social cognition. *Psychological review*, *127*(4), 505.
Spaccavento, S., Marinelli, C. V., Nardulli, R., Macchitella, L., Bivona, U., Piccardi, L., Zoccolotti, P., & Angelelli, P. (2019). Attention Deficits in Stroke Patients: The Role of Lesion Characteristics, Time from Stroke, and Concomitant Neuropsychological Deficits. *Behavioural Neurology*, *2019*, 7835710. https://doi.org/10.1155/2019/7835710
Specht, J., Schroeder, H., Krakow, K., Meinhardt, G., Stegmann, B., & Meinhardt-Injac, B. (2021). Acceptance of immersive head-mounted display virtual reality in stroke patients. *Computers in Human Behavior Reports*, *4*, 100141.
Spooner, D. M., & Pachana, N. A. (2006). Ecological validity in neuropsychological assessment: A case for greater consideration in research with neurologically intact populations. *Archives of Clinical*

Neuropsychology, *21*(4), 327-337. https://doi.org/https://doi.org/10.1016/j.acn.2006.04.004
Spreij, L. A., Gosselt, I. K., Visser-Meily, J. M., & Nijboer, T. C. (2020). Digital neuropsychological assessment: Feasibility and applicability in patients with acquired brain injury. *Journal of Clinical and Experimental Neuropsychology*, *42*(8), 781-793.
Spreij, L. A., Visser-Meily, J. M. A., Sibbel, J., Gosselt, I. K., & Nijboer, T. C. W. (2022). Feasibility and user-experience of virtual reality in neuropsychological assessment following stroke. *Neuropsychological rehabilitation*, *32*(4), 499-519. https://doi.org/10.1080/09602011.2020.1831935
Sreedharan, S. E., Unnikrishnan, J., Amal, M., Shibi, B., Sarma, S., & Sylaja, P. (2013). Employment status, social function decline and caregiver burden among stroke survivors. A South Indian study. *Journal of the Neurological Sciences*, *332*(1-2), 97-101.
St. Jacques, P. L., & Iriye, H. (2022). Putting things into perspective. In (Vol. 34, pp. 1-8): Taylor & Francis.
Stapleton, T., Ashburn, A., & Stack, E. (2001). A pilot study of attention deficits, balance control and falls in the subacute stage following stroke. *Clinical Rehabilitation*, *15*(4), 437-444.
Stein, J. F. (1992). The representation of egocentric space in the posterior parietal cortex. *Behavioral and Brain Sciences*, *15*(4), 691-700. https://doi.org/10.1017/S0140525X00072605
Strasburger, H. (2020). Seven myths on crowding and peripheral vision. *i-Perception*, *11*(3), 2041669520913052.
Strauss, E., Sherman, E. M., & Spreen, O. (2006). *A compendium of neuropsychological tests: Administration, norms, and commentary*. American chemical society.
Striemer, C. L., Ferber, S., & Danckert, J. (2013). Spatial working memory deficits represent a core challenge for rehabilitating neglect. *Frontiers in Human Neuroscience*, *7*, 334.
Suh, K.-S., & Lee, Y. E. (2005). The effects of virtual reality on consumer learning: An empirical investigation. *MIS quarterly*, 673-697.
Sullivan, K., & Bowden, S. C. (1997). Which tests do neuropsychologists use? *Journal of Clinical Psychology*, *53*(7), 657-661.
Sun, J. H., Tan, L., & Yu, J. T. (2014). Post-stroke cognitive impairment: epidemiology, mechanisms and management. *Ann Transl Med*, *2*(8), 80. https://doi.org/10.3978/j.issn.2305-5839.2014.08.05
Surtees, A., Apperly, I., & Samson, D. (2013). Similarities and differences in visual and spatial perspective-taking processes. *Cognition*, *129*(2), 426-438. https://doi.org/https://doi.org/10.1016/j.cognition.2013.06.008
Sveistrup, H. (2004). Motor rehabilitation using virtual reality. *J Neuroeng Rehabil*, *1*(1), 10. https://doi.org/10.1186/1743-0003-1-10
Swift, A., Heale, R., & Twycross, A. (2020). What are sensitivity and specificity? *Evidence-Based Nursing*, *23*(1), 2-4.
Takamura, Y., Fujii, S., Ohmatsu, S., Morioka, S., & Kawashima, N. (2021). Pathological structure of visuospatial neglect: A

comprehensive multivariate analysis of spatial and non-spatial aspects. *iScience*, *24*(4), 102316. https://doi.org/https://doi.org/10.1016/j.isci.2021.102316

