At the crossroads of numerical codes

Behavioral and neurophysiological investigation of the automatic access to magnitude representation and integration

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Résumé

Dès leur plus jeune âge, les êtres humains ont la capacité de percevoir et de manipuler des quantités « non-symboliques » dans leur environnement (e.g., •••). Cette aptitude repose sur deux systèmes préverbaux: un premier pour le traitement exact des petites numérosités (jusqu'à quatre) et un deuxième pour représenter approximativement les grandes numérosités (au-delà de quatre). Alors que ces deux systèmes sont présents chez d'autres espèces animales, les êtres humains possèdent également une capacité unique à représenter les nombres grâce à un système symbolique et abstrait (e.g., "trois", "3"). Au début de l'apprentissage du système symbolique, les configurations canoniques de points (e.g., celles présentes sur les cartes à jouer) et de doigts (e.g., celles utilisées dans une culture pour compter sur ses doigts) semblent jouer un rôle fondamental dans l'association entre les symboles et les quantités. Cependant, peu d'études jusqu'à présent se sont intéressées au traitement de ces configurations canoniques (voir *Chapitre 1*). Cette thèse a pour objectif d'apporter de nouvelles connaissances sur ces configurations, leur base cérébrale et leur intégration avec les autres codes numériques. Pour commencer, les corrélats neuronaux sous-tendant le traitement des configurations canoniques furent étudiés grâce à un paradigme électrophysiologique (EEG) de stimulation visuelle rapide. Cela permit de montrer que ces configurations étaient spontanément discriminées des représentations non-canoniques, suggérant un accès plus rapide à la magnitude qu'elles représentent (*Chapitre 2*). En combinant le paradigme EEG avec une présentation multi-codes, il a ensuite été montré que les configurations canoniques de points, de doigts, les chiffres arabes et les mots-nombres convergeaient vers une représentation commune de la magnitude, au sein des régions pariéto-occipitales du cerveau (*Chapitre 3*). Ce processus semble toutefois dépendre des ressources cognitives engagées dans un traitement numérique (*Chapitre 4*). Enfin, en vue de dépasser certaines limites méthodologiques auxquelles d'autres études se sont confrontées (e.g., l'instruction, la présentation des stimuli), un nouveau paradigme comportemental visant à

examiner l’intégration entre les codes numériques a été mis au point (*Chapitre 5*). Celui-ci permit de confirmer la présence d’un effet de distance inter-notations, soutenant l’existence d’une représentation commune aux quantités canoniques et aux chiffres. Dans l’ensemble, les résultats repris dans cette thèse (discutés dans le *Chapitre 6*) mettent en évidence les processus à la fois spécifiques et communs aux représentations des différents codes numériques.

Abstract

Very early in life, humans have the ability to perceive and manipulate non-symbolic numerical magnitudes in their environment (e.g., •••). This capacity is thought to be supported by two core systems: one for the exact processing of small numerosities (up to four) and another one for the approximate representation of large numerosities (beyond four). While humans share these core numerical systems with many species, they also possess a unique ability to represent numbers with an abstract symbolic code (e.g., the number word “three” and the Arabic digit “3”). At the start of learning symbolic numerals, canonical dot arrays (e.g., such as dice faces or playing cards) and canonical finger configurations (e.g., culture-typical patterns of raised fingers to count a specific number) were assumed to play a foundational role in the association between symbols and quantities. In the current literature, however, most studies have focused on the integration of non-symbolic and symbolic magnitude representations, leaving aside the canonical configurations of dots and fingers (see *Chapter 1*). The aim of the current thesis is to provide novel insight into those specific numerical codes, their cerebral basis and their integration with other symbolic representations. First, the neural correlates of canonical dot and finger processing were examined with a fast periodic visual stimulation (FPVS) paradigm and electrophysiological recordings. Canonical configurations were found to be spontaneously discriminated from non-canonical patterns, supporting a more automatic access to their magnitude representation (*Chapter 2*). Then, by combining the FPVS paradigm with a multi-code presentation, it was shown that canonical dot patterns, canonical finger configurations, Arabic digits and number words converged into a shared magnitude representation within the parieto-occipital regions of the brain (*Chapter 3*). Yet, this magnitude integration was found to depend on the cognitive resources devoted to numerical processing (*Chapter 4*). Finally, to overcome some methodological limitations of previous studies (e.g., instruction, stimulus presentation), an original behavioral paradigm was proposed for investigating the integration of canonical

quantities and symbolic numerals (*Chapter 5*). Using this paradigm, results confirmed the presence of a cross-notational distance effect, further supporting the existence of a common representation for canonical quantities and digits. Overall, the findings reported in this thesis (discussed in *Chapter 6*) highlight both specific and common processes for the representation of several numerical codes.

Table of contents

Résumé **5**

Abstract **7**

Acknowledgments **13**

Chapter 1. General Introduction **17**

1 Developmental trajectory of number representations 19

1.1 The non-symbolic format and the approximate number system *20*

1.2 The acquisition of the symbolic format and the exact number system *24*

1.3 A third iconic format to link non-symbolic and symbolic number representations *28*

2 Neurophysiological research on numerical formats 32

2.1 Neural correlates during explicit numerical judgment tasks *32*

2.2 Implicit measures of magnitude representation *36*

2.3 Common magnitude representation within the parietal cortex? *40*

3 Research objectives and outline of the PhD thesis 42

4 References 45

Chapter 2. Canonical representations of fingers and dots trigger an automatic activation of number semantics: an EEG study on 10-year-old children **59**

1 Introduction 61

2 Methods 65

2.1 Participants *65*

2.2 Behavioral naming task *66*

2.3 EEG task *69*

2.4 EEG data acquisition and analysis *70*

3 Results 72

3.1 Naming results *72*

3.2 EEG results *76*

4 Discussion 79

5 References 85

Chapter 3. A shared numerical magnitude representation evidenced by the distance effect in frequency-tagging EEG 93

1 Introduction 95

2 Methods 101

2.1 Participants 101

2.2 Stimuli 101

2.3 EEG procedure 102

2.4 EEG acquisition and preprocessing 102

2.5 EEG frequency domain analyses 103

2.6 Behavioral comparison task 104

3 Results 105

3.1 EEG responses 105

3.2 Behavioral results 109

3.3 Brain-behavior correlations 110

4 Discussion 112

5 References 116

6 Appendix: Data analysis of uni-code and intra-format presentations 122

6.1 Uni-code presentations 122

6.2 Intra-format presentations 127

6.3 Discussion 131

6.4 References 135

Chapter 4. Frequency-tagging EEG reveals instruction-driven magnitude integration using the numerical distance effect 137

1 Introduction 139

2 Methods 142

2.1 Participants 142

2.2 EEG procedure 143

2.3 EEG acquisition and preprocessing 144

2.4 EEG frequency domain analyses 145

3 Results 146

3.1 General visual responses 146

3.2 Discrimination responses ... *147*
4 Discussion ... 148
5 References ... 153
Chapter 5. Quantities and digits activate a common distance-related representation of magnitude: evidence from a behavioral matching task ... 157
1 Introduction ... 159
2 Methods ... 164
2.1 Participants ... *164*
2.2 Stimuli ... *164*
2.3 Procedure ... *165*
3 Results ... 167
3.1 Follow-up analyses: size congruency ... *168*
3.2 Follow-up analyses: digit smaller vs. larger than quantity ... *171*
4 Discussion ... 173
5 References ... 178
Chapter 6. General Discussion ... 181
1 Summary of the research context and general aims ... 181
2 Overview of the main findings ... 184
3 Discussion and future research directions ... 188
3.1 The way of canonical configurations ... *188*
3.2 A role for canonical representations in the acquisition of numerical symbols? ... *194*
3.3 Hemispheric asymmetry in the neural underpinnings of magnitude processing ... *199*
3.4 Fast Periodic Visual Stimulation, a powerful paradigm to measure automatic numerical processing? ... *204*
3.5 Can we use the distance effect as a marker of magnitude access? ... *210*
4 Conclusions ... 214
5 References ... 215

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Chapter 1. General Introduction

As humans living in a numerate society, we must every day deal with numerical information presented under various codes and contexts. While waiting in the queue for the fitting room, we quickly estimate the number of pieces we have after reading the sign that says "limited to 10 items". We can easily write down the age of a child when he proudly raises four fingers, or get to square 5 in the goose game when our dice shows five points. All of these activities seem automatic, effortless, and yet they represent one of the greatest challenges a child must face to develop future mathematical skills. Why does it seem so natural to process numerical information, and yet so difficult at the same time? Numbers may seem easy because they are supported by an innate numerical sense. Within a few weeks of their birth, human infants are already capable to perceive numerical information in their environment (Feigenson et al., 2004). However, it becomes complicated when numbers go beyond the limits of this intuitive system. As children grow up, they will gradually be involved in more complex numerical processes that require the use of a sophisticated symbolic code. Unlike the first innate system, this cultural construct must be learned and it will take several years for children to master it (Carey and Barner, 2019). Eventually, infants will come to understand that the word "*five*" they hear (or read) represents the same quantity as the five birds they see in the sky, which also correspond to the drawing of the abstract symbol "*5*". Hence, a full comprehension of numbers involves binding together these numerical representations and one fascinating related matter, to which this PhD thesis is devoted, is to uncover the mechanisms behind this process.

The first aim of this PhD thesis was to provide new insights about a specific numerical format composed by structured dot patterns (e.g., those found on dices or playing cards) and finger-counting configurations (e.g., raising the thumb, index and major fingers to represent "3"). Because of their "canonical" or "iconic" nature, these configurations can be represented more precisely than unstructured patterns and may facilitate the access to magnitude representation (Mandler & Shebo, 1982; Di Luca et al., 2008). It was accordingly assumed that both canonical dot and finger configurations may be beneficial for the acquisition of the symbolic format (i.e., number words and Arabic digits; Kreilinger et al., 2022). Yet, while a substantial amount of behavioral studies suggested that canonical dot and finger representations provide a more automatic access to magnitude than non-canonical patterns, the current literature lacks of studies examining their cerebral basis. The first study in this thesis (described in *Chapter 2*) therefore investigates the neural correlates of canonical dot and finger processing. To this aim, 10-year-old children were presented with a frequency-tagging electrophysiological (EEG) paradigm and a behavioral experiment. *Chapter 2* presents the results of both tasks and how they relate to each other. Commonalities and differences between canonical finger and dot representations are also discussed.

A second aim of this PhD thesis was to investigate whether canonical number representations are automatically integrated with other symbolic numerical codes. Despite the considerable efforts made to assess the existence of a shared magnitude representation, reports of previous research do not converge towards a consistent conclusion (e.g., Bulthé et al., 2014; Piazza et al., 2007). Furthermore, these studies have focused solely on the integration of non-symbolic and symbolic number representations. In *Chapters 3 & 4*, we propose a novel approach to examine the common underlying magnitude of iconic and symbolic notations. This approach is based on the combination of a frequency-tagging EEG paradigm, with a multi-code presentation (i.e., Arabic digits, number words, canonical finger configurations, canonical dot patterns) and the distance effect as an indicator of magnitude access (Dehaene et al., 1998). *Chapter 3* develops the methodological and empirical arguments that led to the elaboration of this experimental design. Findings reported in this study shed new light on the brain's ability to integrate magnitude information across Arabic digits, number words, canonical dot and finger configurations. Following the results of *Chapter 3*, the next study of this thesis (*Chapter 4*) aims at questioning the spontaneous nature of such magnitude integration process: does it occur whenever individuals are exposed to numbers and quantities? Or only when they are explicitly engaged in magnitude processing? Using the same multi-code EEG design as in *Chapter 3*, new data was collected from adults while varying their attentional focus to (1) no explicit numerical processing, (2) explicitly oriented processing of parity and (3) explicitly oriented processing of magnitude. Finally, the last study of this thesis (*Chapter 5*) develops a novel integrative paradigm where both quantities and symbols are presented simultaneously in the form of a same-different matching task. Adult participants were presented with canonical arrays of digits and had to indicate whether the quantity of digits and the digit value were equal (matched) or unequal (mismatched). They were expected to show better performance in identifying mismatched configurations that depicted a large difference between the quantity and the digit (= 4) compared to those with a close difference (=1). Such a distance effect in their performance would support a shared magnitude representation for canonical quantities and symbolic digits.

The present chapter aims to set the theoretical context for this PhD thesis, providing the main concepts, theories and assumptions that led to the specific research questions. The first part gives an overview of the formats and systems humans have to represent numbers, how they develop, how they interact and how they relate to future mathematical achievement. The second part is dedicated to neurophysiological research and reviews the main findings about how the human brain processes and integrates numerical information. Finally, a brief introduction of the studies reported in *Chapters 2-5* is provided at the end of the chapter.

1 Developmental trajectory of number representations

Humans share with other species the ability to manipulate (e.g., compare, estimate) *non-symbolic* quantities (e.g., set of items/dots). This capacity is thought to be supported by two core (preverbal) systems: an approximate number system (ANS) for processing large quantities and a parallel individuation system (PIS) for fast and accurate processing of small numerosities (1-4). Over the course of development, children will gradually acquire a language-based *symbolic* number system. This system relies on the use of abstract symbols (e.g., Arabic digits, number words) to represent exact numerical quantities. Consequently, children must learn to map these new symbols on their non-symbolic representations and several accounts exist in the literature to explain how this mapping occurs. Furthermore, canonical configurations (e.g., dice-like dot patterns, finger-counting) have been argued to provide an "in-between" or *iconic* representation of numbers favoring the occurrence of this acquisition. The following sections give an overview of how these numerical codes develop and interact with each other.

1.1 The non-symbolic format and the approximate number system

Very early in life, humans can rely on an approximate sense of number to process (e.g., understand, estimate or compare) non-symbolic quantities. This capacity exists across ages, cultures and animal species, therefore suggesting that the ANS has a long phylogenetic history (Odic & Starr, 2018). A few months after birth, human babies are indeed already able to distinguish between arrays of dots (Xu & Spelke, 2000), sequences of sounds (Lipton & Spelke, 2003) and sequences of actions (Wood & Spelke, 2005). For instance, Xu and Spelke (2000) habituated 6-month-old infants with one constant number of dots, varying in size and location, until their looking time decreased. Then, babies were presented with a different number of dots that lead to a rebound in their fixation time and indicated that the novel numerosity was successfully discriminated (Xu & Spelke, 2000). Newborns were even found to associate auditory sequences of repeated syllables with images containing the same number of items, suggesting that the ANS holds an abstract, modality-independent, representation of numerosity (Izard et al., 2009). Because members of cultures with limited or no numerical vocabulary are also able to compare large approximate numbers (Frank et al., 2008; Pica et al., 2004), the ANS was assumed to develop before *and* independently of language. Further supporting the non-verbal nature of the ANS, several animal species were shown to deal with non-symbolic numerosities

(Mehlis et al., 2015). As examples, fishes rely on numerosity discrimination to join the largest social group (Mehlis et al., 2015), coyotes can distinguish between two sets of food items to select the greatest quantity (Baker et al., 2011), and even newborn chicks are capable of small numerosity discriminations (Rugani et al., 2013). Finally, the ANS can develop in the absence of visual and verbal input, as congenitally blind individuals and deaf signers were found to rely on the ANS to represent non-symbolic quantities (see Buyle et al., 2021, for a review on numerical processing in blind and deaf individuals).

Although the ANS is universally present, its accuracy can vary from one individual to another. In school-aged children, adolescents and adults, ANS precision is usually measured by briefly presenting non-symbolic arrays of dots (for the visual modality), fast enough so that they cannot be counted. Participants have then to make numerical estimation (using number words) or to compare it with another array of dots presented simultaneously or subsequently (Odic & Starr, 2018). The accuracy of the ANS is then determined by the most difficult ratio that an individual can successfully discriminate. The ANS indeed follows the Weber-Fechner's law, which typically manifests in discrimination performances by two effects (fig. 1): the distance effect, referring to a decrease in performance as the absolute distance between the numerosities to be compared decreases, and the size effect, indicating that for equal distance, performance also decreases with increasing number size (Dehaene, 2003; Moyer & Landauer, 1967; Whalen et al., 1999). The distance and size effects result from the representation of quantities by the ANS (fig. 1), which is assumed to resemble Gaussian distributions organized on a left-to-right oriented and logarithmically compressed Mental Number Line (MNL, Feigenson et al., 2004; Ren et al., 2022). Consequently, the more the numerosity representations overlap, the harder they are to discriminate. Our ability to discriminate two numerosities thus depends on the ratio (i.e., the relative distance) between them.

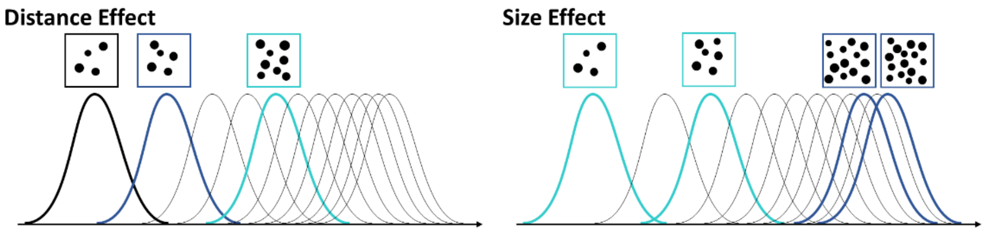

Figure 1. ANS numerical representations on the MNL. Quantities are represented in the form of Gaussian distributions. The more the representations overlap, the harder the discrimination is. Therefore, discriminating between the numerosities “4” and “5” is more complicated than between “4” and “8” (i.e., the distance effect); and discriminating between “4” and “6” is easier than between “13” and “15” although they are separated by the same absolute distance (i.e., the size effect). The ratio corresponds to the relative distance between numerosities, thus reflecting the combination of the distance and size effects.

Acuity of the ANS increases over the life span. At 6-months of age, infants are able to discriminate arrays of 8 *versus* 16 and 16 *versus* 32 dots, thus a ratio of 1:2 (Xu & Spelke, 2000; Xu et al., 2005). They however fail when the ratio is reduced to 2:3 (i.e., 8 *versus* 12 and 16 *versus* 24), while 9-month-olds succeed (Xu & Arriaga, 2007). As children grow up, the ANS acuity continues to increase gradually until it reaches discrimination performance at a ratio of 9:10 in adulthood (Halberda & Feigenson, 2008). Nonetheless, there can be large individual differences in discrimination performances. It was indeed found that among 14-year-old adolescents, some presented difficulties to discriminate numerical ratios finer than 2:3, whereas others could achieve a ratio of 9:10 (Halberda et al., 2008). Importantly, Halberda and colleagues (2008) showed that individuals’ ANS acuity related to their mathematics achievement, a finding that has been replicated in many subsequent studies (see Chen & Li, 2014 and Schneider et al., 2017 for reviews on the associations between ANS and math competencies). For instance, Starr and colleagues (2013) found that 6-month-old infants’ number sense correlated with their mathematical abilities 3 years later. The ANS precision was therefore assumed to be a strong predictor of later mathematical achievement. Critically, even when other factors contributing to children’s mathematical development are considered, such as inhibitory control and home environment, the ANS continues to play a unique role in predicting early mathematical skills (Silver et al., 2020).

However, the ANS is not the only system humans possess to represent non-symbolic quantities. When asked to enumerate as fast and accurately as possible the number of dots displayed on a screen, adults were found to perform nearly perfectly for the numerosities 1-4, after which performance sharply declined with increasing numerosity (fig. 2; Kaufman et al., 1949; Krajcsi et al., 2013; Mandler & Shebo, 1982). The source of this discontinuity between the processing of small numerosity sets (< 4), referred to as subitizing, and large sets (> 4) has been the focus of much discussion (Piazza et al., 2011). Among the first theories, it was for example suggested that configurations of up to four objects create recognizable visual patterns (e.g., 2 dots form a line, 3 dots a triangle, 4 dots a quadrilateral) enabling fast and precise quantification through a pattern recognition system (Mandler & Shebo, 1982; Krajcsi et al., 2013). Hence, the process of subitizing would be very similar to the mechanism of visual Gestalt perception, referring to a holistic form of object processing where individual elements are visually integrated into a global entity (Benoit et al., 2004, Bloechle et al., 2018a; Navon, 1977). Accordingly, small dot patterns could be estimated holistically without serial counting of local elements (Bloechle et al., 2018a). Nowadays, a much more widespread and accepted theory is that small and large numerosity sets rely on two distinct representational systems. Rather than being estimated by the ANS, small numerosities are assumed to depend on a parallel individuation system (PIS) dedicated to multiple objects processing (Piazza et al., 2011, Trick & Pylyshyn, 1994). Other non-numerical functions, such as visual working memory, also rely on the PIS and exhibit the same capacity limit of 3-4 items. It was accordingly found that the maintenance of a few items in the visual working memory reduced the subitizing capacity. However, loading the visual working memory did not decrease the precision of large numerosity discriminations, further supporting the idea that small and large numerosities are processed by independent systems (Piazza et al., 2011).

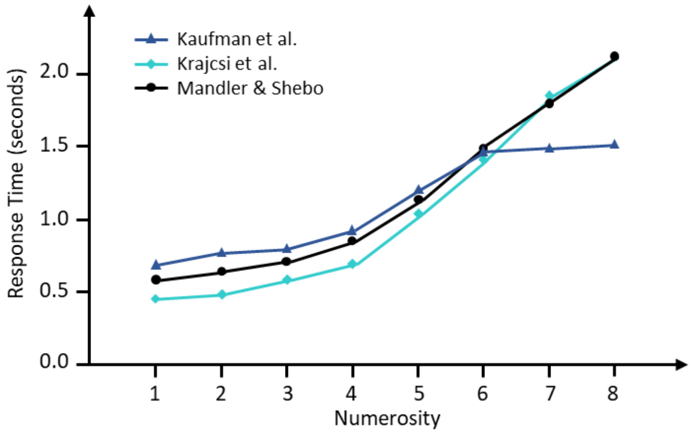

Figure 2. Subitizing. Adapted results from Kaufman et al. (1949; dark blue triangles), Krajcsi et al. (2013; light blue diamonds) and Mandler & Shebo (1982; black circles). Mean response time needed to give the magnitude of a dot array as a function of its numerosity. Response times start to increase sharply after the subitizing range (after 4).

1.2 The acquisition of the symbolic format and the exact number system

Unlike the ANS and the PIS, which are assumed to be present from birth (Feigenson et al., 2004), the exact number system requires explicit teaching and learning of symbolic codes (e.g., Arabic digits and number words). This is because such codes are intrinsically abstract, since they do not convey any numerical information *per se*. For several decades now, researchers have been interested in the question of how symbols gain their meaning, also known as the "symbol grounding problem". A long-standing theory, referred to as the ANS mapping account, states that symbols gain their meaning by being mapped onto their approximate non-symbolic representation (Dehaene, 1997). Accordingly, several studies have shown that the efficiency (or accuracy) of the symbol-to-magnitude mapping is predictive of good mathematical abilities over and above the ANS acuity (Brankaer et al., 2014;

Holloway & Ansari, 2009; Jang and Cho, 2018; Libertus et al., 2016; Mundy & Gilmore, 2009; Pinheiro-Chagas et al., 2014). For instance, Mundy and Gilmore (2009) evaluated children's digit-dot mapping ability with a forced-choice quantity matching task. They showed that the children were able to map symbolic and non-symbolic numerical representations and that this capacity was related to their mathematical achievement, more than their performance in single format (i.e., digits only or dots only) comparison tasks. In the same line, the precision of 5- to 7-year-old children's mapping between the ANS and number words, measured by the variability in verbal number estimations, was found to predict their formal math abilities (Libertus et al., 2016). Recently, Jang and Cho (2018) highlighted the importance of an accurate mapping between symbolic numerals and their corresponding ANS magnitude for the development of mathematical competences. They showed that mapping precision contributed to arithmetic abilities in children and served higher complex quantitative reasoning in adults. This difference between children and adults was interpreted by the authors as reflecting different levels of mathematical expertise. On the one hand, children in the early stage of acquiring the quantitative meaning of numerical symbols may be highly dependent on the symbol-magnitude correspondence when working with symbolic numbers. On the other hand, adults who have mastered the symbolic code may rely less on the ANS mapping and more on symbolic principles (e.g., ordinality and symbol-symbol associations) to solve simple calculations (Lyons et al., 2014). However, they appeared to keep relying on the symbol-to-magnitude mapping for more complex quantitative reasoning (Jang and Cho, 2018).

A second line of evidence in favor of the symbol-to-magnitude mapping is the finding that a similar distance effect emerges when human adults compare both symbolic and non-symbolic numerical magnitudes (Dehaene et al., 1990; Holloway & Ansari, 2008; Moyer & Landauer, 1967; Sasanguie et al., 2012). For instance, Van Opstal and Verguts (2011) observed that adults were faster to judge whether an Arabic digit and a number word were equal or not when the two numerals represented distant magnitudes than closer ones. Given that any pair of arbitrary symbols should be as discriminable, these findings were taken as evidence that symbolic numerals automatically activate their corresponding non-symbolic magnitude (Dehaene, 2001; Feigenson et al., 2013; Piazza, 2010). However, a parallel line of research considered this argument insufficient to state that non-symbolic and symbolic magnitudes were commonly represented by the ANS (see Reynvoet & Sasanguie, 2016 for a review). Instead, it could be that the two formats are processed by separate systems producing similar distance-related effects (Krajcsi et al., 2016). Using a primed naming task, Roggeman and colleagues (2007) demonstrated differential coding of symbolic and non-symbolic numerosities. Participants were briefly presented with a prime, after which they had to indicate the quantity of a target numerosity. Primes and targets were either Arabic digits or dot arrays, and the distance between the prime and target values varied across trials. While digit primes were found to affect target values around the prime as a function of distance, leading to a V-shape priming pattern (see also Reynvoet et al., 2002), dot primes affected all target values smaller or equal to the prime, resulting in a stepwise curve (fig. 3a). These findings led to the conclusion that symbolic and non-symbolic numerosities are represented by qualitatively different coding mechanisms: a place coding for digits and a summation coding for dot arrays (fig. 3b). In the place coding scheme, a digit activates its corresponding representation with a maximal strength, but also activates neighboring number representations with decreasing strength; whereas in the summation coding scheme, a dot array activates a segment of the mental number line that includes the complete range of number representations up to target quantity (Roggeman et al., 2007).

