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RESEARCH ARTICLE

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

Khawla Ajana[a,b], Gauthier Everard[b,c], Thierry Lejeune[b,c,d] and Martin Gareth Edwards[a,b]

[a]Secteur Des Sciences Humaines, Institut de recherche en sciences psychologiques (IPSY), Université Catholique de Louvain, Louvain-la-Neuve, Belgium; [b]Louvain Bionics, Université Catholique de Louvain, Louvain-la-Neuve, Belgium; [c]Secteur des Sciences de la Santé, Institut de Recherche Expérimentale et Clinique, Neuro Musculo Skeletal Laboratory (NMSK), Université catholique de Louvain, Brussels, Belgium; [d]Cliniques universitaires Saint-Luc, Service de médecine physique et réadaptation, Brussels, Belgium

ABSTRACT

Background: Treisman (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 variance 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.

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KEYWORDS
Visual search; serious game; spatial attention; inhibition; executive function; kinematics; immersive virtual reality

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., color 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,

CONTACT Martin Gareth Edwards martin.edwards@uclouvain.be Institute for Research in Psychological Sciences (IPSY), Université Catholique de Louvain, Place Cardinal Mercier 10, bte L3.05.01, B1348 LouvainlaNeuve, Belgium.
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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 color.

Importantly, Triesman and Gelade (Treisman & 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 color 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 et al., 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 modeling 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 behavior 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 (Treisman & 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 contralesional compared to ipsilesional 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.

Methods

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.

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 modeling 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 24 molehills (4 × 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 colored 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 (70 hz), 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 6 × 4 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).

Procedure

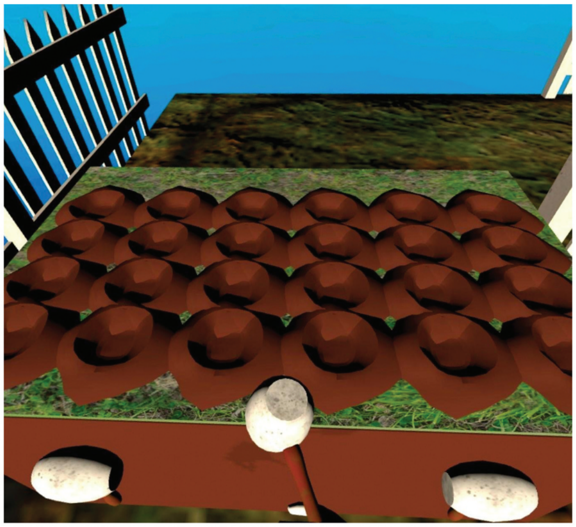
The study was run in a controlled laboratory at the Psychological Sciences Research Institute of the University of Louvain and in the Cliniques universitaires Saint-Luc, Brussels. The total test session lasted

1 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 six 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.

Methods of data analyses

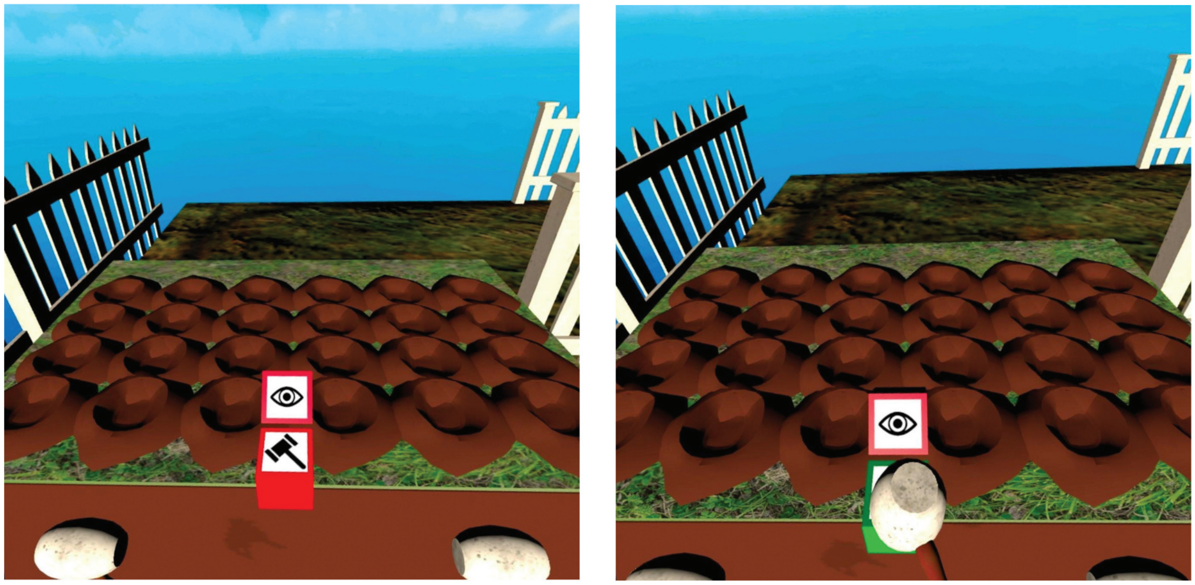
Data analyses were performed using SPSS 27.0 (IBM) and repeated measures of ANOVAs. The independent variables were search task (feature vs conjunction search), distractors (11, 17, and 23), and laterality (ipsilateral vs contralateral space relative to the dominant hand response). Ipsilateral space was 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 analyzed 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 10 Hz cutoff frequency filter. Three-dimensional controller positions were then plotted by time to visually ensure that data had been correctly acquired.