Tan, W., Xu, Y., Liu, P., Liu, C., Li, Y., Du, Y., Chen, C., Wang, Y., & Zhang, Y. (2021). A method of VR-EEG scene cognitive rehabilitation training. *Health information science and systems*, *9*, 1-9.

Tanaka, T., Sugihara, S., Nara, H., Ino, S., & Ifukube, T. (2005). A preliminary study of clinical assessment of left unilateral spatial neglect using a head mounted display system (HMD) in rehabilitation engineering technology. *Journal of NeuroEngineering and Rehabilitation*, *2*(1), 1-9.

Tatemichi, T., Desmond, D., Stern, Y., Paik, M., Sano, M., & Bagiella, E. (1994). Cognitive impairment after stroke: frequency, patterns, and relationship to functional abilities. *Journal of Neurology, Neurosurgery & Psychiatry*, *57*(2), 202-207.

Technologies, U. (n.d.-a). *Food Pack - Mixed*. https://assetstore.unity.com/packages/3d/props/food/food-pack-mixed-154349

Technologies, U. (n.d.-b). *Modern Supermarket*. https://assetstore.unity.com/packages/3d/environments/modern-supermarket-186122

Ten Brink, A. F., Biesbroek, J. M., Oort, Q., Visser-Meily, J. M. A., & Nijboer, T. C. W. (2019). Peripersonal and extrapersonal visuospatial neglect in different frames of reference: A brain lesion-symptom mapping study. *Behavioural Brain Research*, *356*, 504-515. https://doi.org/https://doi.org/10.1016/j.bbr.2018.06.010

Tennant, L. K., Murray, N. P., & Tennant, L. M. (2004). Effects of strategy use on acquisition of a motor task during various stages of learning. *Perceptual and motor skills*, *98*(3_suppl), 1337-1344.

Terruzzi, S., Albini, F., Massetti, G., Etzi, R., Gallace, A., & Vallar, G. (2023). The Neuropsychological Assessment of Unilateral Spatial Neglect Through Computerized and Virtual Reality Tools: A Scoping Review. *Neuropsychology Review*. https://doi.org/10.1007/s11065-023-09586-3

Theeuwes, J. (2010). Top–down and bottom–up control of visual selection. *Acta psychologica*, *135*(2), 77-99.

Thomas, L. E., & Lleras, A. (2009). Inhibitory tagging in an interrupted visual search. *Attention, Perception, & Psychophysics*, *71*(6), 1241-1250.

Thomas, T., & Sunny, M. M. (2017). Altered Visuo-spatial Processing in the Peri-personal Space: A New Look at the Hand-Proximity Effects. *Journal of the Indian Institute of Science*, *97*(4), 443-450. https://doi.org/10.1007/s41745-017-0057-x

Timmerer, C. (2017). Immersive Media Delivery: Overview of Ongoing Standardization Activities. *IEEE Communications Standards Magazine*, *1*(4), 71-74. https://doi.org/10.1109/MCOMSTD.2017.1700038