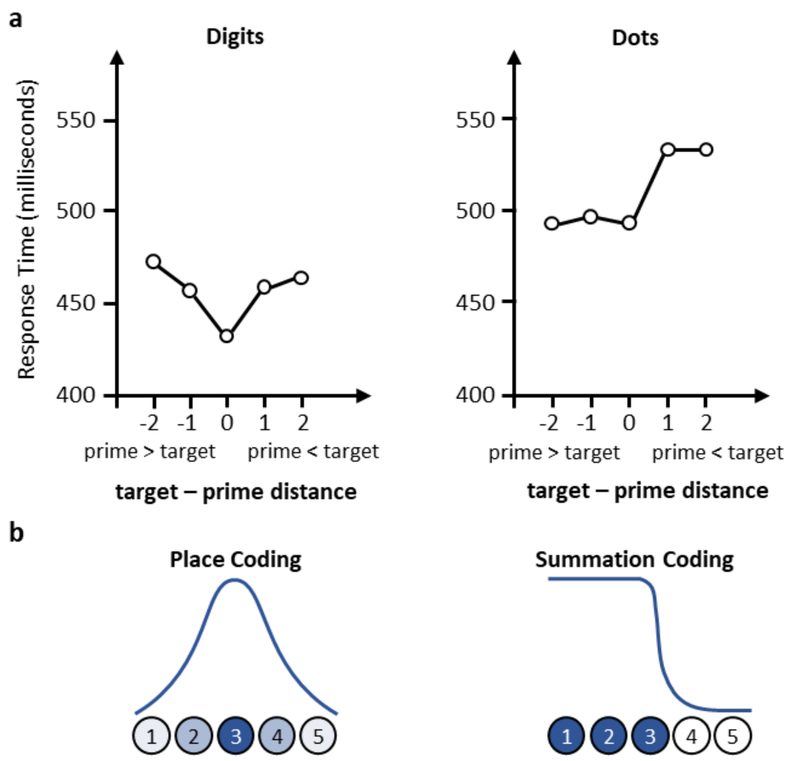

Figure 3. Different priming patterns (a) reflect different coding mechanisms (b) for digits and dots. Adapted results from Roggeman et al. (2007). **(a)** Mean response time needed to give the magnitude of a digit (left panel) or a dot array (right panel) as a function of the prime-target distance. The digit priming pattern forms a V-shape curve whereas the dot priming pattern forms a stepwise curve. These priming patterns were assumed to reflect a Place coding for digits and a Summation coding for dots **(b)**. In the Place code scheme, a digit activates its representation with a maximal strength and also the neighboring numbers with decreasing strength. In the Summation code scheme, a dot array activates the entire range of quantities below it with equivalent strength.

An alternative hypothesis of how symbols gain their meaning proposes that the correspondence between non-symbolic and symbolic numerosities does occur, but only for the numerical range 1-4 (Carey and Barner, 2019). Several findings indeed supported that children first succeed in mapping number words and digits to small dot arrays (1-3) before they acquire the meaning of larger numbers (4-6, Benoit et al., 2004, 2013). It was therefore suggested that the association between small symbolic and non-symbolic numerosities is supplied by the PIS rather than the ANS. Once children have acquired the cardinal meaning of the first number words, they progressively extend their knowledge to larger numbers through the learning of counting procedures and the use of exact algorithms such as the successor principle (i.e., every number, *N*, as a successor, *N+1*, Carey and Barner, 2019). Crucially, this implies that neither small or large symbolic numbers acquisition depend on the ANS. Instead, it considers that two separate representational systems underly the processing of large non-symbolic and symbolic numerosities, one approximate and one exact. This alternative account for the acquisition of symbolic numbers has serious implications for studies investigating the relation between numerical representations and mathematical abilities. It seems indeed reasonable to assume that the exact symbolic system would be a better candidate than the ANS for predicting future mathematical achievement. In support with this view, Honoré and Noël (2016) compared the effects of a non-symbolic and a symbolic training on arithmetic abilities among preschool children. The training consisted in a number comparison and a number line positioning tasks, with either dot arrays (for the non-symbolic training) or Arabic digits (for the symbolic training). Although both trainings led to significant benefits in magnitude processing, greater improvement in calculation was found for the children who underwent the symbolic training, compared to those who were trained with non-symbolic numerosities. These findings therefore support that symbolic and non-symbolic numerosities are represented by distinct systems and challenge the major role of the ANS in mathematical development.

1.3 A third iconic format to link non-symbolic and symbolic number representations

Despite the unresolved question of whether non-symbolic and symbolic magnitudes are represented together or apart, it is clear that the acquisition of the exact number system is an essential step for the development of mathematical competences (Jang and Cho, 2018). The use of canonical finger configurations, that is, configurations typically used in a culture to count (e.g., thumb, index and middle finger for “3”) or to show numerosities (e.g., index and middle finger for “2”), may facilitate this process by providing concrete referents for ordinal and cardinal number representations (Butterworth, 1999; Gunderson et al., 2015; Soylu et al., 2018; Van den Berg et al., 2022). These configurations simultaneously exhibit the properties of the non-symbolic format, as the magnitude conveyed by a configuration is expressed by the quantity of fingers raised, and those of the symbolic format, as a set of raised fingers in a learned canonical pattern allows for a direct recognition of the magnitude it represents (Di Luca & Pesenti, 2011). Support for this latter assumption can be found in several behavioral studies which showed that canonical finger configurations are more efficiently enumerated and processed by children than other finger configurations (Lafay et al., 2013; Noël et al., 2005). Canonical finger configurations are therefore considered to possess a specific iconic status that provides a bridge between children’s non-symbolic and symbolic numerical representations (Andres et al., 2008; Di Luca & Pesenti, 2011; Fayol & Seron, 2005; Gunderson et al., 2015). In a longitudinal study, Van Rinsveld and colleagues (2020a) highlighted the link between kindergartens’ performance in enumerating canonical finger configurations and their numerical representation accuracy one year later. Importantly, the predictive value of finger patterns recognition was extended beyond the finger-counting range, thereby supporting the idea that fingers serve as an intermediate stage toward the exact symbolic system through the comprehension of the cardinal principle. Accordingly, it was recently demonstrated that canonical finger configurations efficiently support and facilitate the understanding of the cardinal meaning of number words (Orrantia et al., 2022).

Besides the evidence provided by these developmental studies, several findings in adults showed that canonical finger configurations maintain their facilitating role throughout life and do not disappear when the symbolic numerical representation is acquired (Di Luca & Pesenti, 2011). As for children (Lafay et al., 2013; Noël et al., 2005), adults were indeed found to better enumerate canonical finger configurations than non-canonical ones and to make faster magnitude judgments on Arabic digits when primed with canonical finger configurations (Di Luca & Pesenti, 2008). It was further demonstrated that canonical configurations generate a priming effect of the place coding type, affecting smaller and larger magnitudes around the prime as a function of the distance (Di Luca et al., 2010). On the contrary, non-canonical configurations activated a summation coding representation, equally priming all magnitudes up to the prime value. Di Luca and Pesenti (2010) also showed that the facilitating effect provided by canonical finger configurations could not be accounted for by visuo-perceptual differences (e.g., fingers are always grouped/adjacent in canonical configurations but not necessarily in non-canonical ones). While participants had to decide whether or not a canonical configuration was present among a set of non-canonical distractors representing the same magnitude (fig. 4), their detection time increased with the number of distractors. The authors therefore concluded that the canonical configurations did not benefit from a perceptual salience among non-canonical configurations, regardless of the non-canonical structure (i.e., grouped or ungrouped; Di Luca & Pesenti, 2010). Finally, Badets and colleagues (2010) extended the facilitating effect of canonical finger configurations to the arithmetic domain, by showing that adults were faster to solve simple addition problems when the solution was associated with a correct finger configuration than with a correct set of rods.

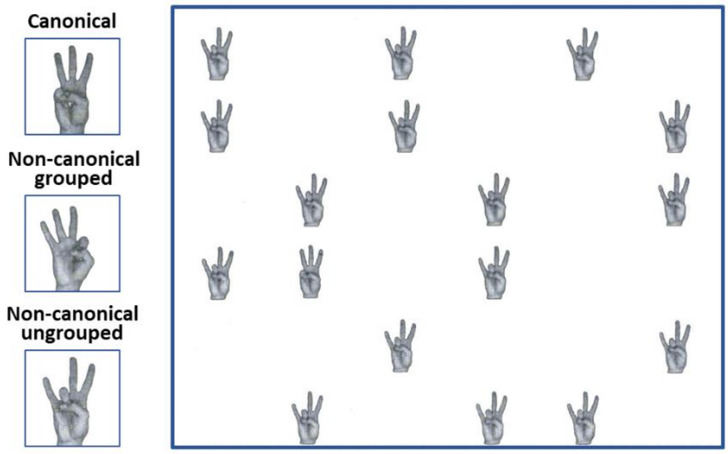

Figure 4. Illustration of the task proposed by Di Luca and Pesenti (2010). Canonical configurations were the target and non-canonical configurations, either grouped or ungrouped, were the distractors. Both target and distractors depicted the same numerosity (in this example: "3"). The task consisted of pressing a key to indicate the presence or absence of the target (in this example: presence). Response times increased with the number of distractors, showing that canonical configurations do not enjoy any visual salience (pop-out effect).

Iconic numerical representations can also be instantiated by canonical configurations of dots, such as those found on dices or playing cards. Although these dot configurations were less extensively studied, there is available evidence that canonical dot patterns can be faster and more accurately processed than random dot configurations in both children (Benoit et al., 2004; Jansen et al., 2014) and adults (Mandler & Shebo, 1982; Wender & Rothkegel, 2000; Wolters et al., 1987). Interestingly, this facilitating effect was found to extend the limitation of the subitizing range to more than four elements (Mandler & Shebo, 1982; Jansen et al., 2004; Krajcsi et al., 2013). As for canonical finger configurations (Van Rinsveld et al., 2020a), Kreilinger and colleagues (2022) observed in a longitudinal study that children's ability to enumerate canonical dot configurations predicted their cardinality understanding, assessed by their performance in a "give a number" task:

children got a bag of marbles and were asked to give the investigator specific numbers of marbles (e.g., “can you give me six marbles?”). In addition, canonical dot configurations may allow children to recognize the relationships between quantities through decomposition in smaller set (e.g., two rows of three dots are making six; Kreilinger et al., 2021). Accordingly, it was found that mastery of canonical dot configurations predicted children’s arithmetic performances (Kreilinger et al., 2021). Overall, these findings therefore suggest that both canonical dot and finger configurations play a major role in the acquisition of the symbolic code and early mathematical skills, presumably through facilitating the comprehension of the cardinality principle (Kreilinger et al., 2021).

2 Neurophysiological research on numerical formats

Along with the behavioral investigation of numerical representations and their link with mathematical achievement, a substantial amount of neuroimaging studies has examined the cerebral basis underlying numerical processing. The following sections first review findings on the brain structures recruited when people are explicitly engaged in numerical judgment tasks, and then provide an overview of implicit paradigms allowing for objective measures of numerical representations in the absence of response-selection processes.

2.1 Neural correlates during explicit numerical judgment tasks

From the end of the 20th century onwards, considerable efforts have been devoted to the identification of the brain regions involved in quantification processes. One of the most influential neuroanatomical frameworks, namely the Triple Code Model (TCM; Dehaene, 1992) posits the existence of three interconnected neural representations: a non-symbolic magnitude representation (i.e., dot arrays), a visual number form (i.e., Arabic digits) and a verbal word frame (i.e., number words). According to the TCM, the parietal cortex, and more specifically the bilateral intraparietal sulci (IPS, fig. 5), holds the representation of the non-symbolic code and has a pivotal role in the processing of numerical magnitude (see Dehaene et al., 2003 for a review). Therefore, the model assumes that both symbolic codes converge to the IPS to gain their meaning, but through different pathways: the occipito-temporal regions for Arabic digits, the perisylvian areas and left angular gyrus for number words (Dehaene & Cohen, 1995). Consistent with this hypothesis, several neuroimaging studies have found that the IPS activity level was modulated by the numerical distance effect during comparative judgments, both with non-symbolic (e.g., Ansari & Dhital, 2006; Castelli et al., 2006; Eger et al., 2015; Kucian et al., 2011) and symbolic magnitudes (e.g., Ansari et al., 2006; Kaufmann et al., 2005; Liu et al., 2006; Pinel et al., 2001). For instance, using functional magnetic resonance imaging (fMRI), Ansari and Dhital (2006) reported stronger blood oxygenation level dependent (BOLD) contrast in IPS associated with smaller distance between to-be-compared sets of items, both in adults and children (see Kucian et al., 2011 for similar results in children). It was further demonstrated that this activity modulation in IPS was more related to the difficulty of estimating countable discrete numerosities (i.e., how *many* blue rectangles vs. how *many* green rectangles) compared to the difficulty of estimating uncountable analog properties (i.e., how *much* blue vs. how *much* green; Castelli et al., 2006). As for non-symbolic magnitude comparisons, several studies reported distant-related IPS activation when comparing symbolic numerosities. Stronger activation levels within the IPS were indeed found to be associated with smaller numerical distances when participants had to make comparisons between two Arabic digits or between two number words (Pinel et al., 2001). In another study by Ansari and colleagues (2006), participants indicated which of two number words was numerically larger, while the physical size of the words could be either congruent to their numerical magnitude (i.e., the smaller number is written in a smaller font) or incongruent (i.e., the larger number is written in a smaller font). Activity in the IPS was found to be modulated by the numerical distance but not by the size congruity, arguing that distance effects in this region reflect activation of the magnitude representation.

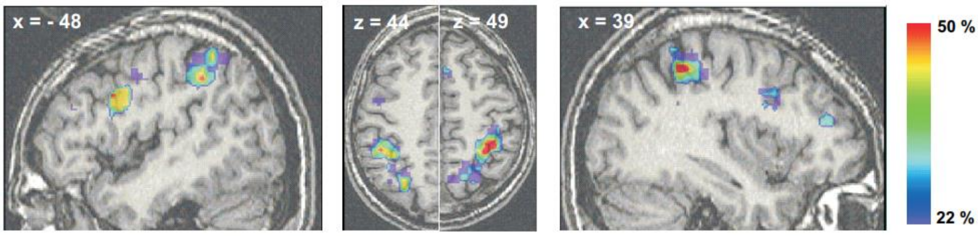

Figure 5. Bilateral activation of the IPS during numerical processing. Retrieved from Dehaene et al., 2003. The horizontal segment of the IPS was activated bilaterally in a variety of contrasts involving numerical quantity manipulation. The color scale indicates the percentage of studies showing activation in a given voxel (see Dehaene et al., 2003 for a full list of studies used). x and z refer to the Talairach coordinate system.

Contrasting with the extensive literature that has focused on brain representations of non-symbolic and symbolic numerosities, only a few neuroimaging studies investigated the specific status of the iconic format. With regard to the canonical finger configurations, Kaufmann and colleagues (2008) provided evidence for intraparietal activations associated with comparative numerical judgments of these patterns, both in children and adults. Two recent electrophysiological (EEG) studies (Soylu et al., 2019; van den Berg et al., 2021) have further examined differences in the processing of canonical and non-canonical finger configurations. Event-related potentials (ERP) were measured while participants had to match finger-numbers with a subsequently presented Arabic digit (Soylu et al., 2019), or to verify if the finger-number was the correct solution of a previously presented addition problem (van den Berg et al., 2021). In both studies, the later P3 component of parietal sites, previously associated with semantic processing, showed enhanced response to canonical finger configurations compared to non-canonical ones. Some differences between the neural correlates of canonical and non-canonical dots processing have also been highlighted. In a positron emission tomography (PET) study, Piazza and colleagues (2002) found additional recruitment of occipital and parietal regions when participants enumerated sets of 6 to 9 dots that were randomly organized compared to when they were presented in a canonical way. Random dot arrangements outside the subitizing range (i.e., > 4) were similarly found to elicit stronger IPS response than spatially organized dot arrangements, which in turn elicited stronger response than canonical (dice-like) dot configurations (Bloechle et al., 2018b). These differences in amplitude of IPS activity according to the spatial arrangement of dot arrays were interpreted as reflecting a more precise representation for canonical than non-canonical dot patterns (Bloechle et al., 2018b). In a recent fMRI study, participants had to estimate briefly presented dot arrays that were either ungrouped or grouped into smaller clusters (Maldonado Moscoso, 2021). A right frontoparietal network was found commonly activated for both kind of arrays, suggesting a similar involvement of the ANS. However, estimations of grouped arrays additionally recruited regions in the left hemisphere and the angular gyrus, which are typically involved during calculation and could therefore account for the advantage of spatial arrangement on numerosity estimations.

The studies reviewed above strongly support the involvement of IPS during numerical comparisons of non-symbolic, symbolic and iconic magnitudes. However, whether activation in this parietal region during explicit numerical comparative judgments genuinely accounts for magnitude processing has been called into question. Indeed, IPS activity was also found to be modulated by response-selection processes during tasks that did not involve any numerical judgment (Culham & Kanwisher, 2001; Gobel et al., 2004; Jiang & Kanwisher, 2003). Since numerical comparisons require response selections, it seems therefore difficult to disentangle distance-related IPS activity from that caused by response-selection processes. For instance, modulation of IPS activity might actually reflects an increase in the difficulty of selecting response for smaller distances (Kucian et al., 2011). Additionally, it has been argued that numerosity judgements are significantly affected by other continuous properties, such as size, area or density (Gebuis et al., 2016; Mix et al., 2002). These non-numerical dimensions may indeed serve as visual cues to indicate which of two numerosities is smaller/larger, and have been found to activate parietal regions analogous to those involved in quantity processing. In their fMRI study, Pinel and colleagues (2004) for example investigated the neural correlates of comparative judgments on three different dimensions: numerosity, physical size and luminance. They found common activation of bilateral IPS and occipitotemporal areas for all kind of judgments, emphasizing the role of IPS in comparison tasks regardless of the dimension involved (see Cohen Kadosh et al., 2005 for similar results). Moreover, each dimension generated a distance effect that modulated the brain activity in overlapping regions along the IPS. Hence, these results challenge the view that distance-related effects in the IPS during numerical comparative judgments capture magnitude processing over and above response selection and stimulus-related activations (Gobel and Rushworth, 2004).

2.2 Implicit measures of magnitude representation

To address the issue of response-selective biases, a parallel line of research has focused on the use of implicit paradigms that avoid the implication of decisional processes. In their seminal study, Piazza and colleagues (2004) used fMRI adaptation (fMRIa) to investigate automatic processing of non-symbolic quantities. Participants were passively and repeatedly exposed to a specific numerosity, in order to create adaptation. Occasionally, a deviant numerosity, either close or distant from the adaptation numerosity, was presented and led to a distance-dependent recovery of fMRI signal in bilateral IPS (i.e., larger recovery of activation when larger ratios of adaptation and deviant numerosity). Dot density and location were carefully controlled so that these non-numerical visual parameters could not be responsible for the response to numerosity deviation. Using similar fMRIa, several studies replicated and extended the results of Piazza et al. (2004) to children (Cantlon et al., 2006), to higher numerosities (Castaldi et al., 2016) and finally to symbolic representations of magnitudes (e.g., Notebaert et al., 2011; see Escobar-Magarino et al., 2022 for a review). Furthermore, fMRIa allowed Roggeman et al. (2011) to distinguish between three successive stages of non-symbolic processing (as predicted by the computational model of Verguts and Fias, 2004), represented in different brain areas along the occipitoparietal stream. Contrasting same *versus* different location of the deviant from the adapted stimuli, the authors showed activation within the inferior occipital gyrus associated with the coding of object location. Then, by contrasting small (-1, -2) *versus* large (+1, +2) deviants, Roggeman and colleagues (2011) found summation coding activation within the middle occipital gyrus. Finally, their contrast of numerically close (-1, +1) and distant (-2, +2) deviants revealed a number-selective coding in the superior parietal lobe, consistent with the results of previous research (Piazza et al., 2004).

In line with the findings of Roggeman et al. (2011), Guillaume and colleagues (2018) recently found a neural signature of early perceptual numerosity representation over the medial occipital cortex. Their study combined EEG recordings with fast periodic visual stimulation (FPVS) and an oddball design. This approach relies on the relatively old observation that when a stimulus property is modulated periodically over time, it generates an evoked response that has a periodic time course, referring to the so-called steady-state visual evoked potential (SSVEP, Regan, 1977, fig. 6a). The oddball design consists in modulating a specific stimulus feature (i.e., the oddball, or the deviant) at fixed intervals within a rapid stream of standard (or base) stimuli (Norcia et al., 2015). In the study of Guillaume et al. (2018), participants were passively viewing arrays of 10 dots at a fast 10-Hz rate (i.e., 10 stimuli per second) and a deviant numerosity (e.g., 14 dots) was periodically appearing in the stream every 8^{th} stimuli (i.e., at a frequency of 10/8 = 1.25 Hz, fig. 6b). Analyzing the brain responses in the frequency domain, it is expected to find a response elicited at 10 Hz, reflecting the general visual presentation, and another one elicited at 1.25 Hz, specific to the periodic feature manipulation (i.e., the numerosity, fig. 6c). Interestingly, the latter would be observed if (and *only if*) the brain has successfully discriminated the deviant feature from the standards (e.g., 14 dots is different from 10 dots) *and* has generalized the feature over all deviants (e.g., the deviant always contains 14 dots). Guillaume and colleagues (2018) were thus able to observe response at the periodic change of numerosity (1.25 Hz), with an amplitude that increased as the ratio between the base and the deviant numerosities became larger. These neural sensitivity to the numerical deviation was recorded in posterior regions, mostly concentrated over the medial occipital sites (see Van Rinsveld et al., 2020b for similar method and results). However, only responses recorded within the right occipitoparietal sites were found to correlate with the participants' numerical ratio effect measured in an independent comparison task. Together, these results demonstrated an early perceptual discrimination of non-symbolic quantities starting in visual areas, which may successively reach higher-level numerical regions along the occipitoparietal stream (Guillaume et al., 2018).

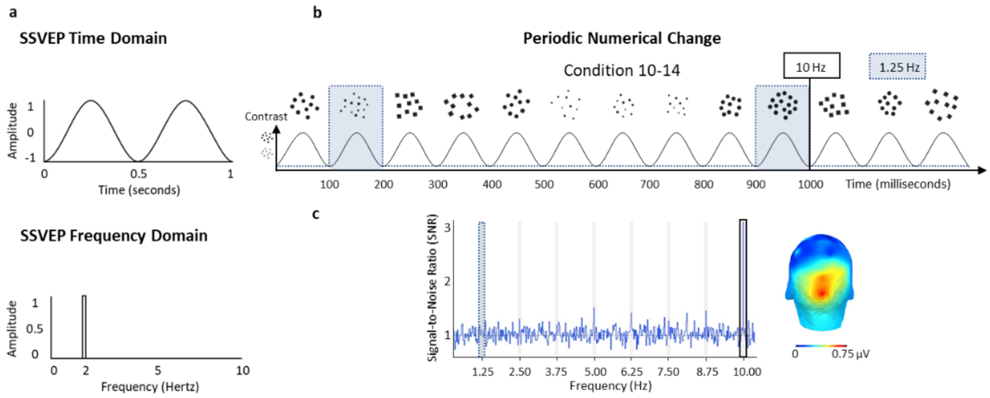

Figure 6. (a) Conceptual illustration of steady-state responses in the time and frequency domains. Adapted from Norcia et al. (2015). Sinusoidal response shows two peaks over a period of 1 second in the time domain (upper panel), which correspond to a single spectral component at 2 Hertz in the frequency domain (lower panel). **(b) Illustration of the FPVS design.** Adapted from Guillaume et al. (2018). Arrays of dots were visually presented at 10 Hz (i.e., 10 arrays/second) with a sinusoidal contrast modulation. Base numerosity was always 10 and a deviant numerosity (in this example: 14) was introduced in the stream every eighth stimuli (i.e., at 1.25 Hz). **(c) Results from the study of Guillaume et al. (2018).** Frequency domain analyses showed one response elicited at 10 Hz (black border), generated by the visual presentation rate, and another at 1.25 Hz (blue dotted border), induced by the periodic numerical change and thus indicating the successful discrimination of

the deviant numerosity. Note that this discrimination response is usually distributed over several harmonics (e.g., 2.5, 3.75, 5, … highlighted in grey). The topographical map shows approximate location of the discrimination response as a function of its amplitude (color scale).