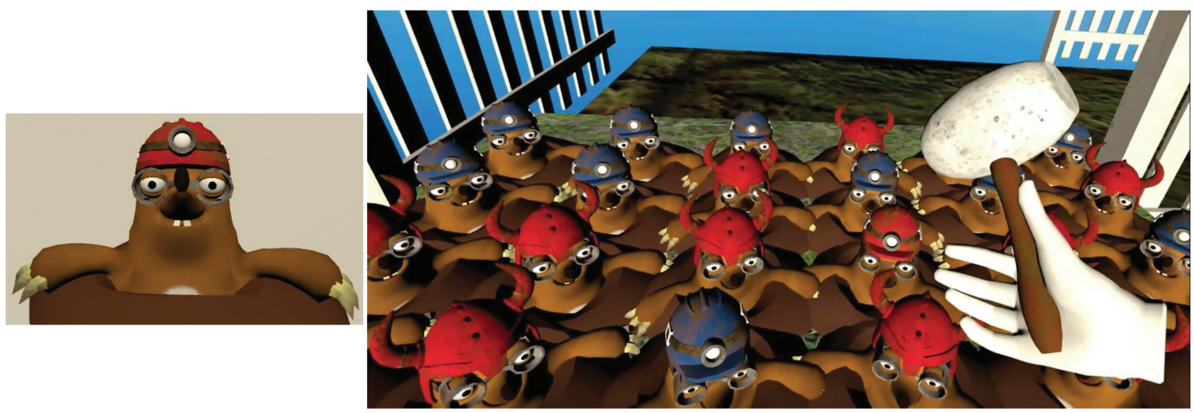


(a)

Figure 1. (a) The mole target and distractor stimuli were presented within a 4×6 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; (b) 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; (c) 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.



(b)



(c)

Figure 1. (Continued).

From the total data set (i.e., 144 trials × 58 participants; 8352 trials), 195 error responses to distractor stimuli (2.3%) and 265 trials showing omissions (3.2%) were removed. 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.