Tipper, S. P., Howard, L. A., & Jackson, S. R. (1997). Selective reaching to grasp: Evidence for distractor interference effects. *Visual Cognition*, *4*(1), 1-38.
Toba, M. N., Rabuffetti, M., Duret, C., Pradat-Diehl, P., Gainotti, G., & Bartolomeo, P. (2018). Component deficits of visual neglect: “Magnetic” attraction of attention vs. impaired spatial working memory [Article]. *Neuropsychologia*, *109*, 52-62. https://doi.org/10.1016/j.neuropsychologia.2017.11.034
Tong, T., & Chignell, M. (2014). Developing a serious game for cognitive assessment: choosing settings and measuring performance. Proceedings of the second international symposium of Chinese CHI,
Tong, T., Chignell, M., Tierney, M. C., & Lee, J. (2016). A serious game for clinical assessment of cognitive status: validation study. *JMIR serious games*, *4*(1), e5006.
Toro, C., Deuschl, G., & Hallett, M. (2000). Movement-related electroencephalographic desynchronization in patients with hand cramps: evidence for motor cortical involvement in focal dystonia. *Annals of Neurology: Official Journal of the American Neurological Association and the Child Neurology Society*, *47*(4), 456-461.
Tosi, A., Pickering, M. J., & Branigan, H. P. (2020). Speakers' use of agency and visual context in spatial descriptions. *Cognition*, *194*, 104070. https://doi.org/https://doi.org/10.1016/j.cognition.2019.104070
Treisman, A., & Sato, S. (1990). Conjunction search revisited. *Journal of experimental psychology: human perception and performance*, *16*(3), 459.
Treisman, A., & Souther, J. (1985). Search asymmetry: a diagnostic for preattentive processing of separable features. *Journal of Experimental Psychology: General*, *114*(3), 285.
Treisman, A. M., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive psychology*, *12*(1), 97-136.
Trepkowski, C., Eibich, D., Maiero, J., Marquardt, A., Kruijff, E., & Feiner, S. (2019, 2019). The effect of narrow field of view and information density on visual search performance in augmented reality.
Treviño, M., Zhu, X., Lu, Y. Y., Scheuer, L. S., Passell, E., Huang, G. C., Germine, L. T., & Horowitz, T. S. (2021). How do we measure attention? Using factor analysis to establish construct validity of neuropsychological tests. *Cognitive Research: Principles and Implications*, *6*(1), 1-26.
Tsirlin, I., Dupierrix, E., Chokron, S., Coquillart, S., & Ohlmann, T. (2009). Uses of virtual reality for diagnosis, rehabilitation and study of unilateral spatial neglect: review and analysis. *Cyberpsychology & behavior*, *12*(2), 175-181.
Tuena, C., Pedroli, E., Trimarchi, P. D., Gallucci, A., Chiappini, M., Goulene, K., Gaggioli, A., Riva, G., Lattanzio, F., Giunco, F., & Stramba-Badiale, M. (2020). Usability Issues of Clinical and Research Applications of Virtual Reality in Older People: A

Systematic Review [Systematic Review]. *Frontiers in Human Neuroscience*, *14*. https://doi.org/10.3389/fnhum.2020.00093

Tupper, D. E., & Cicerone, K. D. (1990). Introduction to the Neuropsychology of Everyday Life.

Turkeltaub, P. E., Goldberg, E. M., Postman-Caucheteux, W. A., Palovcak, M., Quinn, C., Cantor, C., & Coslett, H. B. (2014). Alexia due to ischemic stroke of the visual word form area. *Neurocase*, *20*(2), 230-235. https://doi.org/10.1080/13554794.2013.770873

Tversky, B., & Hard, B. M. (2009). Embodied and disembodied cognition: Spatial perspective-taking. *Cognition*, *110*(1), 124-129.

Tyryshkin, K., Coderre, A. M., Glasgow, J. I., Herter, T. M., Bagg, S. D., Dukelow, S. P., & Scott, S. H. (2014). A robotic object hitting task to quantify sensorimotor impairments in participants with stroke. *Journal of neuroengineering and rehabilitation*, *11*, 1-12.

Urbina, S. (2014). *Essentials of psychological testing*. John Wiley & Sons.

Uswatte, G., Taub, E., Morris, D., Vignolo, M., & McCulloch, K. (2005). Reliability and validity of the upper-extremity Motor Activity Log-14 for measuring real-world arm use. *Stroke*, *36*(11), 2493-2496.