The discrimination response obtained with FPVS presents several advantages. First, similar to fMRIa, it allows for an implicit measurement of automatic processes, since it does not engage participants in any explicit comparison or estimation task. Furthermore, it is produced over a very short period of time and has a very high signal-to-noise ratio (Norcia et al., 2015). This technique has thus become increasingly popular over the last years (e.g., Guillaume et al., 2018, 2020; Georges et al., 2019; Lochy and Schiltz, 2019; Marinova et al., 2021; Van Rinsveld et al., 2020b, 2021). In addition to their previous FPVS study on non-symbolic numerical representations, Guillaume and colleagues (2020) recently investigated the automatic processing of Arabic digits. They presented participants with a stream of base digits at 10 Hz, in which a deviant digit was periodically inserted every eighth stimuli (i.e., at 1.25 Hz). Base and deviant digits were determined according to the targeted numerical feature: in the *magnitude* condition, digits smaller than 5 were presented as bases and digits larger than 5 as deviants (or the other way around), whereas in the *parity* condition, odd digits were presented as bases and even digits as deviants (or the other way around). Both conditions led to clear discrimination responses at the periodic change of the semantic category over occipitoparietal sites, supporting an automatic and spontaneous processing of magnitude and parity features. Finally, their experiment also included a control condition in which the digits were arbitrary allocated to the base and deviant categories. Although the discrimination responses did not reach statistical significance in this control condition, they were nonetheless visually present, suggesting that the brain was able to detect a periodic change based on temporarily constructed rules without any feature being intentionally manipulated. Cautious should therefore be taken when interpreting FPVS responses.

2.3 Common magnitude representation within the parietal cortex?

Evidence from single-notation studies consistently point in the direction of the parietal cortex, and more precisely the IPS, as the main neural correlate of magnitude representations. Therefore, it lends some support to one of the predictions of the Triple Code Model (Dehaene, 1992; Dehaene & Cohen, 1995) that assumes IPS possess an abstract, notation-independent, semantic representation of quantities (Dehaene et al., 2003). The fact that each individual notation is associated with the same brain area is, however, not sufficient to claim that this region represents magnitude in an abstract or integrated way. To further explore the relationship between the representations of numerical formats, several studies have looked at the neural activation underlying cross-notational magnitude adaptation effects. For instance, Piazza et al. (2007) adapted their participants with a stream of Arabic digits or dot arrays close to a given value (e.g., 17, 18 or 19). After this period of adaptation, a deviant numerosity either close (e.g., 20) or distant (e.g., 50) was presented. Crucially, the deviant numerosity could change or remain the same in notation (e.g., digit-dots, dots-digit *or* digit-digit, dots-dots). A similar distant-related recovery (i.e., larger recovery for distant than close deviant) was observed in the IPS regardless of whether the notation varied or not, thereby supporting a notation-independent magnitude representation in this region. They nevertheless observed that the left IPS exhibited a smaller distance effect when deviant dots were presented among Arabic digits. Interestingly, another fMRIa study investigating cross-notational adaptation effect between Arabic digits and number word led to an opposite pattern of results (Cohen Kadosh et al., 2007). The authors indeed found that the right IPS was sensitive to the change in notation, while the left IPS showed notation-independent magnitude processing. Given the contradictory results of these two studies, no robust statement can be made at this stage regarding the existence of an abstract representation of magnitude within the IPS.

More recently, Liu and colleagues (2018) combined passive viewing with ERP recordings to investigate the automatic integration of non-symbolic dot arrays and symbolic Arabic digits. Participants were presented simultaneously with dot quantities and double-digits that could either match or mismatch. Greater amplitude of the negative N1 component (around 130 ms post-stimulus) and the positive P2p component (around 200 ms post-stimulus) over parietal sites were observed in the match condition, although an adjustment for underestimation of the dot arrays had first to be applied. This suggests that the human brain rapidly and automatically integrates the perceived numerosity of dot arrays with the magnitude conveyed by double-digits (Liu et al., 2018). A recent FPVS study however failed to replicate these findings (Marinova et al., 2021). Using a similar design as in Guillaume et al. (2020), participants had to passively look at a stream of small numerosities (1-4) presented at 10 Hz, in which a deviant larger numerosity (6-9) was periodically inserted at 1.25 Hz (i.e., every eighth stimuli), or the opposite (i.e., large numerosities as base and small numerosities as deviant stimuli). Under different conditions, numerosities could be depicted in single-notation (i.e., Arabic digits, dots, numbers words) or in mixed-notation (i.e., digits-dots, digits-number words, dots-number words). Additionally, each experimental condition was coupled with a control condition in which the digits were randomly assigned to the base and deviant categories. Marinova and colleagues (2021) found greater magnitude-related discrimination responses (at 1.25 Hz) in the three single-notation experimental conditions as compared to the control conditions. At the mixed-notation level, significant responses to the periodic change of magnitude were observed for digits-number words and dots-number words, suggesting an automatic integration across these numerical formats. However, and contrasting with the results obtained by Liu et al. (2018), the authors did not find any conclusive evidence for an automatic integration between digits and dots. Indeed, the experimental digits-dots condition did not produce a higher discrimination response than its corresponding control condition.

It is possible that the discrepancies observed between the studies of Liu et al. (2018) and Marinova et al. (2021) stem from different methodological decisions regarding the numerical range (11-63 *versus* 1-10) or the stimulus presentation (simultaneous *versus* sequential). Furthermore, both studies used non-symbolic configurations of dots, known to be represented with decreasing accuracy once they exceed four elements (i.e., above the subitizing range). Instead, the use of canonical dot configurations, which enjoy more similar representational acuity to symbols, may offer new possibilities for assessing integration between numerical codes. In this light, it appears that to date no study has examined the associations between canonical dot or finger patterns and symbolic numeral representations. By reviewing the literature on mixed-format neuroimaging studies, it becomes clear that there is a need to further investigate the integration of magnitude across numerical codes, including canonical number representations.

3 Research objectives and outline of the PhD thesis

The first objective of this PhD thesis was to examine how the brain represents canonical number configurations. To this aim, we used the FPVS technique with 10-year-old children. While this approach has already proven to be efficient in the evaluation of non-symbolic (i.e., dot arrays) and symbolic (i.e., Arabic digits and number words) processing (Guillaume et al., 2018, 2020), it has never been used so far to examine the specific status of iconic number representations. More generally, the current literature lacks neuroimaging studies devoted to the implicit processing of canonical configurations, especially regarding the dot notation. Given the importance of these configurations in children’s mathematical development (Kreilinger et al., 2022), our first study (*Chapter 2*) aimed at providing objective evidence of children’s brain ability to automatically process canonical finger and dot configurations, in the absence of response selection. Furthermore, to precise the nature of the FPVS discrimination response (i.e., does it reflect an automatic access to magnitude representation?), correlation analyses were performed with children’s canonical facilitation effects in an independent behavioral naming task.

A second objective of the current thesis was to evaluate whether the magnitude conveyed by iconic and symbolic numerical codes is integrated in a common system. Despite decades of research, there is still no clear evidence about the existence of a shared magnitude representation. Previous studies indeed led to conflicting results and only used single or pairs of non-symbolic and symbolic notations (Liu et al., 2018; Marinova et al., 2021). In two FPVS studies conducted among young adults (*Chapter 3 & 4*), we used a multi-code presentation design including four different notations: Arabic digits, number words, canonical finger configurations and canonical dot patterns. Several limitations of previous FPVS studies were reviewed and addressed. For instance, experimental *versus* control contrasts leave open the possibility that variations between the conditions other than those explicitly manipulated could cause the presence (or absence) of significant differences in activation. We therefore decided to combine FPVS with a robust marker of magnitude processing that is the distance effect (*Chapter 3*). Distance-related activity modulation was examined by comparing the discrimination responses elicited by a deviant numerosity close *versus* distant from the base numerosity (e.g., base/deviant = 2/3 or 2/8). To ensure the reliability of this neural marker of magnitude processing, correlation analyses were conducted between participants' FPVS response and their performance in an independent behavioral comparison task.

In *Chapter 4*, the spontaneous nature of magnitude integration across iconic and symbolic formats was further questioned: does it occur whenever we are exposed to numbers and quantities, or only when we are explicitly engaged in magnitude processing? Participants were presented with the same multi-code FPVS design as in *Chapter 3*, but with different instructions being given prior to the experiment: in a first condition, they simply had to look at the screen; in a second condition, they were instructed to determine the odd or even numerosity presented during the sequence, while in a third and final condition, they were instructed to identify the smallest or largest numerosity of the sequence. We thus examined the sensitivity of response amplitudes to the distance effect during simple viewing and when explicitly orienting attention towards magnitude or parity. If magnitude is spontaneously integrated, a neural distance effect is expected to be found even when participants are not engaged in any numerical processing. Moreover, by comparing the distance-related discrimination responses under magnitude and parity instructions, it would clarify whether magnitude integration can occur independently of the semantic numerical feature that is deliberately triggered.

The last study of this thesis (*Chapter 5*) aimed to examine whether adults can integrate the magnitude of canonical quantities and number symbols during a same-different matching task in which both information were shown simultaneously. It was indeed argued that same-different judgments are more reliable than numerical comparisons to assess magnitude representations (Van Opstal & Verguts, 2011). In that study, participants were presented with canonical arrays of digits and had to indicate whether the quantity of Arabic digits was equal or unequal to the magnitude conveyed by the digit. The task included matched trials, where the Arabic digit was represented its exact number of times (e.g., 3-3-3) and mismatched trials, where the Arabic digit was depicted less or more times than its exact value (e.g., 3-3). Among the mismatched trials, the difference between the quantity of elements and the digit magnitude could be either small (e.g., 3-3, difference = 1) or large (e.g., 6-6, difference = 4). We hypothesized that if canonical quantities and symbolic numerosities readily activate their common magnitude representation, participants should take less time to identify the mismatch when the quantity and the digit are distant than when they are close to each other. On the contrary, if they are processed by two entirely distinct systems, then no distance effect should emerge.

Finally, *Chapter 6* consists in a general discussion covering the main results of the thesis, their interpretation in light of existing theories and their contribution to the literature. The chapter also presents perspectives for future research and ends with conclusions.

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Chapter 2. Canonical representations of fingers and dots trigger an automatic activation of number semantics: an EEG study on 10-year-old children

Abstract

Over the course of development, children must learn to map a non-symbolic representation of magnitude to a more precise symbolic system. There is solid evidence that finger and dot representations can facilitate or even predict the acquisition of this mapping skill. While several behavioral studies demonstrated that canonical representations of fingers and dots automatically activate number semantics, no study so far has investigated their cerebral basis. To examine these questions, 10-year-old children were presented a behavioral naming task and a fast periodic visual stimulation EEG paradigm. In the behavioral task, children had to name as fast and as accurately as possible the numbers of dots and fingers presented in canonical and non-canonical configurations. In the EEG experiment, one category of stimuli (e.g., canonical representation of fingers or dots) was periodically inserted (1/5) in streams of another category (e.g., non-canonical representation of fingers or dots) presented at a fast rate (4 Hz). Results demonstrated an automatic access to number semantics and bilateral categorical responses at 4 Hz/5 for canonical representations of fingers and dots. Some differences between finger and dot configuration's processing were nevertheless observed and are discussed in light of an effortful-automatic continuum hypothesis.

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Canonical representations of fingers and dots trigger an automatic activation of number semantics: an EEG study on 10-year-old children[1]

1 Introduction

Over the last two decades, a bunch of evidence has revealed a grasp of quantitative concepts in preverbal infants and animals that presumably has developed independently of, and before, language (Butterworth, 1999; Carey, 1998; Dehaene, 1997, 2001; Wynn, 1998). This ability is considered as the root of the approximate representation of non-symbolic quantity and has been attributed to the so-called approximate number system (ANS, Barth et al., 2005, 2006, 2008; Dehaene, 2011; Feigenson et al., 2004). Support for the hypothesis of this shared evolutionary heritage comes from the finding of two major parallels between human and animal number processing: the numerical distance and the number size effects (Gallistel & Gelman, 1992). On the one hand, the numerical distance effect refers to the finding that the ability to discriminate two numerosities improves as the numerical distance between them increases. The number size effect refers to the finding that, for equal numerical distance, discrimination of two numerosities worsens as their numerical size increases. Besides this non-symbolic representation of numbers, children also possess the ability to quickly identify the quantity of a small set of up to 3-4 items without counting. The basis of this so-called subitizing ability is still debated, with patterns and attentional mechanisms being the main explanations (Chi & Klahr, 1975; Mandler & Shebo, 1982; von Glasersfeld, 1982). Interestingly, this skill has been assumed to be a precursor to the acquisition of the meaning of the first few number words (Benoit et al., 2004), and therefore to the access to a more accurate symbolic representation of quantity. The first data

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supporting the idea that the symbolic representation of numbers is more accurate than the non-symbolic one, probably date back several years when Buckley and Gillman (1974) demonstrated, in adults, that the distance and size effects were smaller in tasks involving symbolic numbers than in tasks involving non-symbolic quantities.

Over the course of development, children must therefore learn the mapping that exists between the non-symbolic representation of magnitude and a new, more precise, symbolic system (Mundy & Gilmore, 2009). This acquisition has been put forward as a key factor in children's mathematical development. Furthermore, finger representation has been argued to provide an "in-between" or iconic representation of numbers favoring the occurrence of this transition (Andres et al., 2008; Fayol & Seron, 2005; Moeller et al., 2011; Moeller & Nuerk, 2012). The processing of canonical finger configurations (i.e., hand configuration typically used by an individual to represent or to count to a specific number) was for example shown to give a faster access to number semantics than the processing of non-canonical configurations (Di Luca et al., 2006, see Di Luca & Pesenti, 2008 for similar results with a priming task). Finger-counting also facilitates the understanding of the principle of composition and decomposition of quantities (a full hand of 5 fingers + 3 fingers on the other hand is 8) (Björklund et al., 2019). It finally favors the access to number semantics (for a review, see Di Luca & Pesenti, 2011) and therefore predicts the acquisition of counting and arithmetic skills (Butterworth, 1999).

Besides finger configurations, patterns of dots found on dice or card patterns represent another instantiation of canonical configurations of numbers. Even if the literature on this topic is less extensive, there are striking similarities between canonical representations of dots and canonical representations of fingers. First, as with finger configurations, it has been demonstrated that the enumeration of numerosities was easier when collections of dots are represented in a regular or canonical way (Dawson, 1953; Benoit et al., 2004; Bloechle et al., 2018; Krajcsi et al., 2013; Mandler & Shebo, 1982; Wender & Rothkegel, 2000). Second, dice and card patterns not only help children to enumerate quantities beyond the subitizing range but also allow them to recognize the relationships between quantities and the decompositions of the quantities in smaller sets (e.g., two rows of four dots make 8) (Kreilinger, et al., 2020). Finally, mastery of canonical quantities of dots was shown to be a good predictor of later mathematical abilities (Kreilinger et al., 2020).

In recent years, there has been substantial growth in neuroimaging studies investigating the neural correlates of symbolic (e.g., Arabic numerals), non-symbolic (e.g., dot arrays randomly displayed) and iconic (e.g., numeral finger representations) number processing. While there is a general consensus that the posterior parietal cortex, including the intraparietal sulcus (IPS), is a key node for the representation of the shared semantic aspect of numerical quantity (Dehaene & Cohen, 2007; Dehaene et al., 2003; Nieder & Dehaene, 2009 for reviews), several studies also demonstrated that the pathway to reach this area was modulated by the stimulus format. Whereas non-symbolic quantities activated an area in the posterior superior parietal cortex, the processing of symbolic quantities activated a pathway that does not rely on this intermediate stage (Santens et al., 2010). The intraparietal sulcus (IPS) was therefore identified as the neural substrate of the number-selective representation and the posterior superior parietal cortex was identified as the neural substrate for the processing of non-symbolic quantities. According to Verguts and Fias (2004), only the left parietal cortex acquires a refined precision following the acquisition of numerical symbols, while the right parietal cortex keeps a coarse representation for both symbolic and non-symbolic notations. More recently, another proposal on the respective role of left/right IPS in number processing however emerged from two meta-analyses (Arsalidou et al., 2018; Sokolowski & Ansari, 2016). According to this view, the left and right IPS might be functionally distinct along an *effortful-automatic continuum*: while the right IPS may preferentially be activated for automatized discrimination skills, the left IPS activity may mainly be elicited by effortful, rule-based calculation procedures. In this paper, we would like to examine whether canonical representations of fingers and dots could be automatically detected by the brain. To our knowledge, only one study reported ERP differences in processing canonical and non-canonical finger-numeral configurations (Soylu et al., 2019). Recognition of canonical configurations were indeed marked by higher positivity in the P3 range compared to non-canonical configurations. This result was interpreted in terms of strategy differences (memory recall for canonical configurations vs. counting for non-canonical configurations). However, no brain imaging study has ever assessed the brain network underlying the processing of regular dot patterns. Even though finger and dot configurations share some similarities, they also present some differences. For instance, canonical dot patterns give rise to the perception of shapes (Gestalt) while fingers do not. We therefore still do not know whether the processing of canonical dot and finger patterns leads to comparable or different brain responses.

To examine this question, twenty-three 10-year-old children were asked to perform a behavioral and an EEG experiment using canonical and non-canonical presentations of fingers and dots. In our behavioral task, children had to name as fast and as accurately as possible the number of dots and fingers presented in canonical and non-canonical configurations. If canonical configurations yield a faster access to the number semantics, the naming time should be faster with canonical configurations than with non-canonical ones. For the EEG experiment, we used a Fast Periodic Visual Stimulation (FPVS) approach (Guillaume et al., 2018; Retter & Rossion, 2016; Rossion, 2014). This paradigm comprises the presentation of a base stimulus category at a high-rate frequency (i.e., non-canonical number configurations at 4 Hz) and a deviant stimulus category at a lower frequency (i.e., canonical number configurations every fifth item, so at 0.8 Hz). If the brain is able to generalize across the deviant stimuli and discriminate them from the category of the base stimuli, a selective response in posterior brain areas should be observed at the rate of the deviant category presentation (i.e., 0.8 Hz). Correlation between the behavioral and EEG tasks will moreover be computed in order to assess whether the brain responses to canonical patterns relate to children’s abilities to identify their numerosity. Moreover, as the frequency tagging paradigm was recently used to demonstrate hemispheric specialization for letters (Lochy et al., 2016) and Arabic digits (Lochy & Schiltz, 2019) in preschool children, the lateralization of the brain activation for canonical representations of numbers will also be examined. If canonical representations of fingers and dots trigger a symbolic representation of numbers or if they trigger rule-based calculation procedures, they should preferentially activate the left parietal cortex. However, given the semi-abstract (iconic) representations that canonical configurations of dots and fingers entail, a bilateral activation of the parietal cortex might also be observed.

2 Methods

2.1 Participants

Twenty-three children (11 females, M_{age} = 10.16 years, range = 8.86-10.75 years) in the fourth- (N = 5) and fifth-grade were recruited from different schools in Wallonia (Belgium). At this age, children are supposed to have internalized the numerical meaning of canonical configurations (of fingers and card patterns) and are also supposed to have moved from finger-counting to higher level numerical strategies (i.e., base computations on abstract mental representations of numbers; Floer, 1995; Kaufmann & Wesselowski, 2006). They are nevertheless not yet expert (like adults) and are still developing their abstract representations of numbers. Testing children of this age range will therefore bring some variability and allow the computation of correlations between the behavioral and EEG data.

All children had normal or corrected-to-normal vision and were enrolled in French-speaking schools. Their parents provided their written informed consent and the procedures are in line with the Declaration of Helsinki. To ascertain that the children did not present a cognitive disorder, they all performed several tests measuring general cognitive functions, as well as calculating and reading: (1) the Standard Progressive Matrices (Raven, 1998), which measure logical reasoning through multiple choice problems with increasing complexity; (2) the TempoTest

Rekenen (De Vos, 1992), a timed pen-and-paper test evaluating arithmetic fluency for the four mathematical operations; (3) two reading tests, namely the Alouette-R (Lefavrais, 2005), and the "Lecture en Une Minute" from the LMC-R battery (Khomsi, 1999). One participant was excluded because of abnormally low scores (i.e., more than two standard deviations below the mean of the group) in three of these behavioral tests. The analyses were therefore performed on the remaining 22 children (table 1).

Table 1. General cognitive functions and reading abilities of the 22 children included in the study

	Raw scores		
	Min	Max	*M (SD)*
Behavioral tests			
SPM – logical reasoning index	31	55	43.68 (5.40)
TTR – arithmetic fluency index	53	128	89.14 (21.40)
Alouette-R			
CM – reading accuracy index	92	98	95.41 (1.79)
CTL – reading speed index	113	350	244.95 (66.93)
LUM – reading speed *x* accuracy index	49	105	74.04 (15.68)

2.2 Behavioral naming task

In this task, children had to determine as fast and as accurately as possible the numerosity that was briefly presented at the center of a computer screen. The experiment was executed with E-Prime 2.0 (Psychology Software Tools, USA) and included two stimuli formats: dot arrays and finger representations, separated in two different conditions.

Dot arrays were composed of 4, 5, 6, 7, 8, or 9 dots organized in a canonical or non-canonical way. As we wanted to study the automatic detection of canonical configurations outside the subitizing range, the numerals 1, 2 and 3 were intentionally excluded from the task. For the canonical configurations, a geometrical arrangement of dots, similar as the one presented on playing cards, was assigned to each numerosity (fig. 1a & 1b). For the non-canonical configurations, each number was associated with a random distribution of dots. To control for the low-level perceptual features of the stimuli, the dot arrays were created following the same methodology as the one used by Crollen, Castronovo and Seron (2010). In a first set of stimuli, the luminance (i.e., the sum of the area of all dots) and the total area occupied by the dots were equal for all numbers. As a consequence, the density of the array (i.e., the free area around each dot) and the size of the dots were varying as a function of the numerical magnitude (fig. 1a). In the second set of stimuli, the density and the size of the dots were controlled to be constant across numbers. Consequently, the luminance and the total occupied area were increasing with increasing numerosity (fig. 1b). Within each set of stimuli, the dots were represented by three different forms: circles, triangles or squares, in order to maximize the variability of low-level visual parameters.

Finger representations also included the numbers 4 to 9, organized in canonical configurations: each numerosity was associated with the typical Belgian finger-counting representation (fig. 1c & 1d) and non-canonical configurations: randomly chosen fingers were assigned to each number. To increase the variability of visual parameters, three different drawing designs were used to create the numeral finger representations and their mirror images were also included in the stimuli set. The hands were represented in the palm down orientation.

Each numerosity (i.e., 4-9) was presented 12 times (50% canonical configurations and 50% non-canonical configurations) for a total of 72 trials in each (dot and finger) condition, randomly presented. A trial began with the presentation of a central fixation cross for 500 ms, followed by the brief presentation of the stimulus for 250 ms, immediately occulted by two successive masks of 100 ms. The masks consisted of a black and grey checkerboard pattern covering the whole surface of the screen. At the end of the trial, a question mark appeared on the screen and the child had to say aloud, as fast and as accurately as possible, the number that was presented. As soon as the children gave their answer, the experimenter pressed the space bar to stop the recordings of the reaction times and then encoded the child's answer on an external keypad before the next trial begins. The task started with six practice trials.

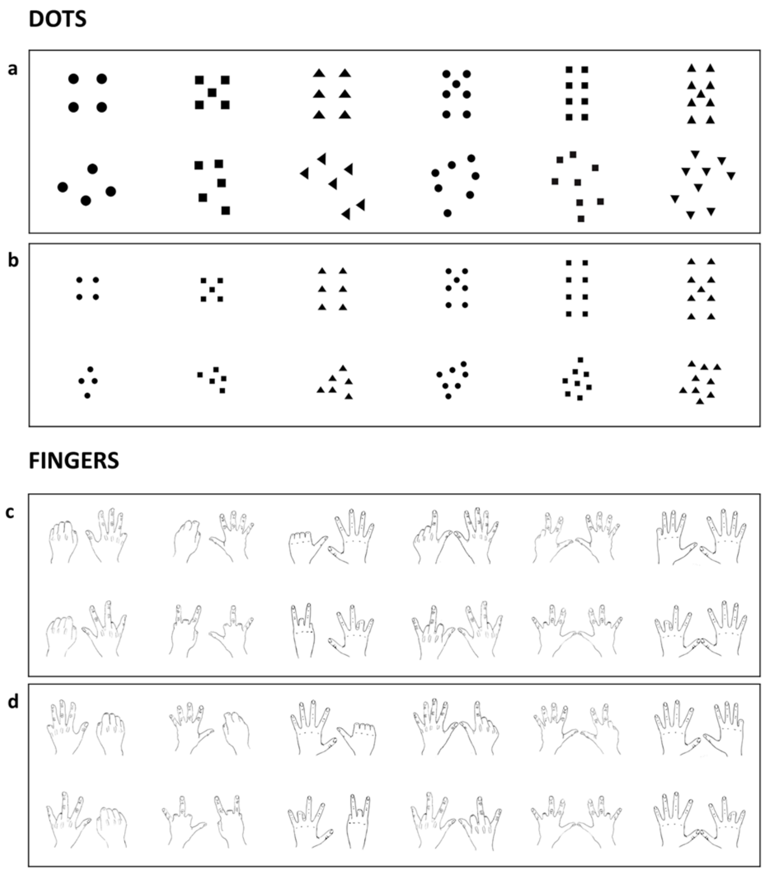

Figure 1. Example of stimuli. Dot arrays with the three different forms of dots (a-b) and numeral finger representations with the three different drawing designs (c-d). First line of each panel represents the canonical configurations. Second line represents the non-canonical ones. **(a)** first set of stimuli controlling for the luminance and the total area occupied by the dots; **(b)** second set of stimuli controlling for the density and the size of the dots; **(c)** numeral finger representations and their mirror images **(d)**.