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

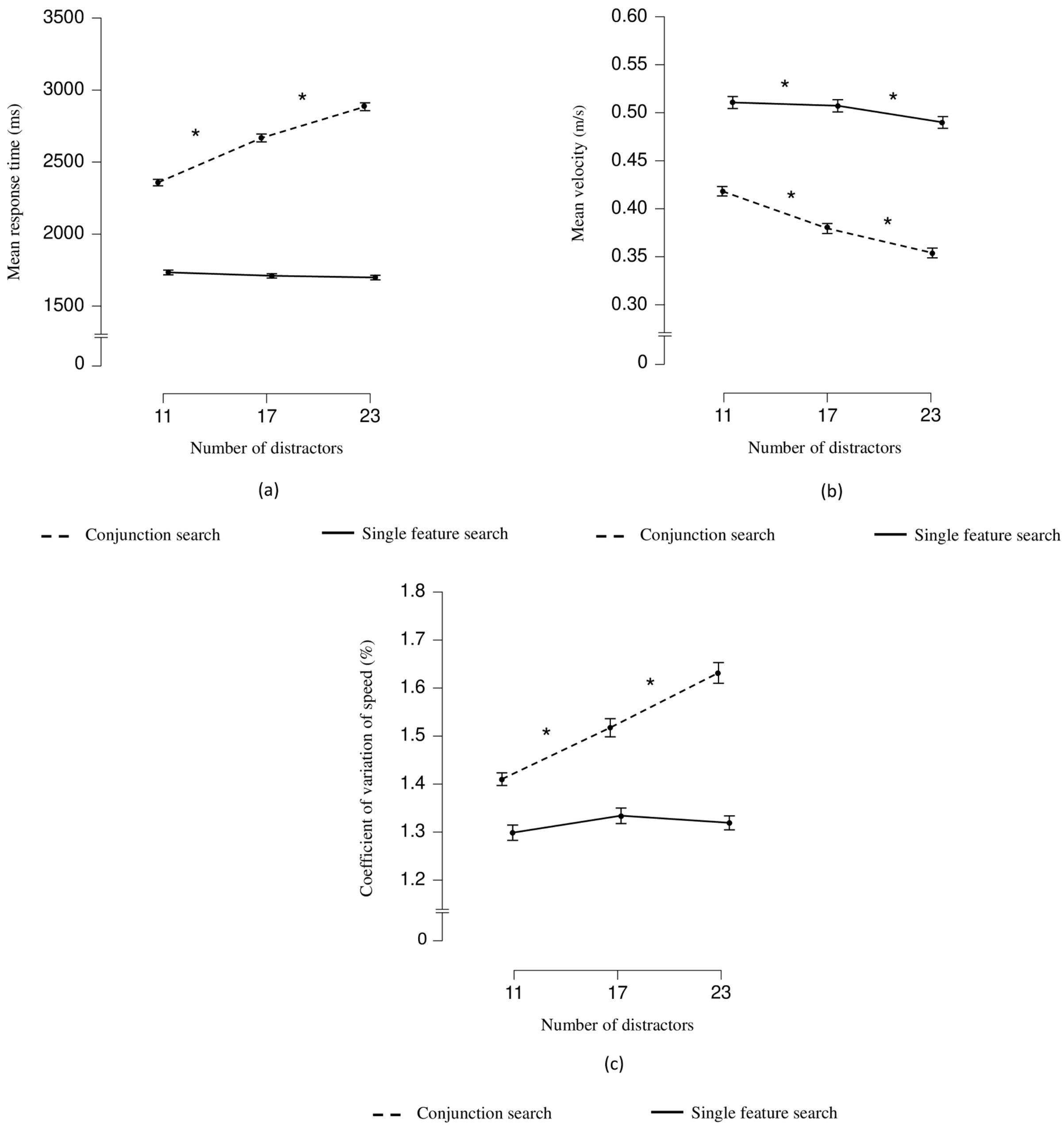


Figure 2. (a) Mean response time (milliseconds) to single feature versus conjunction feature target-distractor stimuli with 11, 17, or 23 distractors. (b) Mean velocity (meter per second) to single feature versus conjunction feature target-distractor stimuli with 11, 17, or 23 distractors. The error 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.

laterality, F (1,57) = 0.05, p = 0.83, η^2 = 0.001. As predicted, there was a significant interaction between search task and distractors, F (2,114) = 117.58, p < 0.001, η^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, η^2 = 0.034, but it was significant in the conjunction search task, F (2,114) = 149.16, p < 0.001, η^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 (see Supplementary Materials 1).

The analysis of mean velocity (MV) showed a main effect of search task, F (1,57) = 386.40, p < 0.001, η^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.

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 color 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/color 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 contralesional 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., 2022; 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 (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.

Data availability statement

The raw data that support the findings of this study are openly available in the open data archive of University of Louvain (https://dataverse.uclouvain.be/dataset.xhtml?persistentId=doi:10.14428/DVN/1BKFA6).

Ethics approval and consent to participate

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. The Saint-Luc-UCLouvain-Hospital-Faculty Ethics Committee approved the study (reference number:2015/10FEV/053).

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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