Vakhnina, N., Nikitina, L. Y., Parfenov, V., & Yakhno, N. (2009). Post-stroke cognitive impairments. *Neuroscience and behavioral physiology*, *39*(8), 719.

Vakil, E. (2012). Neuropsychological assessment: Principles, rationale, and challenges. *Journal of Clinical and Experimental Neuropsychology*, *34*(2), 135-150. https://doi.org/10.1080/13803395.2011.623121

Valladares-Rodríguez, S., Pérez-Rodríguez, R., Anido-Rifón, L., & Fernández-Iglesias, M. (2016). Trends on the application of serious games to neuropsychological evaluation: A scoping review. *Journal of Biomedical Informatics*, *64*, 296-319. https://doi.org/https://doi.org/10.1016/j.jbi.2016.10.019

Vallar, G. (1998). Spatial hemineglect in humans. *Trends in Cognitive Sciences*, *2*(3), 87-97. https://doi.org/https://doi.org/10.1016/S1364-6613(98)01145-0

Vallar, G., & Caputi, N. (2022). The History of Human Neuropsychology. In S. Della Sala (Ed.), *Encyclopedia of Behavioral Neuroscience, 2nd edition (Second Edition)* (pp. 14-39). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-12-809324-5.23914-X

Vallar, G., Rusconi, M., Barozzi, S., Bernardini, B., Ovadia, D., Papagno, C., & Cesarani, A. (1995). Improvement of left visuo-spatial hemineglect by left-sided transcutaneous electrical stimulation. *Neuropsychologia*, *33*(1), 73-82.

Van der Stoep, N., Visser-Meily, J. M., Kappelle, L. J., de Kort, P. L., Huisman, K. D., Eijsackers, A. L., Kouwenhoven, M., Van der Stigchel, S., & Nijboer, T. C. (2013). Exploring near and far regions of space: distance-specific visuospatial neglect after stroke. *Journal of Clinical and Experimental Neuropsychology*, *35*(8), 799-811.

Van Zandvoort, M., Kessels, R., Nys, G., De Haan, E., & Kappelle, L. (2005). Early neuropsychological evaluation in patients with ischaemic stroke provides valid information. *Clinical neurology and neurosurgery*, *107*(5), 385-392.

Vanderploeg, R. D. (2014). *Clinician's guide to neuropsychological assessment*. Psychology Press.

VanGilder, J. L., Hooyman, A., Peterson, D. S., & Schaefer, S. Y. (2020). Post-stroke cognitive impairments and responsiveness to motor rehabilitation: A review. *Curr Phys Med Rehabil Rep*, *8*(4), 461-468. https://doi.org/10.1007/s40141-020-00283-3

Varnava, A., McCarthy, M., & Beaumont, J. G. (2002). Line bisection in normal adults: direction of attentional bias for near and far space. *Neuropsychologia*, *40*(8), 1372-1378. https://doi.org/https://doi.org/10.1016/S0028-3932(01)00204-4

Vecera, S. P., & Rizzo, M. (2003). Spatial attention: normal processes and their breakdown. *Neurol Clin*, *21*(3), 575-607. https://doi.org/10.1016/s0733-8619(02)00103-2

Verma, R., Arya, K. N., Sharma, P., & Garg, R. K. (2012). Understanding gait control in post-stroke: Implications for management. *Journal of Bodywork and Movement Therapies*, *16*(1), 14-21. https://doi.org/https://doi.org/10.1016/j.jbmt.2010.12.005

Verstraeten, S., Mark, R., & Sitskoorn, M. (2016). Motor and cognitive impairment after stroke: a common bond or a simultaneous deficit. *Stroke Research & Therapy*, *1*(1), 1.