2.3 EEG task

The experiment took place in a quiet, low-lit room. During testing, the child was seated in front of a table, on which a monitor with a 800 x 600 pixel resolution was placed at a distance of 1 m to display the task. The testing was composed of eight sequences of visually presented stimuli for 44 s, for a total experiment time of about 8 min. Each sequence consisted in 40 s of stimulation with additional 2 s of gradual fade in at the beginning and 2 s of gradual fade out at the end of the sequence. A fixation cross appeared at the center of the screen 2 to 5 s before the sequence started and stayed at the same position during the entire sequence. To maintain a constant level of attention throughout the stimulation, children were instructed to press the space bar each time they detected the cross had briefly changed color (from blue to red, for 200 ms, 6 random color changes per sequence).

The eight sequences were divided between the two conditions: half with the dot arrays and the other half with the numeral finger representations. Within each sequence, stimuli were presented at a constant frequency rate of 4 Hz (i.e., four images per second, 250 ms per image) by means of sinusoidal modulation of contrast from 0 to 100 % (fig. 2a). In both conditions, the non-canonical stimuli were used as the base category presented at 4 Hz (fig. 2b), and every fifth item (4/5 so at a 0.8-Hz frequency) was a canonical stimulus (i.e., the deviant category). The stimuli were the same as the ones used for the naming task. The way they were created (i.e., low-level visual parameters control and variability) ensures that any resulting finding reflects generalization beyond specific visual features. The stimuli set thus consisted of six numerosities (i.e., 4-9) in six different versions (fig. 1) for a total of 36 base (i.e., non-canonical configurations) and 36 deviant (i.e., canonical configurations) stimuli within each condition. They were randomly presented at the center of the screen with no immediate repetition of the same stimulus. The experiment was created and executed with a software running on JavaScript (Java SE Version 8, Oracle Corporation, USA).

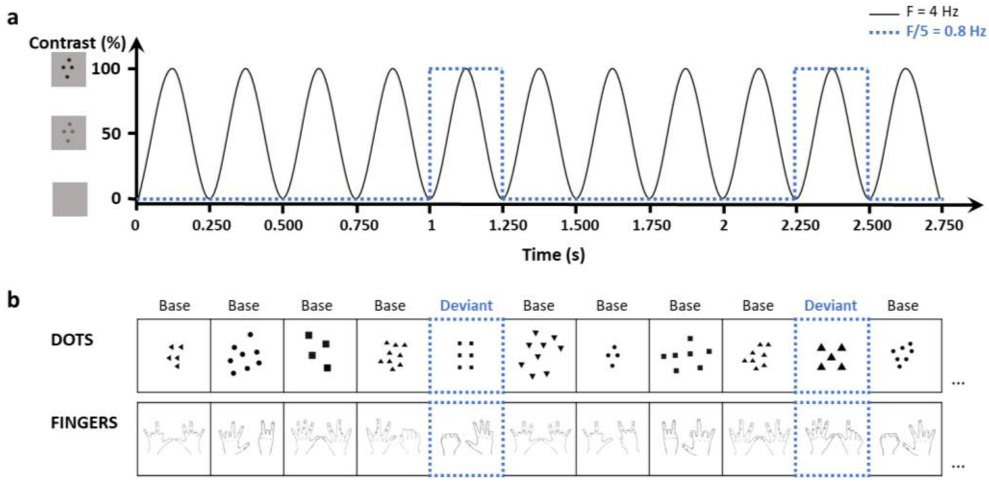

Figure 2. Experimental design. (a) Stimulation over time: four stimuli per second (4 Hz) presented with a sinusoidal contrast modulation and deviant stimuli presented at 4 Hz/5 = 0.8 Hz. **(b) Example of one dot- and one finger-sequence**: base stimuli consisted of non-canonical configurations of the numerals 4-9 randomly presented, and a canonical configuration (the deviant) was presented every fifth item. Total experiment comprised eight sequences (4x dots, 4x fingers) of 40 s (plus 4 extra seconds of fade in and fade out).

2.4 EEG data acquisition and analysis

EEG was recorded at 2048 Hz using BioSemi Active II system (BioSemi, The Netherlands) with 64 channels at standard 10-20 system locations and four additional posterior electrodes (PO9, I1, I2, PO10). The magnitude of the offset of all electrodes, referenced to the common mode sense, was held below 50 mV.

EEG analyses were carried out using Letswave 6 (https://www.letswave.org/), an open-source toolbox running on MatLab (The MathWorks, USA). Data files were first resampled to 512 Hz to reduce analysis time. Preprocessing included a Fast Fourier Transform (FFT) band-pass filter with cut-off values of 0.1-100 Hz and a FFT multi-notch filter to attenuate electrical noise at three harmonics of 50 Hz. Data were segmented 2 s before and after each sequence and channels that showed a high level of artefacts or noise were interpolated (1.5% of channels on average). Each sequence was then segmented again from stimulation onset until 40 s, in order to contain the largest amount of integer presentation cycles (32 cycles of 1.25 s at 0.8 Hz). Channels were re-referenced to the common average of all electrodes and the four sequences within each condition were averaged per participant.

For the frequency domain analysis, a Fast Fourier Transform was computed to obtain the normalized amplitude spectrum for each channel. Frequency resolution of the resulting spectra was 0.025 Hz (1/40 s), which allows unambiguous identification of the response expected at the frequencies of interest (i.e., 4 Hz for the base stimulation and 0.8 Hz and harmonics for the deviant category detection). Within each condition (i.e., dots and fingers), individual FFT data were averaged across children to allow group analysis. Z-scores were computed at every channel to determine the significant harmonics for both the base (i.e., elicited by the non-canonical stimulation at 4 Hz) and the deviant (i.e., elicited by the canonical presentation at 0.8 Hz) responses. For each discrete frequency bin (x), Z-scores were calculated as followed: $Z(x) = \frac{x - mean(noise)}{standard\ deviation(noise)}$, where the noise was defined as the 20 surrounding bins of each target bin, excluding the immediately adjacent bins and the extreme (min and max) bins (Lochy & Schiltz, 2019). The number of significant harmonics was determined as the largest chain of consecutive harmonics showing a Z-score larger than 1.64 ($p < .05$, one-tailed, signal > noise).

The signal-to-noise ratio (SNR) for the EEG spectrum was obtained by dividing the amplitude at each frequency by the average amplitude of 20 surrounding bins (ten on each side; Liu-Shuang et al., 2014). For visualization purposes, SNR was then averaged across children within each condition to assess general peak responses at the frequencies of interest. To quantify the responses in microvolts, baseline-corrected amplitudes were calculated by subtracting the average voltage amplitude of the 20 surrounding bins (Retter & Rossion, 2016). Finally, sums of baseline-corrected amplitudes at the deviant category frequency (0.8 Hz) and significant harmonics (excluding the base stimulation frequency) were computed to quantify and visualize general topography of the target response for each child and for the group-level.

3 Results

3.1 Naming results

Analyses of variance (ANOVA) were conducted on the children's reactions times (RT) and percent of correct responses (PCR) in the behavioral naming task. RT were first logarithmically transformed because they were not normally distributed. The Greenhouse-Geisser correction was applied when the sphericity assumption was violated, but non-corrected degrees of freedom are reported for ease of comprehension.

3.1.1 Dot condition

A 2 (configuration: canonical or non-canonical) x 6 (numerosity: 4, 5, 6, 7, 8, or 9) repeated-measures ANOVA was performed on ln-transformed RT. The ANOVA showed a main effect of *Configuration*, $F(1, 21) = 89.12$, $p < .001$, $\eta_p^2 = 0.81$, a main effect of *Numerosity*, $F(5, 105) = 107.32$, $p < .001$, $\eta_p^2 = 0.84$, and a significant interaction between *Configuration* and *Numerosity*, $F(5, 105) = 10.49$, $p < .001$, $\eta_p^2 = 0.33$. RT were indeed significantly lower (better performance) for the canonical configurations compared to the non-canonical configurations (fig. 3a). Moreover, canonical and non-canonical RT varied according to the numerosity (fig. 3a). To further investigate the interaction between *Configuration* and *Numerosity,* an averaged RT for numerosities 4, 5, 6 (i.e., small numerosities) was calculated as well as an averaged RT for numerosities 7, 8, 9 (i.e., large numerosities). A score reflecting the advantage of the canonical configuration (i.e., the canonical gain) was then computed by subtracting the canonical RT from the non-canonical RT respectively for small and large numerosities. A two-tailed paired-samples t-test was finally performed on these measures and revealed a smaller gain for the small ($M \pm SD = 417.01 \pm 271.13$) as compared to the large ($M \pm SD = 1543.72 \pm 1352.38$) numerosities, $t(21) = -3.93$, $p < .01$ (fig. 3e).

Similar results were obtained from the 2x6 repeated-measures ANOVA performed on the PCR: a main effect of *Configuration*, $F(1, 21) = 113.87$, $p < .001$, $\eta_p^2 = 0.84$, a main effect of *Numerosity*, $F(5, 105) = 24.97$, $p < .001$, $\eta_p^2 = 0.54$, and a significant interaction between *Configuration* and *Numerosity*, $F(5, 105) = 17$, $p < .001$, $\eta_p^2 = 0.45$. PCR were indeed significantly higher for the canonical configurations compared to the non-canonical configurations and they varied according to the numerosity (fig. 3b). To further investigate the interaction between *Configuration* and *Numerosity*, the canonical gain (i.e., canonical PCR – non-canonical PCR) for small (i.e., 4-5-6) and large (i.e., 7-8-9) numerosities was computed (fig. 3b). A two-tailed paired-samples t-test was then performed to compare the canonical gain for the small and large numerosities (fig. 3f). This test revealed a smaller gain for the small ($M \pm SD = 5.05 \pm 7.05$) than for the large ($M \pm SD = 34.85 \pm 16.46$) numerosities, $t(21) = -7.65$, $p < .001$.

3.1.2 Finger condition

We did the same analyses for the fingers as for the dots. The 2 (configuration: canonical or non-canonical) x 6 (numerosity: 4, 5, 6, 7, 8, or 9) repeated-measures ANOVA performed on ln-transformed RT showed a main effect of *Configuration*, $F(1, 21) = 180.08$, $p < .001$, $\eta_p^2 = 0.9$, a main effect of *Numerosity*, $F(5, 105) = 9.93$, $p < .001$, $\eta_p^2 = 0.32$, and a significant interaction between *Configuration* and *Numerosity*, $F(5, 105) = 17.36$, $p < .001$, $\eta_p^2 = 0.45$. RT were indeed significantly lower (better performance) for the canonical configurations compared to the non-canonical configurations (fig. 3c). Moreover, canonical and non-canonical RT varied according to the numerosity (fig. 3c). RT of small (i.e., 4-5-6) and large (i.e., 7-8-9) numerosities were averaged, canonical gain scores were calculated (Fig. 3c) and a two-tailed paired-samples t-test was then conducted to compare the mean canonical gain for the small and the large numerosities (fig. 3e). The test showed no significant difference between the canonical gain for the small ($M \pm SD = 1223.61 \pm 619.53$) and large ($M \pm SD = 1425.35 \pm 993.51$) numerosities, $t(21) = -1.12$, $p = 0.27$. The canonical gain was therefore analyzed separately for each numerosity using post-hoc pairwise comparisons (with Bonferroni correction). It was found that the canonical gain of numerosity 4 was significantly smaller from those of numerosities 5, 6, 7 and 8 (all $p < .05$) but it did not differ from the canonical gain of numerosity 9 ($p = .43$).

Similar results were obtained from the 2x6 repeated-measures ANOVA performed on the PCR: a main effect of *Configuration*, $F(1, 21) = 123.50$, $p < .001$, $\eta_p^2 = 0.86$, a main effect of *Numerosity*, $F(5, 105) = 6.32$, $p < .001$, $\eta_p^2 = 0.23$, and a significant interaction between *Configuration* and *Numerosity*, $F(5, 105) = 27.07$, $p < .001$, $\eta_p^2 = 0.56$. PCR were indeed significantly higher for the canonical configurations compared to the non-canonical configurations and they varied according to the numerosity (fig. 3d). The two-tailed paired-samples t-test conducted to compare the canonical gain for the small (i.e., 4-5-6) and the large (i.e., 7-8-9) numerosities revealed a smaller gain for the small ($M \pm SD = 20.20 \pm 15.76$) than for the large ($M \pm SD = 37.63 \pm 16.26$) numerosities, $t(21) = -3.94$, $p < .01$ (fig. 3f).

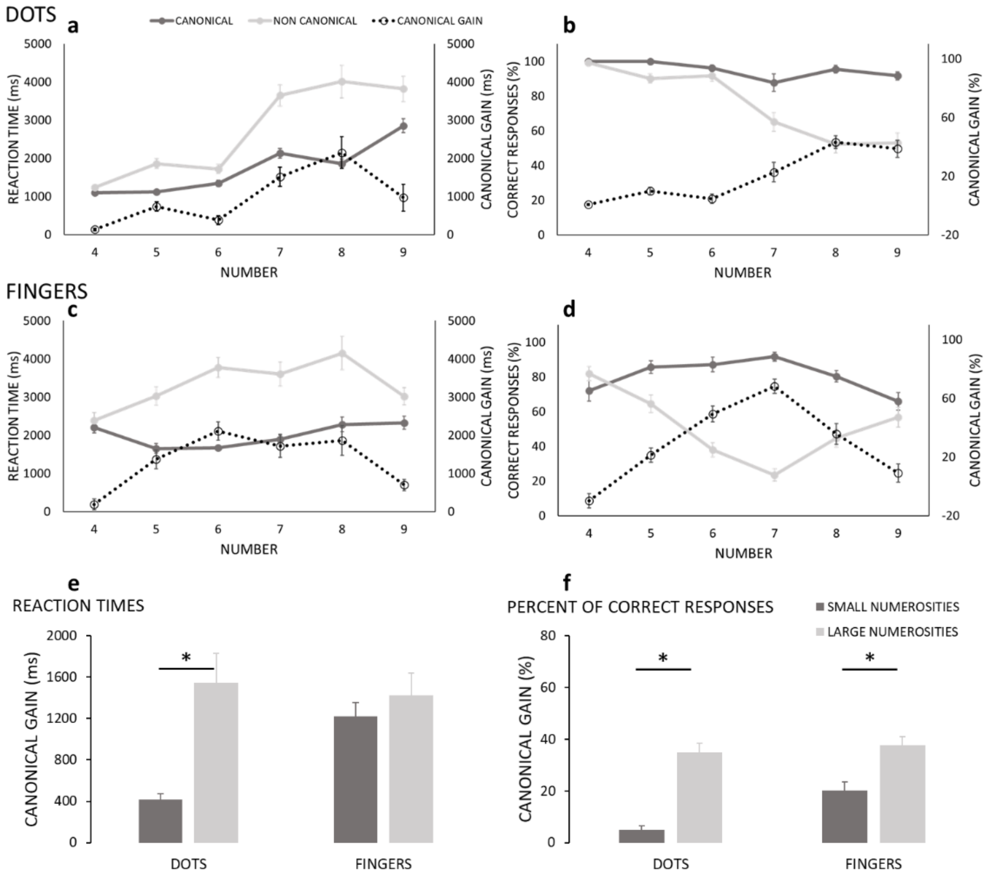

Figure 3. Naming task results. (a-d) Children's performance in the naming task for canonical (in dark grey) and non-canonical (in light grey) configurations. **Dot condition: (a) reaction times and (b) percent of correct responses** for each numerosity (4-9). **Finger condition: (c) reaction times and (d) percent of correct responses** for each numerosity. The dotted line shows the canonical gain resulting from the difference between the canonical and non-canonical configurations for each numerosity. (e-f) Mean canonical gain scores for small and large numerosities in the dot and finger conditions. **Canonical gain for (e) the reaction times** and **(f) the percent of correct responses**. Bars represent standard errors of the mean.

3.2 EEG results

3.2.1 Periodic responses

Responses synchronized with the base frequency (4 Hz) were significant up to 9 harmonics (from 4 Hz to 36 Hz). The electrodes showing the greatest response were O1 for the dots (fig. 4a) and PO8 for the fingers (fig. 4b). Sums of baseline-corrected amplitudes for the channels PO7, O1, Oz, O2 and PO8 were averaged, resulting in a base response amplitude of 2.90 μV in the dot condition and 4.35 μV in the finger condition.

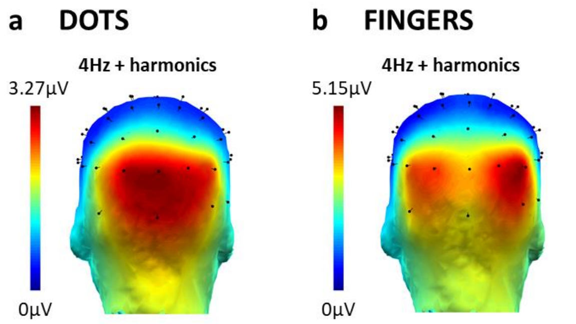

Figure 4. Base responses. Responses elicited at the base rate (i.e., 4 Hz) in the **(a) dot** and **(b) finger** condition. Topographies display the sum of amplitude responses for the significant ($Z > 1.64$) harmonics (from 4 Hz to 36 Hz).

Categorical responses elicited by the presentation of canonical configurations at a 0.8 Hz rate were significant from 0.8 Hz to 5.6 Hz (six harmonics excluding the base stimulation frequency). Scalp topographies of the sum of significant harmonics suggested posterior bilateral responses for dots and fingers (fig. 5). One child was excluded from the analyses of the finger condition because of an abnormally high amplitude in the right hemisphere (i.e., more than three standard deviations above the group average) and too much noise in the left hemisphere. Baseline-corrected amplitudes were summed and ranked for the 68 channels to identify the channels with the highest responses. In both conditions (i.e., dots and fingers) the eight channels showing the greatest amplitude of response were located in the parieto-occipital region (from 1.88 µV (PO8) to 0.96 µV (P9) for the dots; from 0.49 µV (PO8) to 0.25 µV (P10) for the fingers). Channels P7, P9, PO7, PO9 and contralateral channels P8, P10, PO8, PO10 were averaged to create left and right regions of interest (ROI) in the dot condition. To keep similar ROI while respecting the selection criteria for the channels with the highest responses, only electrodes P7, PO7, and P10, PO8 were averaged to create left and right ROI in the finger condition. SNR response spectra recorded on these channels are depicted on figure 5.

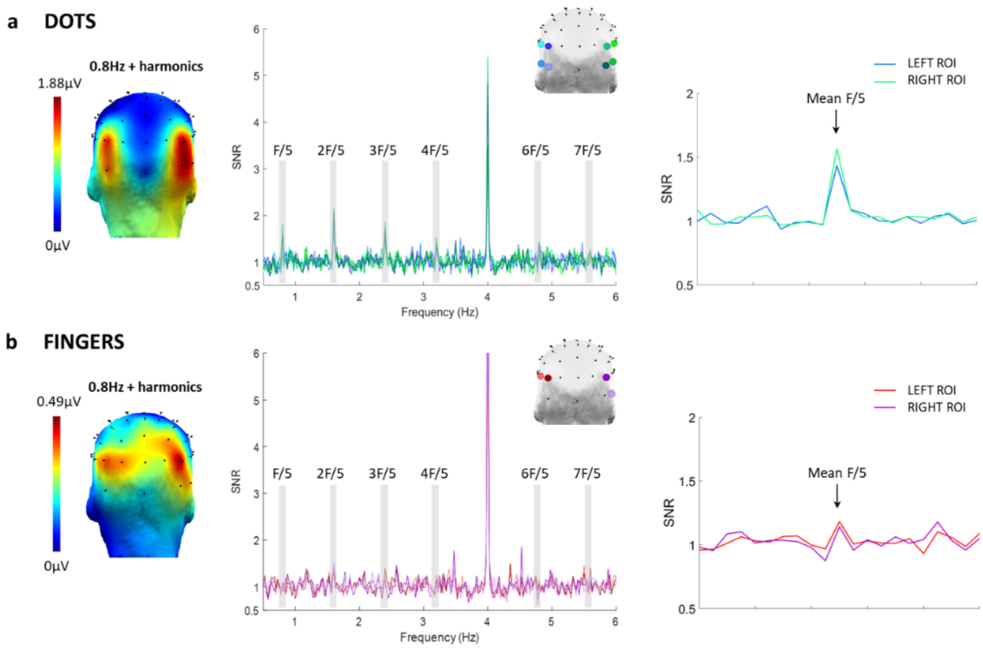

Figure 5. Categorical responses. Responses elicited by canonical detection in the **(a) dot** and **(b) finger** condition. Topographies (on the left) display the sum of amplitude responses for the significant ($Z > 1.64$) harmonics (from 0.8 Hz to 5.6 Hz, excluding the 4-Hz base frequency). SNR response spectra (middle and right) show the electrodes with the greatest response for each condition: P7, P9, PO7, PO9, P8, P10, PO8, PO10 for the dots and P7, PO7, P10, PO8 for the fingers. The frequencies of significant harmonics are marked as F/5 (0.8 Hz), 2F/5 (1.6 Hz) and so on until 7F/5 (5.6 Hz). The response at 4 Hz represents the response synchronized with the base stimulation frequency. On the right, the averaged SNR of the significant

harmonics (excluding the base) is represented centered with 10 surrounding bins on each side.

3.2.2 Lateralization scores and correlations with behavioral data

Lateralization scores (LS) were calculated for each child in each condition, as the difference between the amplitude responses in the right and the left ROI. Positive LS reflected right-lateralized responses (14/22 children for the dots; 10/21 children for the fingers) whereas left-lateralized responses were represented by negative LS. These LS ranged from -2.20 μV to 3.22 μV in the dot condition and there was no significant hemispheric dominance, $t(21) = 1.46$, $p = .16$ (fig. 6a). In the finger condition, LS ranged from -0.91 μV to 0.91 μV and there was no significant hemispheric dominance, $t(20) = 0.17$, $p = .87$ (fig. 6a).

Two-tailed Spearman non-parametric correlation analyses were then conducted to investigate whether the children's LS were correlated with their behavioral canonical gain score. In order to substantially reduce the number of correlations to be performed, Inverse Efficiency Scores (IES) were computed. These scores combined speed and error measures and were calculated as followed: $\frac{Mean(RT)}{Mean(PCR)}$, with Mean(RT) and Mean(PCR) corresponding respectively to the average RT and PCR for numerosities 4-9. The canonical gain score was then computed by subtracting the canonical IES from the non-canonical IES. Individual data and mean canonical gain of the group are depicted on figure 6b. One child was shown to have an abnormally high canonical gain score (i.e., around three standard deviations above the group average) in the finger condition and was therefore excluded from the finger's correlation analysis. As two correlations were performed (one for each condition), results were considered as significant when the p-value was smaller than 0.025 (0.05/2). Results did not show a significant correlation in the dot condition, $r_s(20) = 0.11$, $p = .64$ but revealed a significant correlation in the finger condition, $r_s(18) = 0.56$, $p = .011$ This positive correlation indicated that a higher canonical gain was associated with a right-lateralized response (fig. 6c).

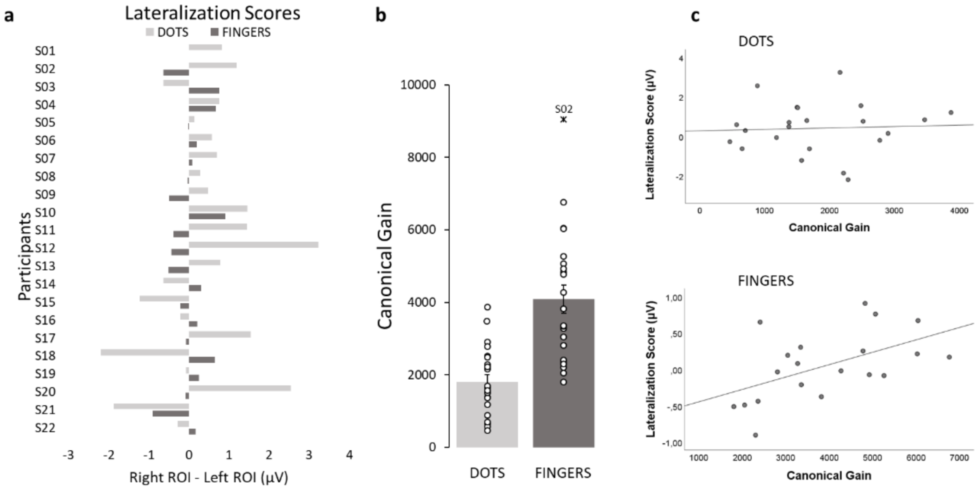

Figure 6. Lateralization scores and correlations with behavioral data. (a) Individual lateralization scores for the dot (in light grey) and the finger (in dark grey) condition. Note that participant S01 had been excluded from the finger's EEG analyses. **(b) Mean canonical gain** calculated on IES in the naming task, for the dots (in light grey) and the fingers (in dark grey). Dots represent individual data and bars represent standard errors of the mean. The star identifies the outlier. **(c) Correlation** between the lateralization scores and the canonical gain for each participant in both conditions (except participants S01 and S02 in the finger condition).

4 Discussion

During schooling, children acquire a system to represent numerical values symbolically. Similar to the pre-existing non-symbolic system, the new system allows children to manipulate or compare magnitudes, but now in exact, symbolic forms such as verbal numbers or Arabic digits. By learning to map the acquired symbolic system onto an already-existing non-symbolic system, children increase the accuracy of their numerical processes (Dehaene, 2011; Nosworthy et al., 2013; Price et al., 2012). This learning process is quite complex but can be boosted by the use of canonical finger and dot configurations (Benoit et al., 2004; Bloechle et al., 2018; Dawson, 1953; Hornung et al., 2017; Krajcsi et al., 2013; Mandler & Shebo, 1982; Van Rinsveld et al., 2020; Wender & Rothkegel, 2000). There is indeed evidence showing that different forms of canonical processing interact with numerical cognition (Kreilinger et al. 2020; Soylu et al., 2018, 2019). More particularly, it has been shown, at a behavioral level and in adults, that canonical configurations can trigger an automatic access to number semantics (Benoit et al., 2004; Di Luca & Pesenti, 2008). The aim of the present paper was to further investigate this question by examining the neural responses elicited by the detection of canonical configurations in 10-year-old children. We wanted to explore whether these brain responses may reflect an automatic access to semantic numerical information. Furthermore, we wanted to examine whether canonical configurations of fingers and dots would lead to comparable or different brain responses. We finally wanted to explore whether the brain responses to canonical (finger and dot) patterns relate to the children's number detection abilities in a numerosity naming task.

To examine these different questions, 10-year-old children were presented a behavioral naming task and a Fast Periodic Visual Stimulation Paradigm in EEG, both involving canonical and non-canonical dot and finger configurations. In accordance with the literature showing that fingers play a functional role in mathematics development, our behavioral results demonstrated that canonical finger configurations give a faster access to number semantics than non-canonical finger configurations (Di Luca & Pesenti, 2008). This conclusion was also supported by our EEG data showing that canonical representations of fingers elicited bilateral posterior (parieto-occipital) activity. This means that the brain extracted some common information over the deviant stimuli and generalized across the various numerosities.

Interestingly, dot enumeration was also faster and easier when the dots formed recognizable play card patterns. This last result is in line with Gestalt theories of perception (Wagemans et al., 2012) and probably refers to the "grouping" process, which is also reflected by the fact that the classical subitizing limit (increase of enumeration latencies with numerosities above 3) disappears when the items can be grouped into smaller subsets (Ciccione & Dehaene, 2020; Starkey & McCandliss, 2014; Wender & Rothkegel, 2000). As already observed with fingers, canonical representations of dots moreover elicited bilateral parieto-occipital activity. In the literature, bilateral parietal regions were identified as the brain areas responding to numbers across stimulus formats (Dehaene et al., 2003). Arabic numerals, spelled-out number words, and even non-symbolic stimuli like sets of dots or tones can indeed activate this region (Le Clec'H et al., 2000; Piazza et al., 2006; Pinel et al., 2001). Although our EEG data do not allow a precise localization of brain activity, they nevertheless indicate that the brain spontaneously reacted to the canonical nature of these numerical stimuli, with a response that was generalized across visual format (i.e. dots and fingers) and numerosities (i.e. 4-9 items).

Some differences between dot and finger configurations were nevertheless highlighted. Our behavioral data for example demonstrated that the enumeration of dot arrays was faster than finger naming. This might be observed for different reasons. First, the non-canonical configurations of dots could be more familiar and therefore processed faster than the non-canonical configurations of fingers. Second, finger patterns are not symmetrical (unlike dot patterns) but follow a specific order of fingers raised one after the other and therefore involves a kind of sequential processing (while processing is more simultaneous with dots, Kreilinger et al., 2021). Third, dot configurations allow for multiplication and addition (2 rows of 3 + 1 = 7 dots) while finger configurations only allow addition operations (one full hand of 5 fingers + 2 fingers makes 7). The canonical gain was nevertheless larger in the finger condition than in the dot condition. The fact that the canonical gain of the finger condition was so low for the numbers 4 and 9 (fig. 3) may moreover indicate that the representations of 5 and 10 as one or 2 full hands have a superior semantic anchor and therefore improve the processing of the numbers close to these references. Even in the non-canonical condition, participants may indeed have detected the numbers 4 and 9 by simply perceiving that one finger was lowered on one hand.

At the brain level, the neural response observed in the dot condition was larger than the one reported for the discrimination of canonical finger configurations. As already mentioned, shape-related effects were nevertheless present in this condition (Wagemans et al., 2012). Indeed, deviant stimuli were always a rectangular shape, while the non-canonical stimuli had more variable shapes. Given this confound with shape in the dot condition, we cannot preclude that the electrophysiological effect for the dot condition reflects visual processes. However, as the base rate response was smaller for dots than for fingers, we can reasonably assume that the generalization across canonical dot configurations also involves number detection. Such a clear distinction between shapes was not present in the finger condition. The interpretation of the effect is therefore easier in this condition, and the claims we make in favor of an automatic activation of number semantics can be stronger.

The finding that the parietal cortex is consistently activated across varying stimuli formats does, however, not necessarily imply that number is only represented within an abstract format-independent system. In recent years, there has accordingly been a growing interest in examining the number processing capacities of both hemispheres and the differences in the brain activation patterns of symbolic compared to non-symbolic number processing (Ansari et al., 2007; Cantlon et al., 2009; Holloway et al., 2010; Piazza et al., 2007; Venkatraman et al., 2005). Numerical magnitudes, regardless of their input format, may indeed be represented by a number-selective coding system situated in the parietal cortex but symbolic and non-symbolic quantities may reach this region through different pathways (Roggeman et al., 2007; Santens et al., 2010; Verguts & Fias, 2004). Whereas non-symbolic inputs access the number-selective representation through the posterior superior parietal cortex, the processing of symbolic inputs does not require this intermediate step. The symbolic status of numerical representation may instead stem from the fact that primary visual regions contact IPS directly or via a visual number form located in the left hemisphere (as suggested in the triple code model: Dehaene 1992).

As canonical representations of numbers possess a symbolic as well as a non-symbolic status, the present experiment aimed to examine whether the recognition of canonical representations of number could induce some hemispheric asymmetries. The symbolic status of canonical configurations is precisely conferred by the fact that their numerosity is recognized exactly without the need to be counted. However, these canonical configurations also remain non-symbolic since they carry by themselves the cardinality of the collection presented (Thevenot et al., 2014). As bilateral activations were reported for finger and dot configurations, our EEG data do not allow us to conclude that canonical representation of numbers have exactly the same status as enculturated numerical symbols preferentially represented in the left hemisphere. Interestingly, however, a significant association between the behavioral canonical gain and right-lateralized brain response was highlighted in the finger condition only. In line with two meta-analyses (Arsalidou et al., 2018; Sokolowski & Ansari, 2016) demonstrating that the left and right IPS might be functionally distinct along an *effortful-automatic continuum*, our data might therefore suggest a more automatized processing of canonical finger information and a more rule-based calculation processing of canonical dot configurations. Supporting this last idea, a study of Ciccione and Dehaene (2020) recently demonstrated that a visual grouping format facilitates the enumeration process because subgroups of dots allow for multiplication or combination of multiplication and addition, two rule-based calculation procedures.

To conclude, our data demonstrate that canonical configurations of dots and fingers can trigger a fast access to number semantics in 10-year-old children. While fingers seem to provide a more automatic access to number semantics than dots, future studies should further examine the specificities of finger and dot configurations in accessing the representation of numbers. It will also be important to further examine how grouping and form recognition affect the numerical meaning of canonical dot configurations. It would finally be very interesting to examine how and when these specific forms of (iconic) number representations develop. At what age do they arise? Are they similar or different in 10-year-olds and in adults? And (how) are they related to the emergence of responses to other number symbols (e.g., Arabic digits)?

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Chapter 3. A shared numerical magnitude representation evidenced by the distance effect in frequency-tagging EEG

Abstract

Humans can effortlessly abstract numerical information from various codes and contexts. However, whether the access to the underlying magnitude information relies on common or distinct brain representations remains highly debated. Here, we recorded electrophysiological responses to periodic variation of numerosity (every five items) occurring in rapid streams of numbers presented at 6 Hz in randomly varying codes – Arabic digits, number words, canonical dot patterns and finger configurations. Results demonstrated that numerical information was abstracted and generalized over the different representation codes by revealing clear discrimination responses (at 1.2 Hz) of the deviant numerosity from the base numerosity, recorded over parieto-occipital electrodes. Crucially, and supporting the claim that discrimination responses reflected magnitude processing, the presentation of a deviant numerosity distant from the base (e.g., base "2" and deviant "8") elicited larger right-hemispheric responses than the presentation of a close deviant numerosity (e.g., base "2" and deviant "3"). This finding nicely represents the neural signature of the distance effect, an interpretation further reinforced by the clear correlation with individuals' behavioral performance in an independent numerical comparison task. Our results therefore provide for the first time unambiguously a reliable and specific neural marker of a magnitude representation that is shared among several numerical codes.

Reference

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A shared numerical magnitude representation evidenced by the distance effect in frequency-tagging EEG[2]

1 Introduction

Humans must everyday deal with numerical information presented under various formats, codes and contexts. Imagine for example an activist demonstrating for the environment's sake who is asked to quickly estimate and then communicate the number of people gathered for the event. The activist's capacity to rapidly estimate the number of people will, on the one hand, rely on the so-called *Approximate Number System* (ANS), a preverbal process supporting the ability to grasp the numerosity of non-symbolic quantities (e.g., collections of items, Dehaene, 2011; Gallistel & Gelman, 2000). Its ability to share this numerical information to others will, on the other hand, depend on an acquired *Symbolic Number System* (SNS) based on specific, learned codes (e.g., Arabic digits or number words) (Ansari, 2008; Dehaene, 2011; Mundy & Gilmore, 2009). The mapping between the ANS and the SNS, which is considered as an essential step for the development of mathematical thinking (Brankaer et al., 2017; De Smedt et al., 2013; Kolkman et al., 2013) is furthermore supported by *iconic* representations of quantities (Di Luca & Pesenti, 2011; Kreilinger et al., 2021), such as canonical finger configurations (i.e., typical configurations of the hands used by an individual to count or to show a specific number) or canonical dot patterns (i.e., patterns found on play cards or dices).

A major issue in numerical cognition investigated here, is to understand how these various formats used to represent numerosities are abstracted and integrated in

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order to access the underlying common magnitude information. At first sight, the three formats are characterized by very different surface features leading to an increasing precision in the representation of numerosity, from the approximate non-symbolic, to the intermediate iconic and finally to the very precise symbolic format. However, some evidence suggests that they may be integrated in one shared magnitude representation system. First, a *distance effect* is found in both symbolic and non-symbolic comparison tasks (Halberda & Feigenson, 2008; Holloway & Ansari, 2009; Sasanguie et al., 2012; but see Marinova et al., 2021a). This effect refers to the improvement in our capacity to discriminate two numbers as the numerical distance between them increases (e.g., 3 *versus* 9 is easier than 3 *versus* 4; Dehaene et al., 1998; Moyer & Landauer, 1967). For symbolic numbers, given that any pair of symbols (e.g., 2/9 or 2/6) should be as discriminable, this finding suggests that they automatically activate their corresponding non-symbolic representation (Liu et al., 2018, but see Reynvoet & Sasanguie, 2016). Second, neuroimaging studies have consistently indicated a *common brain region* within the parietal cortex, lying in bilateral intraparietal sulci (IPS), to support the representation of magnitude irrespectively of the numerosity format (Arsalidou & Taylor, 2011; Dehaene et al., 2003; Eger et al., 2009; Nieder & Dehaene, 2009; Nieder, 2020), and this, in various tasks involving numerical comparisons. Finally, the brain activation level in bilateral IPS was found to be *modulated by the distance* between the numbers to be compared (Ansari et al., 2005; Eger et al., 2009; Holloway et al., 2010; Pinel et al., 2001). Thus, available evidence suggests the existence of a shared magnitude representation system, adequately assessed by the distance effect, a reliable marker of numerical semantic access.

However, the evaluation of magnitude processing in explicit comparison tasks could be affected by non-numerical factors like the available perceptual visual information (e.g., size, length, density, similarity, etc.), especially for the non-symbolic format (Gebuis et al., 2016). To overcome this issue, a new line of research has focused on the use of an implicit frequency-tagging EEG paradigm called the *fast periodic visual stimulation* (FPVS) design. This approach is based on the steady-state visual evoked potentials: under periodic visual stimulation at a certain frequency, brain regions coding for this visual input elicit a response at the exact same frequency. Therefore, knowing the stimulation frequency, it is possible to track the brain response with electroencephalography (Norcia et al., 2015). Frequencies of interest usually consist in a higher rate, reflecting the general visual stimulation (e.g., 6 images/second = 6 Hz) and a lower rate, at which a deviant stimulus is periodically inserted within the stream of images (e.g., every fifth image is a deviant, so that deviants appear at 6 Hz/5 = 1.2 Hz). Analyzing the brain responses elicited by the stimulation, a low-level response synchronized with the general (higher rate) stimulation frequency should emerge and, if the brain is able to both discriminate every deviant stimulus and generalize over the deviants' category, a selective response should also be observed at the lower rate frequency of the deviant presentation (Norcia et al., 2015). Recently, this paradigm was shown to provide a reliable measure of the spontaneous and automatic processing of non-symbolic (Georges et al., 2020; Guillaume et al., 2018; Van Rinsveld et al., 2020) and symbolic (Guillaume et al., 2020) numerosities. In the latter study (Guillaume et al., 2020), a stream of *base* digits were presented at a constant frequency of 10 Hz and a periodic *deviant* digit was introduced every eight stimuli (deviant presentation frequency of 10 Hz/8 = 1.25 Hz). To examine *magnitude* processing, digits smaller and larger than five were contrasted as base/deviant (and *vice versa*). In a *control* condition, the digits were arbitrary allocated to the base/deviant categories. Significant brain responses synchronized with the deviant magnitude presentation (1.25 Hz) were recorded over occipitoparietal regions, suggesting automatic discrimination of a magnitude change (smaller/larger than 5). However, and more unexpectedly, some responses were also observed in the control condition, suggesting that the brain was able to create a deviant category based on temporarily constructed rules. Therefore, it cannot be excluded that associative and/or physical confounding factors may have biased the responses observed in the experimental condition. This caveat is intrinsically linked to the use of Arabic digits, as there are only 9 different elements.

One potential way to address this issue could therefore be to vary the representation codes of numerosities. Increasing the variety of low-level physical parameters would indeed considerably reduce the possibility for the brain to create arbitrary associations or to detect regular repetitions. This would also give the possibility to assess numerical magnitude processing at a higher level of abstraction, as it would require participants to generalize magnitude information across formats. Accordingly, a recent study (Marinova et al., 2021b) used the same magnitude contrast (small/large, Guillaume et al., 2020) but with mixed codes (i.e., dots and digits, number words and dots, digits and number words). Results suggest an automatic integration of magnitude across number words and dots, digits and number words, but not dots and digits. There are, however, two limitations that are worth mentioning. First, the use of the non-symbolic format (i.e., dots) seems inadequate in a design which contrasts small (< 5) and large (> 5) numerosities. Small non-symbolic numerosities (below 4) were repeatedly shown to benefit from greater precision (i.e., they can be *subitized*) and better mapping with their corresponding symbolic representation (Feigenson et al., 2004; Hutchison et al., 2019; Mandler & Shebo, 1982; Sullivan & Barner, 2014; Van den Berg et al., 2020). Numerosities smaller than 3, moreover, have almost identical non-symbolic and iconic representations, while these two formats are clearly distinct for larger numerosities. Additionally, as small symbolic numerosities are more frequently encountered in daily life, it cannot be excluded that the responses obtained (Marinova et al., 2021b) actually reflect a difference of complexity in the processing of small *versus* large numerosities, rather than the processing of magnitude *per se*. A second limitation is that the representation codes were only compared two by two, which can supposedly be explained by the fact that the symbolic format contains two different codes (i.e., digits and number words) while the non-symbolic format is only represented by dots. While these comparisons allow for an examination of integration across formats, they only partially address the issue of low-level physical parameter biases discussed above.

In the current study, we overcame these two limitations by using two symbolic codes – Arabic digits and number words – and two iconic codes – canonical dot patterns and canonical finger configurations – that were mixed in order to create a multi-code design and combined with a FPVS paradigm. Going further than previous studies, we used here a more fine-grained measure of access to number semantics – the distance effect – instead of a rather coarse small/large magnitude contrast. Participants were visually presented with a stream of one specific numerosity (the base) at a constant frequency of 6 Hz (i.e., 6 stimuli per second) and a deviant numerosity was periodically inserted within the stream every fifth stimulus (i.e., 6 Hz /5 = 1.2 Hz). The deviant numerosity could be either close (e.g., 2222/3/2…, distance = 1) or distant (e.g., 2222/8/2…, distance = 6) from the base numerosity (fig. 1a), with a total of four close pairs (i.e., 2/3, 3/2, 8/9, 9/8) and four distant pairs (i.e., 2/8, 8/2, 3/9, 9/3). Finally, both the base and deviant numerosities were presented in randomly mixed codes (i.e., digit, word, dots and fingers). In addition to the brain response synchronized with the general visual stimulation rate (6 Hz), a brain response at the deviant presentation frequency (1.2 Hz) is expected if the brain is able not only to *discriminate* the deviant from the base numerosity (e.g., 3 is different from 2) but also to *generalize* over the deviant's various representation codes (e.g., the deviant is always 3 but presented as digit, word, dots or fingers). Furthermore, if this discrimination response truly reflects magnitude processing, a modulation of its amplitude should be observed according to the distance between the base and the deviant stimuli (e.g., larger discrimination responses in distant than close sequences). Participants were finally asked to perform a behavioral comparison task in which they had to choose the smaller/larger of two numerosities. Pairs of numerosities were the same as in the EEG experiment and also presented in randomly mixed codes (fig. 1b). The observation of a correlation between EEG and behavioral data would support the assumption that our FPVS multi-code design provides a reliable measure of magnitude processing.

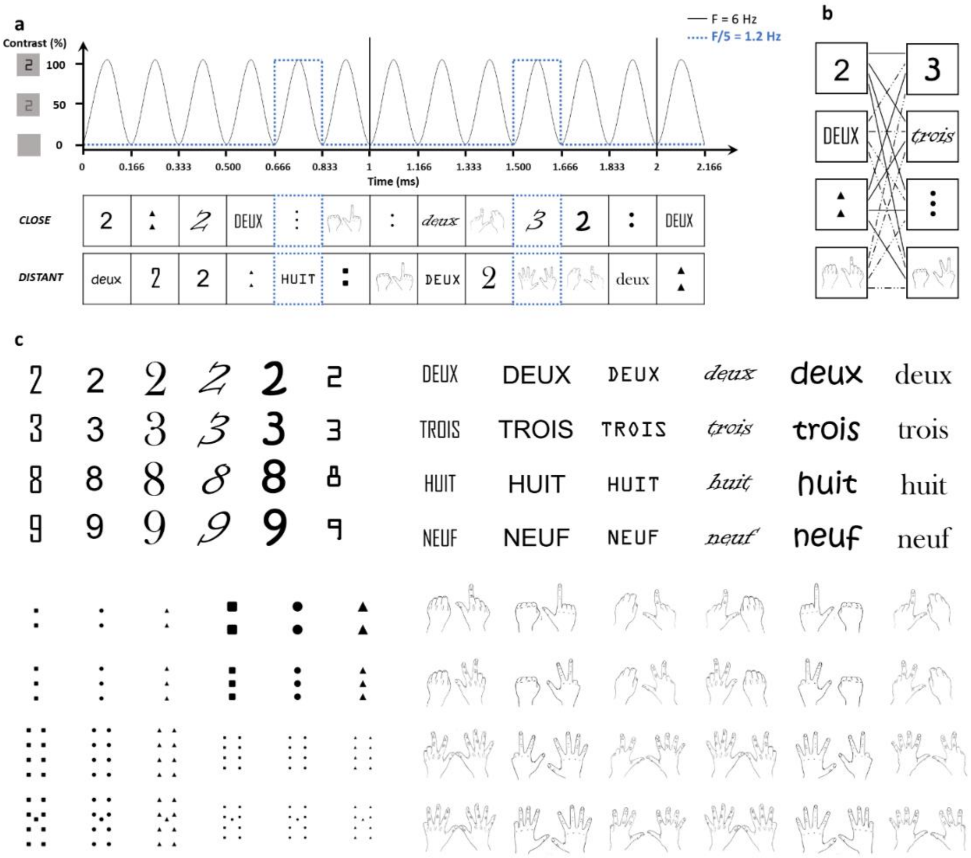

Figure 1. (a) EEG experimental design. Two numerosities were presented in randomly mixed codes (digit, word, dots, fingers) at a constant frequency of 6 Hz (i.e., 6 stimuli per second): a base numerosity (for instance “2”) and a deviant numerosity (for instance “3” in the close condition and “8” in the distant condition,) which appeared every fifth base stimuli (i.e., at 6 Hz/5 = 1.2 Hz, highlighted in blue). **(b) Behavioral task design.** Participants had to choose the smaller/larger of two numerosities (for instance the close pair “2/3”) presented in every possible code (digit, word, dots, fingers). Note: “deux” means “two” in French, “trois” means “three” and “huit” means “eight”. **(c) Stimuli.** Arabic digits, number words, canonical dot configurations (first three on the left control for the density and size of

the dots, last three on the right control for the luminance and total area occupied by the dots) and canonical finger configurations.

2 Methods

2.1 Participants

Twenty-five French speaking participants aged between 18 and 31 years old and with corrected-to-normal vision were tested, but two were excluded due to poor quality EEG signal. Analyses were therefore conducted on the remaining 23 participants (15 females, $M_{\text{age}} \pm SD_{\text{age}} = 22.17 \pm 2.8$). The procedures were in line with the Declaration of Helsinki and approved by the local "Comité d'Éthique Hospitalo-Facultaire Saint-Luc – UCLouvain" (2019/12SEP/400 – B403201941534). Participants gave their written informed consent and were compensated 10 € per testing hour.

2.2 Stimuli

Numerosities 2, 3, 8 and 9 were presented in four different codes – Arabic digit, number word, canonical dot pattern and canonical finger configuration (fig. 1c). For each numerosity, Arabic digits and number words were presented in six different fonts. Half of the words were written in upper-case, half in lower-case letters. Variations of font and case added some variability in the low-level perceptual features. In the same vein, three different geometrical forms (i.e., circles, triangles and rectangles) were used for the canonical dot patterns. As in previous studies (Crollen et al., 2010; Marlair et al., 2021), a first set of dots controlled for the density and the size of the dots while a second set controlled for the luminance and the total area occupied by the dots. Finally, canonical finger configurations were represented by the typical Belgian finger-counting configurations. Three different drawing designs were used and their mirror images were also included in the stimuli set. In total, all codes included six different representations of each numerosity (fig. 1c).

2.3 EEG procedure

Participants were seated at 1-m distance from a screen displaying stimuli with an 800 x 600-pixel resolution. The task consisted in eight sequences of 60 s stimulation, with additional 2 s of gradual fade-in and 1 s of gradual fade-out, created and executed with a software running on JavaScript (Java SE Version 8, Oracle Corporation, USA). During the sequences, 236 x 236-pixel numerosities were visually presented at the center of the screen at a constant frequency rate of 6 Hz (i.e., 6 items per second) by means of sinusoidal modulation of contrast from 0 to 100 % (fig. 1a). One base numerosity was presented throughout the sequence and a deviant numerosity was periodically inserted every fifth item (thus at 6 Hz/5 = 1.2 Hz frequency), both presented under different codes. The stimuli were randomly chosen in the stimuli set (fig. S1) with no immediate repetition of the same stimulus. The eight sequences were separated in four *close* pairs of base/deviant presentation (i.e., 2/3, 3/2, 8/9, 9/8) and four *distant* pairs (i.e., 2/8, 8/2, 3/9, 9/3, fig. 1a). Participants were instructed to fixate the center of the screen and pay attention to the numerical quantities presented. They could be asked, at the end of a sequence, which was the smallest or largest number they saw. When done so (37.5 % of the sequences) the task was flawless (100 % accuracy). A short break was made between each sequence to ensure low artifacts in the EEG signal.

2.4 EEG acquisition and preprocessing

EEG was recorded at 2048 Hz with a 68-channel BioSemi Active II system (BioSemi, The Netherlands). Sixty-four electrodes were placed according to the standard 10-20 system and four extra channels were added on posterior sites (PO9, PO10, I1, I2). The magnitude of the offset of all electrodes, referenced to the common mode, was held below 50mV. Analyses of the EEG data were carried out using Letswave 6 (https://www.letswave.org), an open-source toolbox running on MatLab (The MathWorks, USA). To reduce data processing time, data files were first downsampled to 512 Hz. Then, two Fast Fourier Transform filters were applied: a band-pass with cut-off values of 0.1-100 Hz and a multi-notch at three harmonics of 50 Hz. Data were segmented 2 s before and 1 s after each sequence for inspection of artifact-ridden or noisy electrodes. Less than 2 % of the channels were interpolated using the three nearest neighboring electrodes. The EEG signal was not corrected for the presence of ocular movements since the FPVS approach is highly immune to these ocular artefacts (Regan, 1989; Rossion, 2014). Each sequence was re-segmented from the stimulation onset (excluding the 2 s of gradual fade in) until 60 s, to include the largest amount of integer presentation cycles (72 cycles of 833.33 ms at the 1.2-Hz frequency). All channels were finally re-referenced to the common average.

2.5 EEG frequency domain analyses

To allow frequency domain analyses, a Fast Fourier Transformation was applied on each sequence. Normalized amplitude spectra were obtained for the 68 channels with a frequency resolution of 0.0167 Hz (1/60 s) and three indices were extracted from the data.