Verstraeten, S., Mark, R. E., Dieleman, J., van Rijsbergen, M., de Kort, P., & Sitskoorn, M. M. (2020). Motor Impairment Three Months Post Stroke Implies A Corresponding Cognitive Deficit. *Journal of Stroke and Cerebrovascular Diseases*, *29*(10), 105119. https://doi.org/https://doi.org/10.1016/j.jstrokecerebrovasdis.2020.105119

Viau, A., Feldman, A. G., McFadyen, B. J., & Levin, M. F. (2004). Reaching in reality and virtual reality: a comparison of movement kinematics in healthy subjects and in adults with hemiparesis. *Journal of neuroengineering and rehabilitation*, *1*(1), 11. https://doi.org/10.1186/1743-0003-1-11

Vogeley, K., & Fink, G. R. (2003). Neural correlates of the first-person-perspective. *Trends in Cognitive Sciences*, *7*(1), 38-42. https://doi.org/https://doi.org/10.1016/S1364-6613(02)00003-7

Voinescu, A., Fodor, L.-A., Fraser, D. S., Mejías, M., & David, D. (2019). Exploring the usability of nesplora aquarium, a virtual reality system for neuropsychological assessment of attention and executive functioning. 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR),

von Salm-Hoogstraeten, S., Bolzius, K., & Müsseler, J. (2020). Seeing the world through the eyes of an avatar? Comparing perspective taking and referential coding. *Journal of Experimental Psychology: Human Perception and Performance*, *46*(3), 264.

Walsh, K. R., & Pawlowski, S. D. (2002). Virtual reality: A technology in need of IS research. *Communications of the Association for Information Systems*, *8*(1), 20.

Wang, C., Chen, X., & Knierim, J. J. (2020). Egocentric and allocentric representations of space in the rodent brain. *Current Opinion in Neurobiology*, *60*, 12-20. https://doi.org/https://doi.org/10.1016/j.conb.2019.11.005

Wattanasoontorn, V., Boada, I., García, R., & Sbert, M. (2013). Serious games for health. *Entertainment Computing*, *4*(4), 231-247. https://doi.org/https://doi.org/10.1016/j.entcom.2013.09.002

Wechsler, D., & Kodama, H. (1949). *Wechsler intelligence scale for children* (Vol. 1). Psychological corporation New York.

Weintraub, S., & Mesulam, M. M. (1988). Visual hemispatial inattention: stimulus parameters and exploratory strategies. *Journal of Neurology, Neurosurgery & Psychiatry*, *51*(12), 1481-1488.

Weir, J. P. (2005). Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *The Journal of Strength & Conditioning Research*, *19*(1), 231-240.

Weiss, P., & Katz, N. (2004). The potential of virtual reality for rehabilitation. *J Rehabil Res Dev*, *41*(5), 7-10.

Welsh, T. N., & Elliott, D. (2004). Movement trajectories in the presence of a distracting stimulus: Evidence for a response activation model of selective reaching. *The Quarterly Journal of Experimental Psychology Section A*, *57*(6), 1031-1057.

Welsh, T. N., Elliott, D., & Weeks, D. J. (1999). Hand deviations toward distractors Evidence for response competition. *Experimental Brain Research*, *127*(2), 207-212.

Wen, D., Lan, X., Zhou, Y., Li, G., Hsu, S.-H., & Jung, T.-P. (2018). The Study of Evaluation and Rehabilitation of Patients With Different Cognitive Impairment Phases Based on Virtual Reality and EEG [Opinion]. *Frontiers in Aging Neuroscience*, *10*. https://doi.org/10.3389/fnagi.2018.00088

Wilken, J., Kane, R., Sullivan, C., Wallin, M., Usiskin, J., Quig, M., Simsarian, J., Saunders, C., Crayton, H., & Mandler, R. (2003). The utility of computerized neuropsychological assessment of cognitive dysfunction in patients with relapsing-remitting multiple sclerosis. *Multiple Sclerosis Journal*, *9*(2), 119-127.

Wilkinson, M., Brantley, S., & Feng, J. (2021). A mini review of presence and immersion in virtual reality. Proceedings of the Human Factors and Ergonomics Society Annual Meeting,

Wilson, B., Cockburn, J., & Halligan, P. (1987). Development of a behavioral test of visuospatial neglect. *Archives of physical medicine and rehabilitation*, *68*(2), 98-102.