First, Z-scores were computed on the average amplitude spectrum for each condition (i.e., 4 sequences in the close condition and 4 sequences in the distant) to assess significant responses at the frequencies of interest (i.e., 6 Hz for the general visual stimulation and 1.2 Hz for the deviant presentation) and harmonics. At every channel, Z-scores were calculated with the formula: $Z(x) = \frac{x - mean(noise)}{standard\ deviation(noise)}$, where *x* represents a frequency bin and the *noise* is defined as the 20 surrounding bins of each target bin excluding the immediately adjacent and the extreme (min and max) bins (Liu-Shuang et al., 2014; Lochy et al., 2016; Retter & Rossion, 2016). The largest chain of consecutive harmonics with a Z-score larger than 1.64 ($p < .05$, one-tailed, signal > noise) determined the number of significant harmonics.

Then, the amplitude at each frequency bin was divided by the noise to compute the *signal-to-noise ratio* (SNR). SNR of the four sequences per condition (close and distant) across all participants were averaged in order to visualize the general peak responses and their distribution over the significant harmonics of the frequencies of interest.

Finally, to quantify the responses and visualize their topography, sums of *noise-corrected amplitudes* – obtained by subtracting the noise from the signal of each frequency bin – were calculated on the significant harmonics of the general visual stimulation frequency (6 Hz) and the deviant discrimination frequency (1.2 Hz, but excluding the 6-Hz frequency) in each distance's condition.

2.6 Behavioral comparison task

The task was created and executed with E-Prime 2.0 (Psychology Software Tools, USA). The participants were seated in front of a computer screen with a response button located on either hemispace. A fixation cross first appeared on the center of the screen for 500 ms. Then two numerosities (250 x 250-pixels size) were simultaneously presented on the left and right sides of the fixation cross (at equidistance from the central cross and the edge of the screen). The participants were asked to press as fast and as accurately as possible the button on the side corresponding to the smallest or to the largest magnitude. The instruction (i.e., press for the smallest/largest) was counterbalanced between subjects. The next trial began at button press. Reaction times and accuracy were recorded for every trial.

Half the trials presented close pairs of numerosities (i.e., 2/3 and 8/9) and the other half distant pairs (i.e., 2/8 and 3/9). For each pair, numerosities were presented on the left or on the right of a fixation cross (e.g., 2-left/3-right and 3-left/ 2-right). In both conditions (close and distant), the four pairs of numerosities (e.g., 2/3, 3/2, 8/9, 9/8 for the close) presented each possible code (i.e., digit, word, dots or fingers) facing all the codes. For each code, the stimuli were randomly chosen within the stimuli set (fig. 1c). In total, the multi-code task consisted in 2 conditions x 4 pairs x 4 codes presented on the left of the fixation cross x 4 codes presented on the right of the fixation cross, resulting in 128 trials. The trials were divided in two blocks separated by a short break.

3 Results

3.1 EEG responses

Clear peaks of responses were observed in signal to noise ratio spectra (SNR) at the general visual stimulation rate (6 Hz, fig. 2a) and also at the discrimination frequency, albeit visually stronger when the deviant was distant than close (1.2 Hz, fig. 2b). Significant responses ($Z > 1.64$) were found on 7 consecutive harmonics for general visual responses (from 6 to 42 Hz) and on 9 harmonics for discrimination responses (from 1.2 to 10.8 Hz, but excluding the 6 Hz frequency). In line with previous FPVS studies on numerical representation (Guillaume et al., 2020; Marinova et al., 2021b; Marlair et al., 2021), we expected posterior general and discrimination responses, although more visual activation was anticipated for the response to the general visual stimulation than for the discrimination process. This was indeed confirmed by a ranking of the electrodes based on their response amplitude revealing that channels P8, PO8, PO10, O2 elicited the highest general visual responses while channels P8, P10, PO8 and PO10 showed the highest discrimination responses within the right hemisphere. Those were therefore selected to create the right ROIs and contralateral channels (i.e., P7, PO7, PO9, O1 for the general response and P7, P9, PO7, PO9 for the discrimination response) were averaged to create the left ROIs. Amplitude values were then analyzed with 2 (Condition: close or distant) x 2 (Lateralization: left or right) repeated-measures ANOVAs, both for general visual responses and discrimination responses. Greenhouse-Geisser correction was applied when the assumption of sphericity was violated.

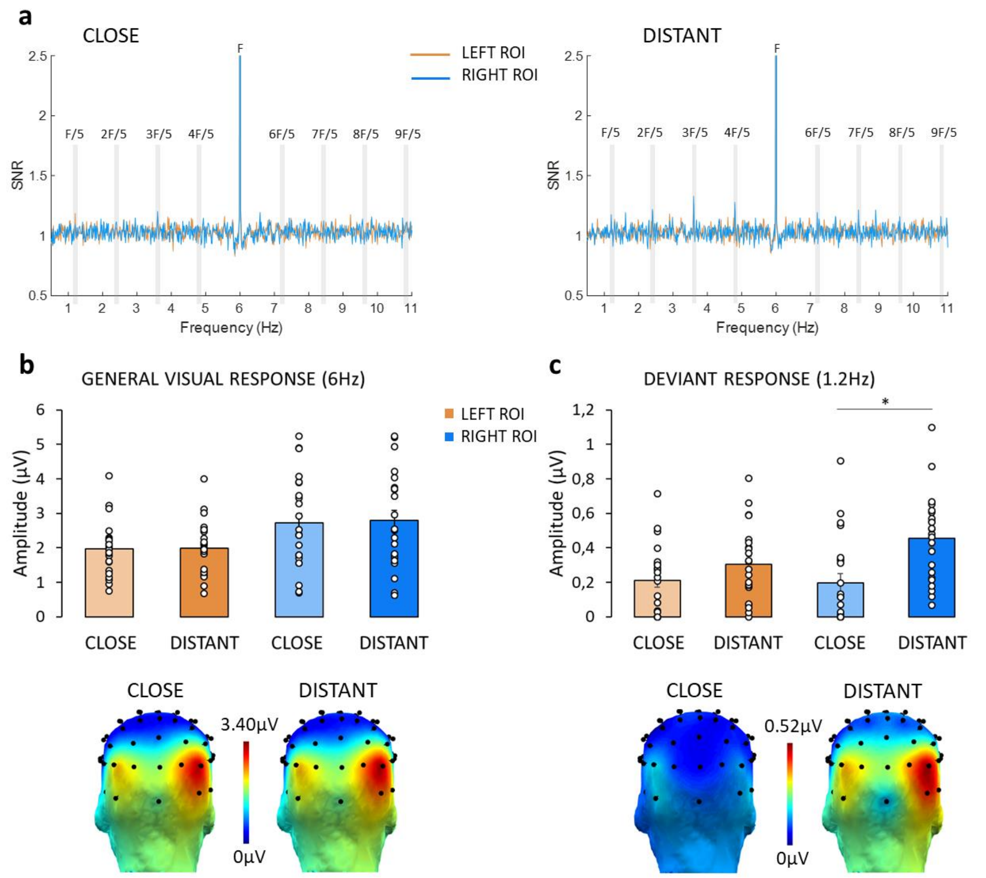

Figure 2. (a) Averaged SNR response spectra show the response peaks at the frequencies of interest in the left (orange) and right (blue) ROI, for the close (left panel) and the distant (right panel) conditions. F = 6 Hz for the general visual stimulation and F/5 = 1.2 Hz + harmonics (highlighted in grey) for the deviant stimulation. **(b) General visual response amplitudes and topographies.** Participant's responses in the left and the right ROI for the close and distant conditions. Topographies display the sum of noise-corrected amplitudes for the significant harmonics (from 6 to 42 Hz). **(c) Discrimination response amplitudes and topographies.** Responses elicited by the presentation of the deviant number in the close and the distant conditions, in the left and right ROI. Topographies display the sum of noise-corrected amplitudes for the significant harmonics (from 1.2 to 10.8 Hz, excluding the 6-Hz frequency). Dots show individual data and bars represent

standard errors of the mean. The asterisk (*) highlights a significant difference with $p < .01$ reflecting stronger discrimination responses for the distant condition in the right ROI only.

3.1.1 General visual responses

Close or distant conditions did not affect general visual responses, $F(1, 22) = 2.72$, $p = .11$, while there was a main effect of *Lateralization*, $F(1, 22) = 13.55$, $p = .001$, $\eta_p^2 = 0.38$, responses being larger in the right ROI ($M \pm SD$ = 2.75 µV ± 1.36) than in the left ROI ($M \pm SD$ = 1.98 µV ± 0.77). The interaction between *Condition* and *Lateralization* was not significant, $F(1, 22) = 1.43$, $p = .24$ (fig. 2b).

3.1.2 Discrimination responses

Distance effect. Results revealed a main effect of *Condition*, $F(1, 22) = 10.45$, $p = .004$, $\eta_p^2 = 0.32$, with larger responses when the deviant numerosity was distant ($M \pm SD$ = 0.38 µV ± 0.17) than close ($M \pm SD$ = 0.21 µV ± 0.19) from the base numerosity (fig. 2c). There was no effect of *Lateralization*, $F(1, 22) = 2.73$, $p = .11$, but a significant interaction between *Condition* and *Lateralization*, $F(1, 22) = 4.76$, $p = .04$, $\eta_p^2 = 0.18$. Paired t-tests per hemisphere showed a clear distance effect in the right ROI (0.26 µV stronger in distant sequences; $t(22) = -3.99$, $p = .001$), but not in the left ROI (0.9 µV; $t(22) = -1.38$, $p = .18$) (fig. 2c).

Individual sequence effect. In order to control for potential stimulus-driven low-level perceptual features that could influence discrimination of the deviant (e.g., larger discrimination response in the sequence 2/3 than 8/9 because 2 and 3 are visually more discriminable than 8 and 9?), we contrasted response amplitudes (averaged over left and right ROIs as there was no main effect of lateralization, fig. 2c) of individual sequence within each condition (table 1). No difference emerged, neither in the close, $F(3, 66) = 1.10$, $p = .35$, nor in the distant condition, $F(3, 66) = 1.80$, $p = .16$, comforting us in the lack of a major confound that would be due to the stimuli themselves.

The same results were obtained when analyzing responses in the ROIs separately. When contrasting right hemispheric response amplitudes of individual sequences within the close and distant conditions, we found no difference, neither in the close, $F(3, 66) = 0.56$, $p = .64$, nor in the distant condition, $F(3, 66) = 1.24$, $p = .30$. No difference emerged in the left ROI either, with $F(3, 66) = 1.32$, $p = .28$ in the close condition, and $F(3, 66) = 1.73$, $p = .17$ in the distant condition.

Order effect. Looking at individual sequences (table 1), it appears clearly that ascending sequences (i.e., the smallest number of the pair is the base and the largest is the deviant stimulus: 2/3, 8/9, 2/8, 3/9) systematically elicited larger discrimination responses than descending sequences (i.e., the largest number of the pair is the base and the smallest is the deviant stimulus: 3/2, 9/8, 8/2, 9/3). Averaging ascending and descending sequences within each condition, we tested for an effect of order (ascending or descending) and condition (close or distant) in a 2x2 repeated-measures ANOVA; Indeed, the main effect of Order was significant, $F(1, 22) = 8.15$, $p = .009$, $\eta_p^2 = 0.27$, ascending sequences elicited larger responses than descending ones ($M_{ascending} \pm SD_{ascending} = 0.41\ \mu V \pm 0.17$; $M_{descending} \pm SD_{descending} = 0.28\ \mu V \pm 0.15$). However, this effect did not interact with Condition (close/distant), $F(1, 22) = 0.62$, $p = .44$, meaning that the distance effect was present similarly for both ascending and descending sequences.

A modulation of performance for ascending/descending sequences was already found in other studies before and interpreted as due to a higher frequency of occurrence in daily-life and stronger associations for ascending sequences (e.g., forward counting is more frequent than backward counting) (Vos et al., 2017; Wong et al., 2021). Nevertheless, and consistently with a recent fMRI-adaptation study (Goffin et al., 2020), order did not influence the distance modulation of the discrimination responses.

Table 1. Discrimination response amplitude (mean and corresponding standard deviation) for each individual sequence. Note that the amplitude values reported here result from a noise correction at the individual sequence level.

		Close sequences		
Base/Deviant	2/3	3/2	8/9	9/8
Amplitude (μV):				
M (SD)	0.33 (0.35)	0.21 (0.22)	0.31 (0.24)	0.25 (0.26)
		Distant sequences		
Base/Deviant	2/8	8/2	3/9	9/3
Amplitude (μV):				
M (SD)	0.48 (0.38)	0.34 (0.26)	0.54 (0.42)	0.34 (0.31)

3.2 Behavioral results

To combine speed and error measures, inverse efficiency scores (IES, RT/ACC) were computed for close and distant conditions, averaging all code pairs (fig. 1b), and were ln-transformed to be compared. Results showed a significant distance effect, $t(22) = 9.41$, $p < .001$. As expected from the literature (Halberda & Feigenson, 2008; Holloway & Ansari, 2009; Sasanguie et al., 2012), participants were better to discriminate pairs of distant numerosities ($M \pm SD$ = 845.92 ms ± 123.15) than pairs of close numerosities ($M \pm SD$ = 1025.78 ms ± 194.90).

Given that multi-code pairs included two different types of format comparisons, either same format pairs (i.e., symbolic *vs.* symbolic, and iconic *vs.* iconic, fig. 3a "intra-format" presentations) or inter-format pairs (i.e., symbolic *vs.* iconic, fig. 3b "inter-format" presentations), and that this factor has been debated as affecting the distance effect (Marinova et al., 2018, 2021a), we assessed whether there was a difference between these two types of format pairs. The 2 (condition: close or distant) x 2 (format type: intra-format or inter-format) repeated-measures ANOVA revealed a main effect of *Condition*, $F(1, 22) = 89.94$, $p < .001$, $\eta_p^2 = 0.80$, but no main effect of *Format Type*, $F(1, 22) = 1.04$, $p = .32$, and no interaction between *Condition* and *Format Type*, $F(1, 22) = 1.48$, $p = .24$. The distance effect was therefore similar regardless of whether the comparisons involved intra- or inter-format presentations (fig. 3c). Let us note that the results of the inter-format type remained the same when removing a potential outlier (particularly high IES in the close condition of the inter-format presentations, fig. 3c), with a significant difference between *Conditions*, $F(1, 21) = 117.14$ $p < .001$, $\eta_p^2 = 0.85$, and no other significant effects ($ps > .35$).

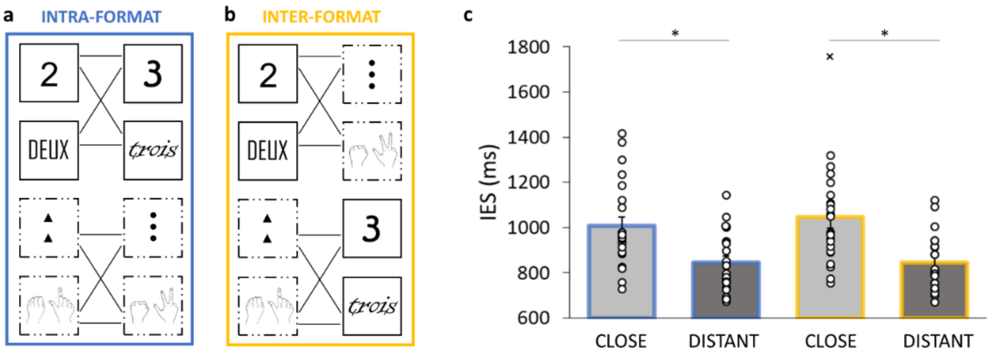

Figure 3. Example of pairs presented in the behavioral task. In intra-format presentations (a), pairs were both symbolic (i.e., digits or words) or iconic (i.e., dots or fingers); **In inter-format presentations (b)**, symbolic format (i.e., digits or words) faced an iconic format (i.e., dots or fingers) and *vice versa*. **(c) Participant's mean IES** in the close (light grey) and distant (dark grey) conditions, for the intra-format (blue) and inter-format (yellow) presentation types, which did not affect the distance effect. Dots show individual data and bars represent standard errors of the mean. Asterisks (*) highlight a significant difference between conditions with $p < .01$. The cross (ˣ) identifies the potential outlier.

3.3 Brain-behavior correlations

Subtraction scores were computed for each participant to quantify the distance effect both at the behavioral and brain levels, in order to relate them to each other. Behaviorally, IES in the distant condition was subtracted from IES in the close condition so that a large distance effect reflected a large difference in performance between close and distant pairs of numerosities. Distance effects ranged from 7 ms to 263 ms, apart from one participant who showed an abnormally high score (610 ms) and was therefore considered as a potential outlier. At the brain level, response amplitude observed in the close condition was subtracted from that in the distant condition. Only responses in the right ROI were used since the difference between conditions was not significant in the left ROI (fig. 2c). A large brain distance effect reflected a large difference between the response amplitudes in the close and distant conditions in the right ROI.

Results showed a clear relationship between participants' behavioral and brain distance effects, revealed by a positive correlation (one-tailed Spearman), $r_s(20) = 0.426$, $p = .024$ without the outlier, $r_s(21) = 0.387$, $p = .034$ with the outlier's data (fig. 4). A greater behavioral distance effect was therefore associated with a greater brain distance effect. This link was moreover specific to discrimination responses, as no such a correlation was found ($r_s(21) = 0.051$, $p = .41$) with the distance effect computed on the general visual response (i.e., difference between the response amplitudes at the general visual frequency, 6 Hz, in the close and distant conditions in the right ROI).

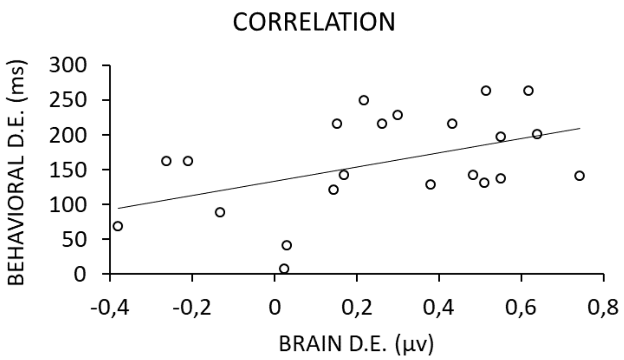

Figure 4. Significant correlation between the behavioral and brain distance effect (D.E.) for each participant except the outlier.

4 Discussion

Although humans can deal with various representations of numerical information (e.g., set of items, fingers configurations, Arabic digits, number words), it remains a challenging question to understand if and how the brain abstracts and integrates the common underlying magnitude information. Previous studies that have attempted to address this issue have systematically been hampered by the inherent confounds between numerical magnitude and low-level physical parameters (e.g., size, density, length, shape, etc). Here we overcame this difficulty by combining a *FPVS paradigm* – which can provide an objective and sensitive measure of numerical processing (Guillaume et al., 2018) – with the *distance effect* – considered as a reliable marker of numerical semantic access (Liu et al., 2018) – and a *multi-code presentation* of numerosities involving Arabic digits, number words, canonical dot patterns and canonical finger configurations. We observed significant discrimination responses of the deviant numerosity, modulated by distance, and with a topography compatible with bilateral parieto-occipital sites. Crucially, these responses reflect the brain's ability to generalize over the deviant's various representation codes and therefore provide robust evidence for an integration between the symbolic (i.e., digits and number words) and the iconic (i.e., canonical finger and dot patterns) formats.

Our results are in line with those of a recent event-related potential (ERP) study which showed evidence for an implicit (i.e., no decisional aspect involved) integration between the symbolic and the non-symbolic formats (Liu et al., 2018). Greater N1 and P2p amplitudes were indeed found when participants were simultaneously presented with a set of dots and a double-digit that matched in magnitude, than when the two numerosities mismatched. In our study, access to the common magnitude information underlying the symbolic and the iconic formats was successfully assessed by the distance effect. The discrimination responses were indeed found to be modulated by the numerical distance between the deviant and the base numerosities, with a significantly stronger response when the base and the deviant were distant (i.e., from 6 units) than close (i.e., from 1 unit). However, and in line with previous ERP and fMRI studies (Dehaene, 1996; Holloway et al., 2010; Piazza et al., 2007), only the right-lateralized responses were found to be modulated by the distance effect. An earlier adaptation fMRI study showed a cross-notation (dots and digits) distance effect within the right parietal cortex (Piazza et al., 2007), but the current findings extend their results in two important ways. First, we provide evidence for a higher level of integration by adding two new numerical representations – words and fingers. Second, contrary to this previous study which contrasted very large distances (i.e., 1-3 units in the close and 31-33 units in the distant conditions) that might have triggered some attentional-arousal system and amplified the activation of parietal cortex (Piazza et al., 2007), we show a more precise neural marker for distance using smaller numerosities and smaller distance between them.

Critically, the amplitude modulation due to distance was not found on the general visual responses, which confirms that the distance effect was specifically induced by the presentation of the deviant numerosity. In support to the claim that the discrimination responses reflect a reliable measure of numerical semantic access beyond mere physical aspects of the stimuli, we also showed that the individual pairs of numerosity presented (e.g., 2/3 and 8/9) did not affect the amplitude of the discrimination responses within each distance's condition (i.e., close or distant). This reinforces the idea that the methodological choice of using a multi-code design is a promising way to overcome the impact of non-numerical factors in the evaluation of magnitude processing. Because we maximized the changes in the physical parameters of the stimuli, it is also unlikely that the brain created temporary associations or detected some regular repetitions that would have induced the discrimination responses. The fact that individual sequences did not affect response amplitudes allows us, moreover, to exclude the possibility that the use of numerosities within (i.e., 2 and 3) or outside (i.e., 8 and 9) the subitizing range (Feigenson et al., 2004; Mandler & Shebo, 1982) could have influenced the results.

At the behavioral level, our data successfully showed the presence of a distance effect in the multi-code comparison task, which was reflected by better performance when participants compared distant than close pairs of numerosities. Furthermore, no cognitive cost was found when the comparisons required to switch between the numerical formats (i.e., from symbolic to iconic or *vice versa*), contrasting with the results of previous studies that used the non-symbolic format (Marinova et al., 2018, 2021a). Since the iconic format leads to greater precision in the representation of numerosity than the non-symbolic format, it could also benefit from a better integration with the symbolic format. Participants indeed showed similar performance when they had to compare intra-format (i.e., symbolic *vs.* symbolic and iconic *vs.* iconic) and inter-format pairs of numerosities (i.e., symbolic *vs.* iconic). As in the EEG experiment, these results therefore suggest an effortless integration between the symbolic and the iconic formats. Participants' behavioral distance effect (i.e., difference in performance between close and distant pairs of numerosities) was moreover associated with their brain distance effect (i.e., difference between the responses elicited by the presentation of a distant and a close deviant numerosity in the right hemisphere). Therefore and remarkably, these two independent measures of sensitivity to distance between numerosities were associated at the individual level, so that a greater sensitivity to distance at the behavioral level was reflected also in a greater sensitivity in brain responses. Crucially, this link between participants' behavioral and EEG data was not found at the general visual stimulation rate (6 Hz), confirming its specificity to distance processing.

Overall, these findings support the claim that the current multi-code FPVS approach can provide an objective, sensitive and yet specific measure of magnitude processing across digits, words, dots and fingers. One limitation of the current study worth mentioning, however, concerns the *spontaneous* nature of the sensitivity to distance. Indeed, although participants were not required to do any task during the EEG stimulation sequence, they were instructed to focus on the presented numerosities so that they could tell (if asked) which was the smaller/larger at the end of a sequence. Their attention was thus pre-directed towards magnitude information and this may have contributed to the emergence of the distance effect. Future studies could therefore specifically address this question by removing any instruction or by orienting participant's attention towards other numerical aspects, such as parity, to see whether the distance effect spontaneously emerges, or not, in these conditions.

To conclude, the current study provides strong evidence for the brain's ability to abstract, generalize and integrate magnitude information across Arabic digits, number words, canonical fingers and canonical dots patterns. Numerical semantic access was reliably assessed by the presence of a distance effect both in the EEG experiment, which was reflected by a modulation of response amplitude according to the distance between the base and the deviant numerosities, and in an independent behavioral numerical comparison task. Critically, brain and behavioral measures of the distance effect related to each other at the individual's level. Finally, the lack of difference in responses to individual sequences indicates that the present multi-code design, combined with a FPVS paradigm, can provide a specific, bias-minimizing measure of magnitude processing.

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6 Appendix: Data analysis of uni-code and intra-format presentations

The same methods as described in *Chapter 3* – i.e., fast periodic visual stimulation design and behavioral comparison task – were also used to investigate uni-code (i.e., canonical dots, canonical fingers, Arabic digits and number words) and intra-format (i.e., iconic: canonical dots-canonical fingers and symbolic: Arabic digits-number words) magnitude representations.

6.1 Uni-code presentations

6.1.1 EEG discrimination responses

Significant discrimination responses (Z > 1.64) were found on 13 consecutive harmonics (from 1.2 to 15.6 Hz, but excluding the 6 Hz and 12 Hz frequency). A ranking of the electrodes based on their response amplitude was done to determine the four channels showing the highest discrimination responses within each hemisphere. For canonical finger configurations, Arabic digits and number words, channels P7, P9, PO7, PO9 and P8, P10, PO8, PO10 were averaged to create the left and right ROIs respectively. For the canonical dot patterns, left and right ROIs were defined respectively as P7, PO7, PO9, O1 and P8, PO8, PO10, O2.

Distance effect. Amplitude values were analyzed with a 4 (Code: dots, fingers, digits or words) x 2 (Condition: close or distant) x 2 (Lateralization: left or right) repeated-measures ANOVA. Results showed a significant three-way interaction between *Code*, *Condition* and *Lateralization*, $F(3,66) = 2.86$, $p = .043$, $\eta^2_p = .12$. Follow-up pairwise comparisons revealed a significant distance effect (larger responses for distant than close sequences) for the canonical dot and finger configurations, but not for the Arabic digits and the number words (table 1, fig. 1). For dots and fingers, the distance effect was furthermore stronger in the right than in the left ROI ($p_s < .05$), although significantly present in both hemispheres.

Table 1. Difference between close and distant discrimination response amplitudes (in µV) and its associate *p-value* for each code and lateralization (left and right ROI). Significant ($p < .05$) difference is marked by an asterisk (*).

Dots		Fingers		Digits		Words	
Left	Right	Left	Right	Left	Right	Left	Right
1.11* (< .001)	1.48* (< .001)	0.61* (< .001)	1.00* (< .001)	0.05 (.55)	0.14 (.10)	0.03 (.76)	-0.03 (.72)

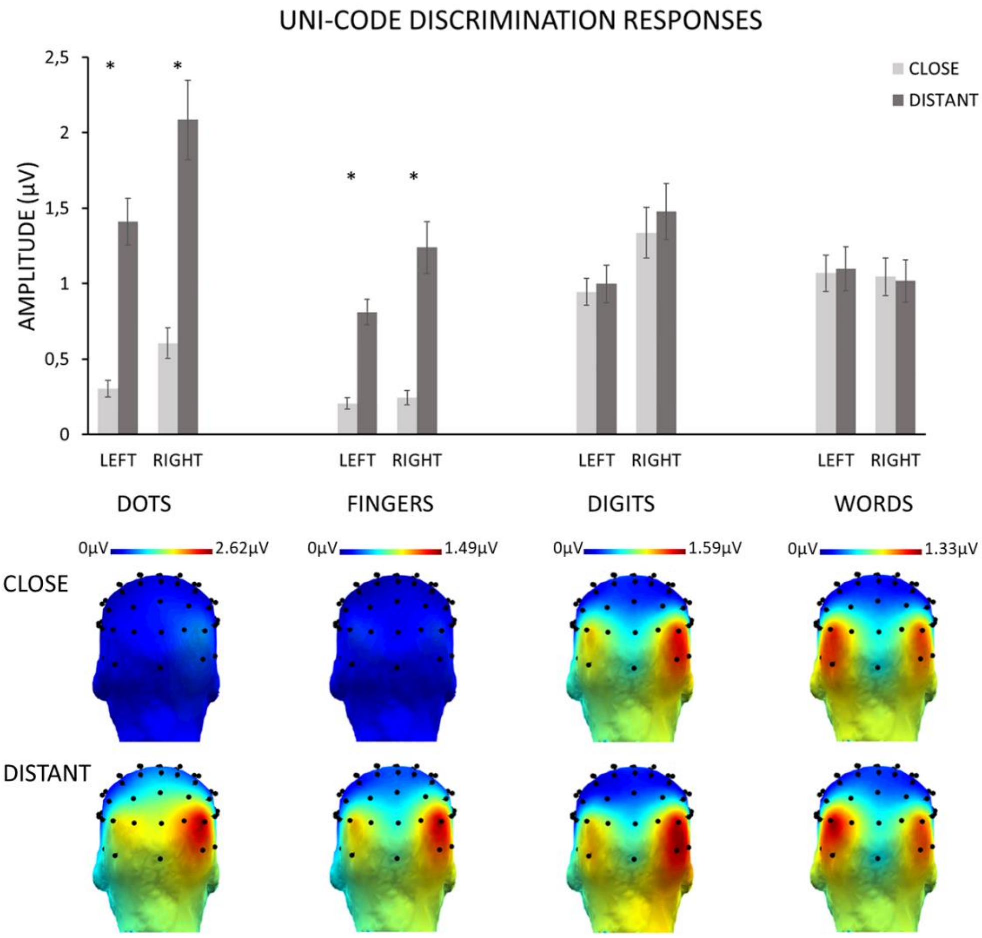

Figure 1. Uni-code amplitudes and topographies. Discrimination response amplitudes in close and distant conditions, for canonical dot patterns, canonical finger configurations, Arabic digits and number words, in the left and right ROI.

Topographies display the sum of noise-corrected amplitudes for the significant harmonics (from 1.2 to 15.6 Hz, excluding the 6- and 12-Hz frequency). Bars represent standard errors of the mean and significant ($p < .05$) differences between close and distant responses are marked by an asterisk (*).

Individual sequence effect. For each code (i.e., dots, fingers, digits and words), response amplitudes of individual sequence (averaged over left and right ROIs) were contrasted within both conditions (i.e., close and distant). Significant differences between sequences emerged in all conditions and codes ($p_s < .05$) except for the distant condition of number words ($p = .35$), suggesting that stimulus-driven low-level perceptual features may have influenced the discrimination of the deviant numerosity (table 2).

Table 2. Individual sequence discrimination response amplitudes (mean and corresponding standard deviation, in µV) for each code and condition. Note that the amplitude values reported here result from a noise correction at the individual sequence level. Significant ($p < .05$) difference between sequences is marked by an asterisk (*).

Dots		**Fingers**		**Digits**		**Words**	
Close* (.01)	Distant* (.003)	Close* (.02)	Distant* (< .001)	Close* (.006)	Distant* (< .001)	Close* (.002)	Distant (.35)
2-3	2-8	2-3	2-8	2-3	2-8	2-3	2-8
0.55	1.65	0.35	1.50	0.94	1.06	1.33	0.98
(0.40)	(0.78)	(0.43)	(0.94)	(0.55)	(0.62)	(0.76)	(0.75)
3-2	8-2	3-2	8-2	3-2	8-2	3-2	8-2
0.50	1.75	0.42	0.75	1.31	1.90	1.20	1.07
(0.50)	(1.30)	(0.45)	(0.52)	(0.90)	(1.21)	(0.75)	(0.72)
8-9	3-9	8-9	3-9	8-9	3-9	8-9	3-9
0.62	2.28	0.12	1.06	1.41	0.95	0.92	1.24
(0.54)	(1.15)	(0.17)	(0.66)	(0.96)	(0.68)	(0.73)	(0.80)
9-8	9-3	9-8	9-3	9-8	9-3	9-8	9-3
0.25	1.44	0.17	0.86	0.85	1.06	0.75	1.04
(0.32)	(1.13)	(0.22)	(0.54)	(0.59)	(0.63)	(0.57)	(0.82)

6.1.2 Behavioral results

To combine speed (RT) and error (ACC) measures, inverse efficiency scores (IES, RT/ACC) were computed for close and distant conditions. A 4 (Code: dots, fingers, digits or words) x 2 (Condition: close or distant) repeated-measures ANOVA on Ln-transformed IES revealed a significant interaction between *Code* and *Condition*, $F(3,66) = 26.11$, $p < .001$, $\eta^2_p = .54$. Follow-up pairwise comparisons showed a significant distance effect (i.e., lower IES/better performance in distant *versus* close comparisons) for each code (table 3, fig. 2). This behavioral distance effect was found to be significantly stronger for the canonical finger configurations as compared to the other codes ($p < .001$), but it did not differ between dots, digits and words ($p_s > .05$).

Table 3. Difference between close and distant IES (in ms) and its associate *p-value* for each code. Significant ($p < .05$) difference is marked by an asterisk (*).

Dots	Fingers	Digits	Words
124.1* (< .001)	287.8* (< .001)	87.5* (< .001)	90.0* (< .001)

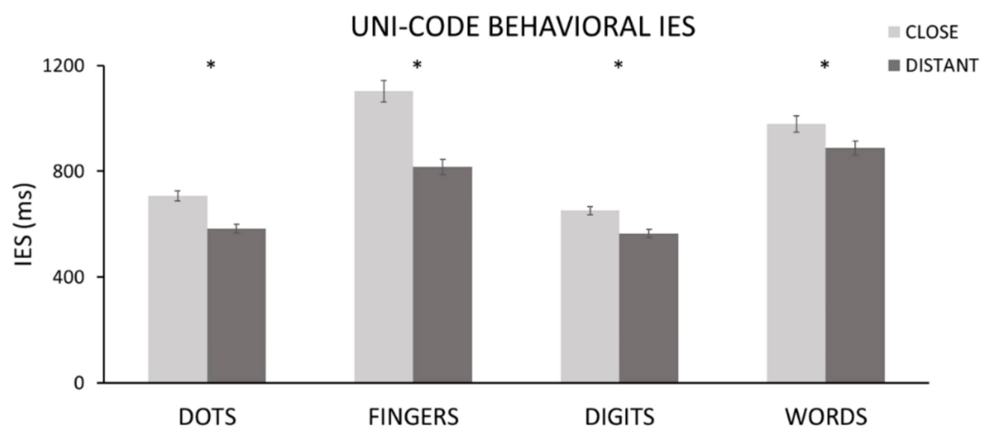

Figure 2. Uni-code behavioral IES in the close (light grey) and distant (dark grey) conditions. Bars represent standard errors of the mean and significant ($p < .05$) differences between condition are marked by an asterisk (*).

6.1.3 Brain-behavior correlations

Subtraction scores were computed for each participant to quantify the distance effect both at the behavioral and brain levels: behaviorally, distant IES were subtracted from close IES, while at the brain level, response amplitudes (averaged over left and right ROIs) in the close condition were subtracted from that in the distant condition. By doing so, a large distance effect reflected a large advantage of the distant condition over the close condition at both behavioral and brain levels. One-tailed Spearman correlations (with Bonferroni correction for multiple correlations) were performed but failed to show a significant correlation between behavioral and brain distance effects for the canonical dot patterns, canonical finger configurations, Arabic digits or number words (table 4, fig. 3).

Table 4. Correlation (one-tailed Spearman) between behavioral and brain distance effects and associated *p-value* for each code. Bonferroni correction for multiple comparisons was applied.

Dots	Fingers	Digits	Words
r_s = -0.29 (.37)	r_s = -0.19 (.79)	r_s = 0.36 (.19)	r_s = -0.01 (1.00)

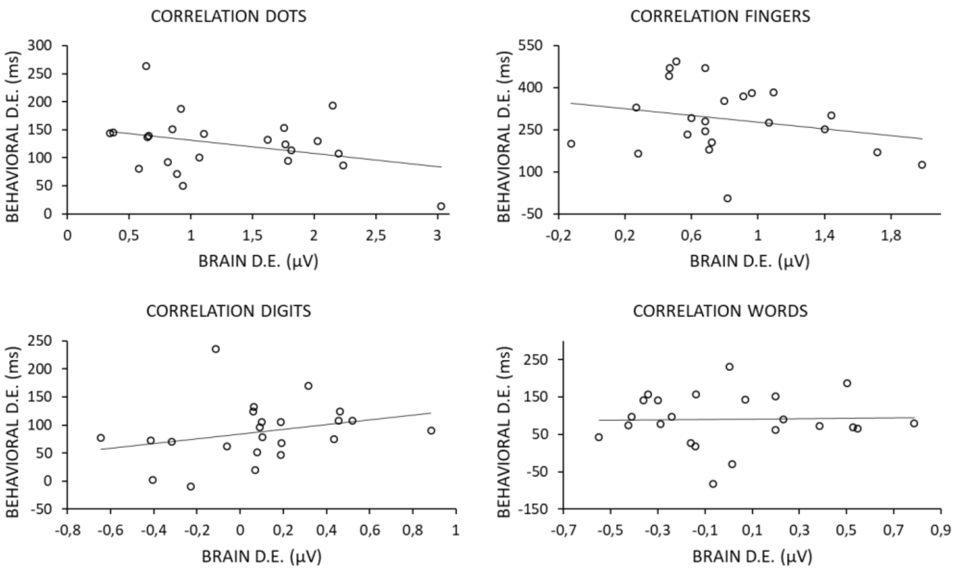

Figure 3. Uni-code correlations. Correlation between the behavioral and brain distance effect (D.E.) for each participant. None is significant (with p < .05, Bonferroni correction applied).

6.2 Intra-format presentations

6.2.1 EEG discrimination responses

Significant discrimination responses (Z > 1.64) were found on 13 consecutive harmonics (from 1.2 to 15.6 Hz, but excluding the 6 Hz and 12 Hz frequency). Based on the maximum amplitude ranking, channels P7, P9, PO7, PO9 and P8, P10, PO8, PO10 were averaged to create the left and right ROIs respectively for both the iconic and the symbolic formats.

Distance effect. Amplitude values were analyzed with a 2 (Format: iconic or symbolic) x 2 (Condition: close or distant) x 2 (Lateralization: left or right) repeated-measures ANOVA. Results showed a marginally significant three-way interaction between *Format*, *Condition* and *Lateralization*, $F(1,22) = 4.18$, $p = .053$, $\eta^2_p = .16$. Follow-up pairwise comparisons revealed a significant distance effect (larger responses for distant than close sequences) for both ROIs in the iconic format (albeit significantly stronger in the right ROI, $p = .003$) and for the right ROI only in the symbolic format (table 5, fig. 4).

Table 5. Difference between close and distant discrimination response amplitudes (in µV) and its associate *p-value* for each format and lateralization (left and right ROI). Significant (p < .05) difference is marked by an asterisk (*).

Iconic		**Symbolic**	
Left	Right	Left	Right
0.31* (< .001)	0.63* (< .001)	0.10 (.20)	0.17* (.043)

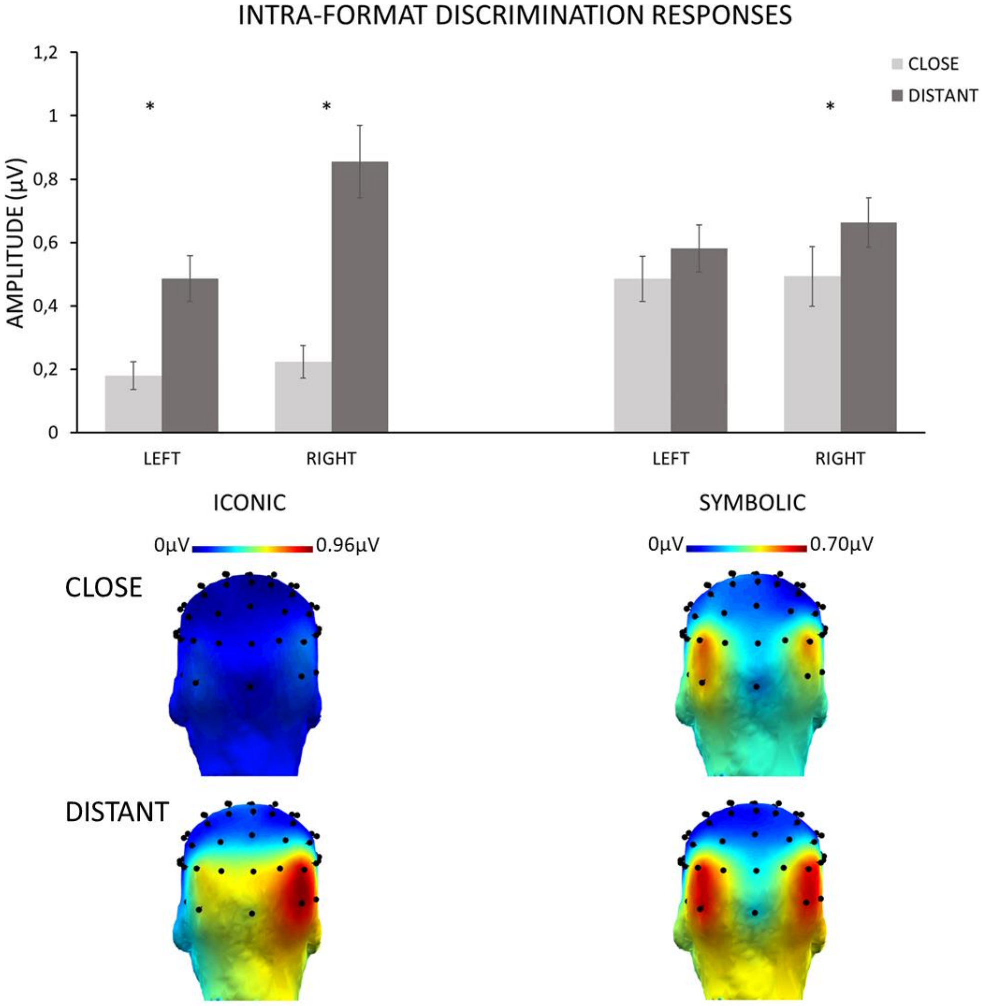

Figure 4. Intra-format amplitudes and topographies. Discrimination response amplitudes in close and distant conditions, for the iconic and the symbolic formats, in the left and right ROI. Topographies display the sum of noise-corrected amplitudes for the significant harmonics (from 1.2 to 15.6 Hz, excluding the 6- and 12-Hz frequency). Bars represent standard errors of the mean and significant ($p <$ .05) differences between close and distant responses are marked by an asterisk (*).

Individual sequence effect. For each format (i.e., iconic and symbolic), response amplitudes of individual sequence (averaged over left and right ROIs) were contrasted within both conditions (i.e., close and distant). While no difference emerged in the close condition of the iconic format (p = .30) and in the distant condition of the symbolic format (p = .17), there was a significant difference between sequences in the distant condition of the iconic format (p < .001) and a marginally significant difference in the close condition of the symbolic format (p = .065, table 6).

Table 6. Individual sequence discrimination response amplitudes (mean and corresponding standard deviation, in µV) for each format and condition. Note that the amplitude values reported here result from a noise correction at the individual sequence level. Significant (p < .05) difference between sequences is marked by an asterisk (*), marginally significant (p = [.05-.07]) by a degree sign (°).

Iconic		**Symbolic**	
Close (.30)	Distant* (< .001)	Close° (.065)	Distant (.17)
2-3 0.32 (0.28)	2-8 0.89 (0.53)	2-3 0.45 (0.47)	2-8 0.52 (0.44)
3-2 0.22 (0.35)	8-2 0.34 (0.36)	3-2 0.59 (0.47)	8-2 0.82 (0.71)
8-9 0.17 (0.19)	3-9 1.11 (0.78)	8-9 0.64 (0.59)	3-9 0.53 (0.37)
9-8 0.22 (0.34)	9-3 0.42 (0.38)	9-8 0.36 (0.42)	9-3 0.59 (0.39)

6.2.2 Behavioral results

Inverse efficiency scores (IES, RT/ACC) were computed for close and distant conditions to combine speed (RT) and error (ACC) measures. A 2 (Format: iconic or symbolic) x 2 (Condition: close or distant) repeated-measures ANOVA on Ln-transformed IES revealed a significant interaction between *Format* and *Condition*, $F(1,22) = 11.63$, $p = .003$, $\eta^2_p = .35$. Follow-up pairwise comparisons showed a significant distance effect (i.e., lower IES/better performance in distant *versus* close comparisons) for both format (table 7, fig. 5), albeit significantly stronger for the iconic than the symbolic (p = .001).

Table 7. Difference between close and distant IES (in ms) and its associate *p-value* for each format. Significant ($p < .05$) difference is marked by an asterisk (*).

Iconic	**Symbolic**
243.8* (< .001)	92.8* (< .001)

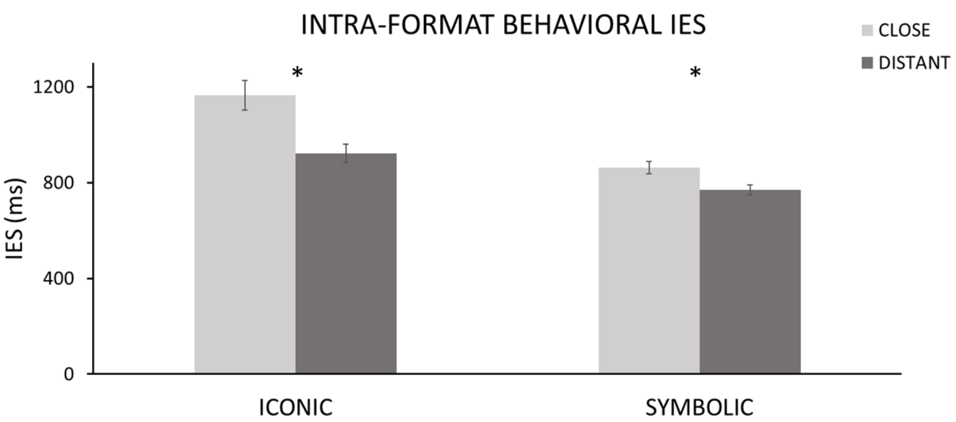

Figure 5. Intra-format behavioral IES in the close (light grey) and distant (dark grey) conditions. Bars represent standard errors of the mean and significant ($p < .05$) differences between condition are marked by an asterisk (*).

6.2.3 Brain-behavior correlations

Subtraction scores were computed for each participant to quantify the distance effect both at the behavioral and brain levels: behaviorally, distant IES were subtracted from close IES, while at the brain level, response amplitudes (averaged over left and right ROIs) in the close condition were subtracted from that in the distant condition. By doing so, a large distance effect reflected a large advantage of the distant condition over the close condition at both behavioral and brain levels. One-tailed Spearman correlations (with Bonferroni correction for multiple comparisons) were performed and revealed a significant correlation between participant's behavioral and brain distance effects for the symbolic format, $r_s(21) = 0.431$, $p = .04$, but not for the iconic format, $r_s(21) = 0.198$, $p = .36$ (fig. 6).

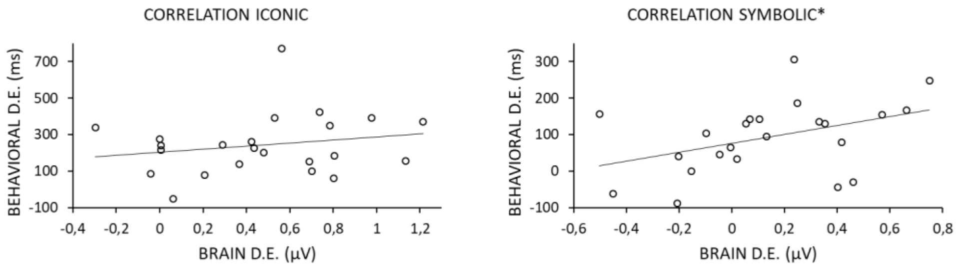

Figure 6. Intra-format correlations. Correlation between the behavioral and brain distance effect (D.E.) for each participant. It is significant for the symbolic format, but not for the iconic format (with $p < .05$, Bonferroni correction applied).

6.3 Discussion

As discussed in the main text of *Chapter 3*, extreme caution should be taken when interpreting FPVS responses because of the possible implication of low-level perceptual biases or arbitrary rule-based categorization processes. This is particularly true regarding the uni-code conditions. Despite the efforts devoted in varying the low-level visual features of the stimuli – such as using different fonts for the Arabic digits and number words – and in controlling for typical confounds of dot arrays (i.e., density, size, luminance, total area, see *2.2 Stimuli*), it is likely that these parameters contributed to the observed discrimination responses. For instance, in the Arabic digit sequence 2/8 (base/deviant), visual differences between the symbol “2” and the symbol “8” may be (at least partially) the source of the responses elicited at the frequency of the deviant presentation (i.e., at 1.2 Hz). With the same reasoning, the number word “deux” (“two” in French) is also visually distinguishable from the word “huit” (“eight” in French) and canonical eight-finger/dot configurations inevitably differ in density from canonical two-finger/dot configurations. Choosing the distance effect as a marker for magnitude processing increased the problem (but offered other advantages discussed in the main text), since it compelled us to limit the base and deviant presentation categories to a single numerosity. This issue was indeed less prominent in studies using a small/large magnitude contrast (e.g., Guillaume et al., 2020; Marinova et al., 2021a) as there were much more visual variations within the base and the deviant presentation categories (but see *1 Introduction* for other limitations of this design). The tricky part is that it is virtually impossible to distinguish the portion of the discrimination response that is attributable to the periodic change in the manipulated feature (in this case magnitude), from that caused by changes in low-level visual properties. However, as the distance effect is obtained by comparing discrimination responses elicited in close and distant sequences, and because there is no *a priori* reason that these responses would be differently impacted by low-level parameters, it could be argued that the resulting effect relates to magnitude change beyond other visual variations. While keeping in mind these caveats and trying to avoid over-interpretation, we thought that it was nevertheless worthwhile to examine the results of the uni-code and intra-format presentations.

All codes (i.e., dots, fingers, digits and words) showed significant discrimination responses at the frequency of magnitude variation (i.e., 1.2 Hz), concentrated over parieto-occipital sites. Topographies of these discrimination responses were thus consistent with previous FPVS findings for canonical dot and finger patterns (Marlair et al., 2021) and for Arabic digits and number words (Marinova et al., 2021a). The canonical dot condition, however, involved more visual processes than it was previously found (Marlair et al., 2021), which might already reflect the contribution of low-level perceptual features (e.g., size, total area) in the discrimination of the deviant magnitude. Furthermore, canonical dots and fingers discrimination responses were significantly modulated by the distance effect, with stronger responses being elicited when the deviant numerosity was distant (e.g., 2/8) than close (e.g., 2/3) from the base numerosity (fig. 1). This is likely to reflect their "in-between" (or iconic) status, meaning that canonical dot and finger configurations inherently share some properties of pure non-symbolic representations. In contrast, neither Arabic digits nor number words discrimination responses were affected by the distance between the base and the deviant numerosities. These findings seem in agreement with the idea that number symbols do not automatically activate their corresponding non-symbolic magnitude representation and would instead be processed by a distinct, more precise, system (Marinova et al., 2021b). As an alternative explanation, it could be that the distance effect in Arabic digit and number word sequences was countered by visual differences between base and deviant numerosities (e.g., it could be that close pairs were perceptually more distinguishable than distant pairs). In this view, it is also possible that low-level perceptual features have favored the emergence of a distance effect in the canonical dot and finger conditions. Differences observed at the individual sequence level (table 2) strengthen the hypothesis that stimulus-driven low-level perceptual features may have influenced discrimination of the deviant numerosity. Indeed, if magnitude variation had been the sole information contributing to discrimination responses, we could have expected that equal magnitude change (i.e., all close sequences or all distant sequences) would yield similar amplitudes. At the behavioral level, a significant distance effect was observed for each code in an independent comparison task (fig. 2). With regard to the two symbolic codes (i.e., digits and words), the brain and behavioral data thus seem to support opposite conclusions. Yet, it was argued that explicit comparisons between symbols might urge participants to activate their corresponding magnitude (Lyons et al., 2012). Thus, the discrepancies between the brain responses and the behavioral measures for digits and words could stem from the use of an implicit *versus* explicit paradigm. Beyond this, the lack of correlation between brain and behavioral data (fig. 3) ultimately casts doubt on whether these uni-code presentations reliably assessed numerical magnitude processing.