Wilson, C. J., & Soranzo, A. (2015). The Use of Virtual Reality in Psychology: A Case Study in Visual Perception. *Computational and mathematical methods in medicine*, *2015*, 151702. https://doi.org/10.1155/2015/151702

Witsken, D. E., D'Amato, R. C., & Hartlage, L. C. (2008). Understanding the past, present, and future of clinical neuropsychology. *Essentials of neuropsychological assessment: Treatment planning for rehabilitation*, 3-29.

Wohlgenannt, I., Simons, A., & Stieglitz, S. (2020). Virtual Reality. *Business & Information Systems Engineering*, *62*(5), 455-461. https://doi.org/10.1007/s12599-020-00658-9
Wolfe, J. M., Cave, K. R., & Franzel, S. L. (1989). Guided search: an alternative to the feature integration model for visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *15*(3), 419.
Wolfe, J. M., & Pokorny, C. W. (1990). Inhibitory tagging in visual search: A failure to replicate. *Perception & Psychophysics*, *48*(4), 357-362.
Woodford, H. J., & George, J. (2007). Cognitive assessment in the elderly: a review of clinical methods. *QJM: An International Journal of Medicine*, *100*(8), 469-484. https://doi.org/10.1093/qjmed/hcm051
Wu, S., & Keysar, B. (2007). The effect of culture on perspective taking. *Psychological science*, *18*(7), 600-606.
Wulf, G., Hossener, E., & Wenderoth, N. (2007). Gabriele Wulf on attentional focus and motor learning. *E-journal Bewegung und Training*, *1*, 1-64.
Wulf, G., & Weigelt, C. (1997). Instructions about physical principles in learning a complex motor skill: To tell or not to tell…. *Research quarterly for exercise and sport*, *68*(4), 362-367.
Yang, M.-L., Yang, C.-C., & Chiou, W.-B. (2010). When guilt leads to other orientation and shame leads to egocentric self-focus: Effects of differential priming of negative affects on perspective taking. *Social Behavior and Personality: an international journal*, *38*(5), 605-614.
Yen, M., & Lo, L.-H. (2002). Examining test-retest reliability: an intra-class correlation approach. *Nursing research*, *51*(1), 59-62.
Zaehle, T., Jordan, K., Wüstenberg, T., Baudewig, J., Dechent, P., & Mast, F. W. (2007). The neural basis of the egocentric and allocentric spatial frame of reference. *Brain Research*, *1137*, 92-103. https://doi.org/https://doi.org/10.1016/j.brainres.2006.12.044
Zang, X., Zinchenko, A., Wu, J., Zhu, X., Fang, F., & Shi, Z. (2022). Contextual cueing in co-active visual search: Joint action allows acquisition of task-irrelevant context. *Attention, Perception, & Psychophysics*, *84*(4), 1114-1129. https://doi.org/10.3758/s13414-022-02470-x
Zhang, C., & Lu, Y. (2021). Study on artificial intelligence: The state of the art and future prospects. *Journal of Industrial Information Integration*, *23*, 100224. https://doi.org/https://doi.org/10.1016/j.jii.2021.100224
Zhang, H., & Pan, J. S. (2022). Visual search as an embodied process: The effects of perspective change and external reference on search performance. *Journal of Vision*, *22*(10), 13-13.
Zheng, J., Chan, K., & Gibson, I. (1998). Virtual reality. *Ieee Potentials*, *17*(2), 20-23.
Zhonggen, Y. (2019). A meta-analysis of use of serious games in education over a decade. *International Journal of Computer Games Technology*, *2019*.

Zimmermann, P., & Fimm, B. (1995a). Test for attentional performance (TAP). *PsyTest, Herzogenrath*, *1995*, 76-77.
Zimmermann, P., & Fimm, B. (1995b). Test for attentional performance (TAP). *PsyTest, Herzogenrath*, *1995*, 76-77.
Zimmermann, P., & Fimm, B. (2004). A test battery for attentional performance. In *Applied neuropsychology of attention* (pp. 124-165). Psychology Press.
Zucchella, C., Capone, A., Codella, V., Vecchione, C., Buccino, G., Sandrini, G., Pierelli, F., & Bartolo, M. (2014). Assessing and restoring cognitive functions early after stroke. *Funct Neurol*, *29*(4), 255-262.
Zygouris, S., Giakoumis, D., Votis, K., Doumpoulakis, S., Ntovas, K., Segkouli, S., Karagiannidis, C., Tzovaras, D., & Tsolaki, M. (2015). Can a virtual reality cognitive training application fulfill a dual role? Using the virtual supermarket cognitive training application as a screening tool for mild cognitive impairment. *Journal of Alzheimer's Disease*, *44*(4), 1333-1347.

SECTEUR DES SCIENCES HUMAINES
FACULTE DE PSYCHOLOGIE ET DES SCIENCES DE L'EDUCATION

INSTITUT DE RECHERCHE EN SCIENCES PSYCHOLOGIQUES

PROMOTEURS :
PROFESSEUR MARTIN GARETH EDWARDS
PROFESSEUR THIERRY LEJEUNE

Khawla AJANA est née à Mohammedia, au Maroc, en 1995. Passionnée par les sciences comportementales, elle a commencé une licence en psychologie à l'Université Hassan II en 2014. Par la suite, elle a rejoint l'Université Sorbonne Paris-Nord pour approfondir ses connaissances en psychologie cognitive et en méthodologie de recherche scientifique. Ensuite, elle a intégré l'Université de Bordeaux, où elle a obtenu un Master en sciences cognitives et en ergonomie.
Son intérêt pour les sciences cognitives et les nouvelles technologies s'est développé tout au long de son parcours académique et professionnel. En 2019, elle a rejoint l'UCLouvain pour entamer un doctorat en sciences psychologiques, sous la supervision des professeurs Martin Gareth Edwards et Thierry Lejeune.

L'évaluation neuropsychologique a subi des changements significatifs en réponse aux critiques des tests papier-crayon. Ces critiques, qui portent sur l'effet d'entrainement et une faible validité écologique entre-autres, ont précipité l'adoption de nouvelles approches. Cette urgence est d'autant plus évidente dans le cadre de la prise en charge des troubles cognitifs chez des patients ayant survécu à un accident vasculaire cérébral. Ceci en raison de l'impact que l'évaluation initiale des troubles cognitifs peut avoir sur leur développement. De plus, ces méthodes traditionnelles ne parviennent pas à capturer la complexité du fonctionnement cognitif, comme dans le cas d'une héminégligence. Les nouvelles technologies, telle que la réalité virtuelle immersive, sont une solution potentielle à ces limitations. Cette thèse a pour objectif de contribuer à l'amélioration de la qualité de l'évaluation neuropsychologique, et à la compréhension des troubles cognitifs dû à un accident vasculaire cérébral. Deux nouveaux jeux sérieux en réalité immersive sont présentés dans cette thèse. Chacun de ces jeux a été conçu pour évaluer des composantes distinctes du fonctionnement cognitif. En outre, dans cette thèse la faisabilité, validité, et l'expérience utilisateur des deux jeux sérieux. Enfin, nous discutons les avantages et les limites de ces jeux sérieux, ainsi que les perspectives futures.

Neuropsychological assessment has undergone significant changes in response to criticisms of paper and pencil tests. These criticisms include practice effects and poor ecological validity and have prompted a need for transformative approaches. This urgency becomes more evident in the context of measuring stroke individuals' performance changes during neurorehabilitation programs, where practice improvements can confound treatment outcomes. Moreover, these traditional methods fail to capture the complexity of cognitive functioning, such as hemineglect. New technologies, such as immersive virtual reality have the potential to address these limitations. This thesis aims to contribute to enhancing the quality of neuropsychological assessment, and to bring new insights into understanding post-stroke cognitive impairment. Throughout this thesis, two novel serious games in immersive virtual environments were introduced. Each of these games was designed to assess distinct components of cognitive functioning. Additionally, this thesis investigated the feasibility, validity, and user experience for the two serious games. Finally, the advantages and limitations of our serious games, as well future perspectives are discussed.