Regarding the within-format presentations (i.e., combination of canonical dot-finger patterns and combination of digits-number words), both iconic and symbolic sequences led to significant discrimination responses (i.e., at 1.2 Hz), which were also located over parieto-occipital regions. In line with the uni-code findings, discrimination responses resulting from the combination of canonical dot and finger patterns were significantly modulated by the distance condition (i.e., close *versus* distant), and this effect was more pronounced in the right hemisphere than in the left (fig. 4). We however failed to show a correlation between these brain responses and the behavioral distance effect measured in the iconic comparison task (fig. 6). Hence, even when combining canonical dot and finger configurations, it is possible that the distance effect on brain activity was mostly reflecting the involvement of low-level visual cues rather than (or more than) the access to numerical magnitude representation. Interestingly enough, a distance effect was also observed on the symbolic discrimination responses (i.e., combination of Arabic digits and number words). These findings could be interpreted as the fact that, when presented with two symbolic codes, the brain automatically activates their corresponding magnitude in order to integrate numerical information, thus eliciting a distance effect. This hypothesis is further reinforced by the finding of a significant correlation with the behavioral distance effect in the symbolic comparison task. It should be noted, however, that although both hemispheres seemed to show a tendency towards larger discrimination responses for distant than close sequences (fig. 4), the distance effect was only found to be significant in right parieto-occipital sites. This might suggest that while the right hemisphere favors the integration of numerical symbols by activating their corresponding magnitude representation, the left hemisphere could rather be involved in the association between digits and number words via a direct asemantic link (Dehaene & Cohen, 1995). However, similar patterns of results were obtained for iconic discrimination responses (i.e., larger distance effect in right than left posterior brain regions) and for the multi-code presentation (i.e., distance effect in right, but not left, parieto-occipital sites, see *3 Results*). Therefore, an alternative interpretation could be that both left and right hemispheres hold a shared magnitude representation, but they might differ in terms of the precision of numerical coding (Piazza et al., 2007). It would be interesting for future studies to directly address the hemispheric asymmetry in numerical processing.

6.4 References

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Chapter 4. Frequency-tagging EEG reveals instruction-driven magnitude integration using the numerical distance effect

Abstract

While humans can readily access the common magnitude of various codes such as digits or dot sets, it is not yet clear whether this integration occurs spontaneously, or only when involved in explicit magnitude processing. We addressed this question by examining the neural distance effect, a robust marker of magnitude processing, with a frequency-tagging approach. By varying the instructions given to participants, we compared spontaneous processing of visually presented numerosities to explicitly oriented processing of magnitude or parity. Electrophysiological responses were recorded while participants were viewing rapid sequences of a base numerosity presented at 6 Hz (e.g., “2”) in randomly mixed codes: digits, number words, canonical dots and fingers. A deviant numerosity either close (e.g., “3”) or distant (e.g., “8”) from the base was inserted every five items. We observed clear discrimination responses of the deviant numerosity despite its code variation. The distance effect (larger responses when base/deviant are distant than close) was present when participants were explicitly oriented to magnitude and parity, but not in simple viewing. We thus argue that abstract magnitude processing is only partly spontaneous. It indeed requires sufficient cognitive resources to be engaged in numerical processing, but occurs whatever semantic aspect of numbers is activated.

Reference

Marlair, C., Lochy, A., & Crollen, V. (under review). Frequency-tagging EEG reveals instruction-driven magnitude integration using the numerical distance effect. *Psychonomic Bulletin and Review.*

Frequency-tagging EEG reveals instruction-driven magnitude integration using the numerical distance effect[3]

1 Introduction

Magnitude is among the most salient and important semantic features of numbers. Because all numerosities, regardless of their notation (e.g., digits, words, dots, fingers), carry magnitude information, there has been considerable interest in understanding whether magnitude is represented in an abstract (i.e., notation-independent) and integrated way. Despite some mixed results (see for instance Marinova et al., 2018, 2021a), a substantial amount of behavioral and neuroimaging studies provided evidence in favor of a shared magnitude representation (Piazza et al., 2007, Holloway et al., 2010; Liu et al., 2015, 2018; Nieder, 2020). Marlair et al. (2022) recently showed that the brain was able to generalize and integrate magnitude information across Arabic digits, number words, canonical finger and dot patterns. In that study, the authors used an implicit frequency-tagging EEG paradigm known as fast periodic visual stimulation (FPVS) with a so-called oddball design (Norcia et al., 2015). Participants were visually presented with a stream of one base numerosity at a constant frequency of 6 Hz and a deviant numerosity was periodically inserted within the stream every fifth stimulus (i.e., at 6 Hz /5 = 1.2 Hz). Both base and deviant numerosities were presented in randomly mixed codes. Results revealed clear electrophysiological responses at 1.2 Hz reflecting the brain's capacity to discriminate the deviant numerosity from the base and to generalize over the deviant's presentation codes (i.e., digit, word, fingers and dots). Most importantly,

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larger discrimination responses were observed when the deviant numerosity was numerically distant from the base numerosity (e.g., base/deviant = 2/8) than when they were numerically closer (e.g., base/deviant = 2/3), which supported the presence of a neural distance effect (Moyer and Landauer, 1967; Dehaene et al., 1998) and thus confirmed the processing of magnitude information in posterior brain regions (Guillaume et al., 2020; Marinova et al., 2021b). This neural distance effect correlated furthermore with behavioral distance effect.

The FPVS technique has proven to be very relevant for assessing the automaticity and objectivity of a specific cognitive function, since it avoids the implication of decision-making processes during the EEG recordings (Guillaume et al., 2020; Rossion, 2014). However, in the study of Marlair et al. (2022), participants' attentional focus was pre-directed to magnitude as they were told prior to the experiment that they might be asked to report the smallest/largest numerosity presented during a sequence. Therefore, although the participants did not have to perform any explicit comparison task during the stimulation, magnitude information was nonetheless relevant to answer the examiner's question. Recently, it has been argued that a distinction should be made between automatic processes: they can be either intentional, if the process remains beneficial and relevant to the ongoing task, or spontaneous, if the process is triggered even when it is irrelevant to the ongoing task (Guillaume et al., 2020). Given this distinction, the data from Marlair and colleagues (2022) only allow us to argue that magnitude integration is an automatic intentional process, but leaves open the question of whether it can occur spontaneously, or even when attention is directed towards other semantic features of numerals such as parity.

Magnitude and parity were previously found to be spontaneously extracted from Arabic digits. Using an FPVS design, Guillaume and colleagues (2020) assessed magnitude processing by contrasting small (1-4) and large (6-9) digits as base/deviant (and *vice-versa*) while parity processing was assessed by contrasting odd and even digits. Crucially, participants were instructed to monitor occasional color-changes in a central fixation diamond to avoid explicit attentional focus on the digits. Clear discrimination responses to the periodic semantic change were observed, but since these experiments only contrasted two categories, there is no guarantee that the semantic feature that was manipulated by the authors (e.g., magnitude or parity) was the sole information triggering these measurable discrimination responses. For instance, digits that are odd or even are also simply visually different, which could contribute to the neural response elicited at the frequency of parity periodic changes.

The current study aimed to examine more deeply the extent to which magnitude can be spontaneously processed. Going a step further than Guillaume and colleagues (2020), we decided to use the same multi-code FPVS paradigm as in Marlair et al. (2022) to evaluate magnitude processing with a more robust marker – the distance effect – and at a higher level of abstraction – across different numerical codes. Crucially, the instruction given to the participants prior to the experiment varied in order to investigate whether access to the common magnitude representation underlying digits, words, dots and fingers can occur without explicitly orienting attention to magnitude information. In a first session (“None”), participants were not given any instruction other than to fixate the middle of the screen. In a second testing session (“Parity”), participants were told to pay attention to the numerosities presented during the sequences of stimulation in order to be able to report which was (were) the odd or even numbers. In addition to the newly acquired data, we decided to reanalyze those previously obtained by Marlair and colleagues (2022) in order to compare the impact of explicitly orienting number processing at the level of magnitude (previous study), at the level of parity (this study), or without instruction (this study). The instruction was never directed to the detection of the deviant numerosity *per se*, but rather aimed at inducing processing of the whole sequence with attention focused on one specific aspect of numbers (or none).

If the brain is able to spontaneously integrate numerical information across the different codes, discrimination responses should be observed at the deviant presentation frequency even when participants' attention is not oriented to any numerical feature (i.e., None instruction). Moreover, to ensure that discrimination responses truly reflect magnitude processing, amplitudes should be modulated by the numerical distance between the base and deviant stimuli (i.e., larger discrimination response when base/deviant are numerically distant than close). If magnitude is spontaneously activated during parity processing, as it was found in behavioral studies (Fias, 1996; White et al., 2012), a similar distance effect should be observed in Parity and Magnitude instructions. However, given that parity was shown to be spontaneously extracted from Arabic digits (Guillaume et al., 2020), and if it becomes more salient when participants focus on this semantic information, then we could also expect to observe a parity effect, rather than a distance effect. Actually, expectations are exactly reversed by comparison to the distance effect: larger discrimination response when the base/deviant differ in parity (i.e., in the close sequences: 2/3, 8/9) than when they share the same parity (i.e., in the distant sequences: 2/8, 3/9).

2 Methods

2.1 Participants

The current study involved 30 French speaking participants (16 males) aged between 18 and 35 years old (M = 24.1, sd = 3.4) who did not present neurological disorders or uncorrected visual impairments. They gave their written informed consent and were compensated for their participation. The number of participants was determined based on previous studies with a similar method (Guillaume et al., 2020; Marinova et al., 2021b; Marlair et al., 2022). The procedures were in line with the Declaration of Helsinki and approved by the local ethics committee of Saint-Luc – UCLouvain (2019/12SEP/400 – B403201941534). The data retrieved from Marlair et al. (2022) were acquired on 23 French speaking participants (8 males, M_{AGE} = 22.17, sd = 2.8).

2.2 EEG procedure

The experimental design was created and executed with a software running on JavaScript (Java SE Version 8, Oracle Corporation, USA). Sequences of 63-s stimulation, including 2 s of gradual fade-in and 1 s of gradual fade out, were displayed on a screen with a 800 x 600-pixel resolution placed 1 m away from the participants. A sequence consisted in the presentation at a constant 6-Hz frequency (i.e., 6 stimuli per second) of one base and one deviant numerosity, with the deviant appearing periodically every fifth base numerosity, so at 1.2 Hz (i.e., 6 Hz/5, fig. 1). As in Marlair and colleagues (2022), numerals 2, 3, 8 and 9 were selected as base and deviant stimuli in order to create four *close* sequences (i.e., base/deviant = 2/3, 3/2, 8/9, 9/8) and four *distant* sequences (i.e., 2/8, 8/2, 3/9, 9/3). Stimuli were displayed at the center of the screen with a resolution of 236 x 236 pixels and by means of sinusoidal modulation of contrast from 0 to 100 %. Both the base and the deviant numerosities were presented under different codes including Arabic digits, number words, canonical dot patterns (i.e., patterns found on play cards) and canonical finger configurations (i.e., typical Belgian finger-counting configurations), randomly selected during the sequence with no immediate repetition of the same stimulus. To add some variability in the low-level perceptual features, Arabic digits and number words were written in six different fonts, fingers were drawn in six different ways and dots varied in shapes (circles, squares or triangles), size and density (examples of stimuli are depicted on fig. 1). The participants underwent the experiment twice, in two different sessions one week apart: the first time, they were told to fixate the middle of the screen where they would see different symbols appear (i.e., “None” instruction) ; the second time, they were instructed to carefully look at the numerosities in order to be able to tell at the end of the sequence (if asked), which was (were) the odd or even number(s) that they saw (i.e., “Parity” instruction). When asked (50 % of the sequences), participants were able to give correct answers 100% of the time.

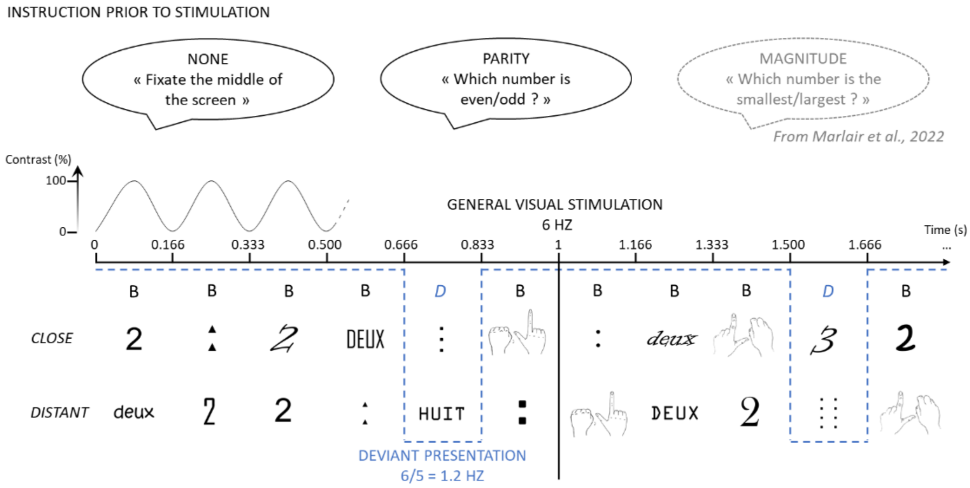

Figure 1. Experimental design. Participants were given an instruction before the stimulation: None (first testing session) or Parity (second testing session). Data for the Magnitude instruction were retrieved from Marlair et al. (2022) (accessible via the Dryad Digital repository, https://doi.org/10.5061/dryad.612jm6469). During the experiment, numerosities were presented in randomly mixed codes and by means of sinusoidal modulation of contrast at a constant frequency of 6 Hz (i.e., 6 stimuli per second), reflecting the general visual stimulation. The deviant (D) numerosity (in the example, "3" in the close sequence, "8" in the distant sequence) appeared periodically every fifth base (B) stimuli (e.g., "2"), resulting in a deviant presentation frequency of 6 Hz/5 = 1.2 Hz. Note: "deux" means "two" in French and "huit" means "eight".

2.3 EEG acquisition and preprocessing

EEG was recorded at 2048 Hz with a 68-channel BioSemi Active II system (BioSemi, The Netherlands). Sixty-four electrodes were placed according to the standard 10-20 system and four extra channels were added on posterior sites (PO9, PO10, I1 and I2). The magnitude of the offset of all electrodes, referenced to the common mode, was held below 50mV. Analyses of the EEG data were carried out using Letswave 6 (https://www.letswave.org), an open-source toolbox running on

MatLab (The MathWorks, USA). Data were downsampled to 512 Hz to decrease the processing time. Then, a band-pass filter with cut-off values of 0.1-100 Hz and a multi-notch filter at three harmonics of 50 Hz were applied. Data were segmented 2 s before and 1 s after each sequence to simplify the inspection of signal quality. Data cleaning included independent component analysis (max 2 components removed) and linear interpolation (< 5% of the whole scalp with 1% of posterior channels). Sequences containing excessive noise and artifacts were removed from the analyses (13 in total) with a maximum of one sequence per condition (close or distant) and per subject. Finally, data were segmented again from the stimulation onset until 60 s, to include the largest amount of integer presentation cycles (72 cycles of 833.33 ms at the 1.2-Hz frequency), and all channels were re-referenced to the common average.

2.4 EEG frequency domain analyses

A Fast Fourier Transformation was applied to each sequence and normalized amplitude spectra were obtained for the 68 channels with a frequency resolution of 0.0167 Hz (1/60 s). Based on the grand-averaged amplitude spectrum for each instruction (i.e., None and Parity) and condition (i.e., close and distant), Z-scores were computed to assess significant responses at the frequencies of interest (i.e., 6 Hz and 1.2 Hz) with the formula: $Z(x) = \frac{x - mean(noise)}{standard\ deviation(noise)}$, where *x* represents a frequency bin and the *noise* is defined as the 20 surrounding bins of each target bin excluding the immediately adjacent and the extreme (min and max) bins (Liu-Shuang et al., 2014; Rossion et al., 2012; Srinivasan et al., 1999). Harmonics with a Z-score larger than 1.64 ($p < .05$, one-tailed, signal > noise) indicated significant responses. Then, *noise-corrected amplitudes* (i.e., [signal – noise] for each frequency bin) were summed for the significant harmonics of the general visual stimulation frequency (6 Hz) and the discrimination frequency (1.2 Hz) to quantify the responses of the participants in each instruction and condition (Retter et al., 2021). The same analysis steps were performed on the data acquired by Marlair et al. (2022) to compute responses for the Magnitude instruction. Responses to the general visual stimulation frequency (6 Hz) and the discrimination frequency (1.2 Hz) were analyzed in the same ROIs as defined by Marlair and colleagues (2022) to allow direct comparison between the instructions: 6-Hz left ROI (O1, PO7, PO9, P7), 6-Hz right ROI (O2, PO8, PO10, P8), 1.2-Hz left ROI (PO7, PO9, P7, P9), and 1.2-Hz right ROI (PO8, PO10, P8, P10).

3 Results

Significant responses (Z > 1.64, see Method) were found on a maximum of 6 harmonics for both the general visual responses (from 6 to 36 Hz) and the discrimination responses (from 1.2 Hz to 8.4 Hz, but excluding the 5th harmonic which corresponds to the 6-Hz general visual stimulation frequency). Amplitude values for these significant harmonics were summed and analyzed, together with those obtained by Marlair et al. (2022), using a Linear Mixed-Model (LMM) with *Instruction* (none, parity or magnitude), *Condition* (close or distant), and *Lateralization* (left or right) as fixed factors and a random intercept by subject.

3.1 General visual responses

The LMM on the general visual responses showed that a significant proportion (71%) of the residual variance could be accounted for by systematic differences between subjects (i.e., the random intercept), *Estimate* = .60, *se* = .13, $p < .001$. While controlling for this effect, a significant interaction between *Instruction* and *Lateralization* was found, $F(2, 268) = 6.12$, $p = .003$. Follow-up pairwise comparisons (with Bonferroni adjustment) showed that the general visual responses significantly differed according to the instruction within the right ROI, ($M_{\text{MAGNITUDE}}$ = 2.76 µV, *se* = 0.18) > (M_{PARITY} = 1.94 µV, *se* = 0.15) > (M_{NONE} = 1.72 µV, *se* = 0.15), all *ps* < .05, but not in the left ROI, all *ps* > .05. Responses in the right ROI were, however, systematically larger than in the left ROI (0.30 µV larger in None, 0.46 µV larger in Parity and 0.77 µV larger in Magnitude instruction, all *ps* < .01). There was no main effect or interaction with *Condition* (close or distant) on the general visual responses (*ps* > .79).

3.2 Discrimination responses

In the LMM run on the discrimination responses, the proportion of the residual variance that could be accounted for by systematic differences between subjects (i.e., the random intercept) was only 5 % and not significant (*Estimate* = .001, *se* = .002, p = .33). Results showed a significant *Instruction* x *Condition* interaction, $F(2,251)$ = 4.12, p = .017 (fig. 2), indicating the presence of a neural distance effect (i.e., larger responses elicited for distant than close deviants) for Parity (0.13 µV stronger, p < .001) and Magnitude (0.18 µV stronger, p < .001), but not for None instruction (0.05 µV stronger, p = .129). It should be noted that the three-way interaction *Instruction* x *Condition* x *Lateralization* was marginally significant, $F(2,251)$ = 2.95, p = .054, suggesting that the influence of instruction on the neural distance effect tended to be more pronounced in the right ROI than in the left ROI (fig. 2).

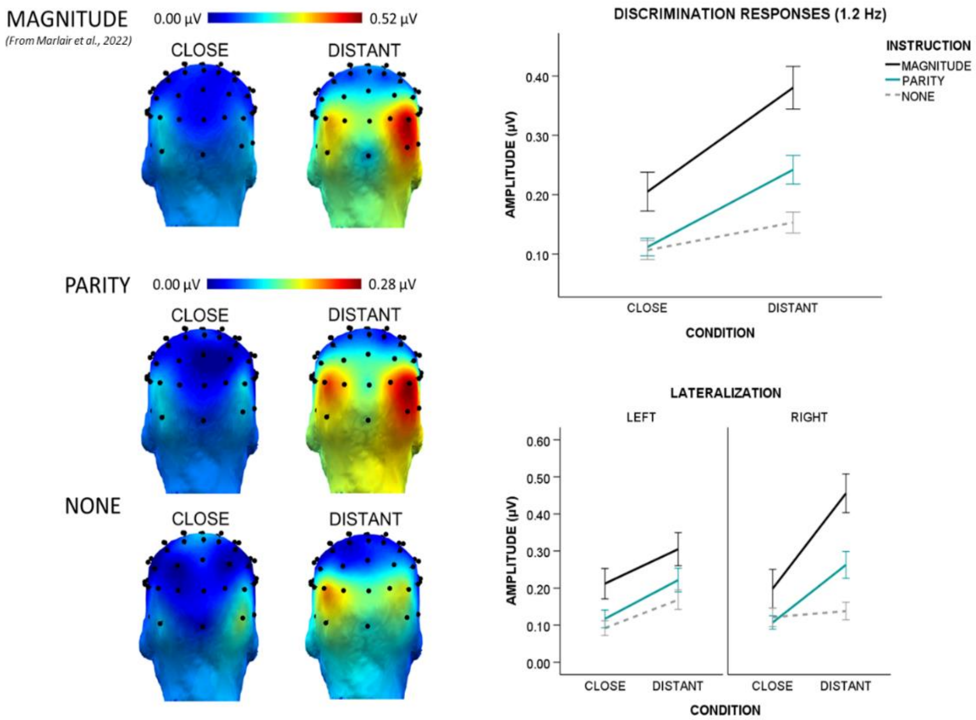

Figure 2. (a) Discrimination response topographies. Topographies display the sum of noise-corrected amplitudes over the scalp, based on the group average, for

the significant harmonics in the close and distant conditions for all instructions: Magnitude (from Marlair et al., 2022), Parity and None (note that the scale is different from that of Magnitude). **(b) Two-way interaction.** Difference between close and distant discrimination responses (averaged over participants and ROIs) according to the instruction (Magnitude – solid black line, Parity – solid green line, None – dotted grey line). Bars represent standard errors of the mean. **(c) Three-way interaction.** Influence of instruction on the difference between close and distant discrimination responses, separately for the left and right ROIs.

4 Discussion

The present study aimed to investigate whether exposure to a number, regardless of its notation, spontaneously activates magnitude information. To this end, we examined the impact of instruction on the emergence of a neural distance effect during viewing of rapid number sequences. In a first session, participants had to simply fixate the center of the screen (None). In a second session, participants had to detect the odd or even number(s) (Parity). In a third and final session, participants had to identify the smallest or largest number of the sequence (Magnitude). The Magnitude data were retrieved from the study of Marlair and colleagues (2022), while the None and Parity instructions were tested in a new group of participants using the same multi-code FPVS paradigm as in Marlair et al. (2022).

A significant neural distance effect was found in both Magnitude and Parity instructions, with larger discrimination responses (at 1.2 Hz) being elicited when the base and deviant numerosities were distant (as compared to close) from each other. The response amplitudes were overall greater in Magnitude than in Parity, but this could be due to the fact that different groups of participants were tested with these two instructions. Taking this inter-individual variability into account, we nevertheless found that the distance effect itself (i.e., the amplitude variation between close and distant conditions) did not differ between the two instructions (fig. 2). Our results thus indicate that even when focusing attention on odd/even numbers, parity was not the salient feature of numbers that was detected as being deviant.

Indeed, if it had been the case, incongruent parity trials (i.e., in close pairs: 2/3, 8/9) should have induced stronger responses than congruent parity trials (i.e., in distant pairs: 2/8, 3/9). However, it must be considered that the design used in this study was intended to measure the distance effect. Therefore, parity variations did not occur on similar/neutral distances. In the future, it would be interesting to compare sequences at more similar distances (e.g., comparing 2/8 and 2/9 or 3/8 and 3/9) to see whether it induces the emergence of the parity (in)congruence effect.

Given that a parity effect was already observed in previous studies (e.g., Guillaume et al., 2020), our results should not be interpreted as an inability to process parity, but rather as the fact that magnitude overcomes parity information. Similar findings have already been found in behavioral numerical comparisons tasks. When participants are asked to judge whether a number is smaller or larger than 5, using two buttons assigned to the left and right hemispaces, they tend to respond faster to small and large numbers with the left and right buttons respectively. This observation refers to the well-known SNARC effect which is typically explained by the spatial distribution of magnitudes on a mental number line, with small magnitudes being represented on the left of the line and large magnitudes on the right (Dehaene et al., 1993). Crucially, the same SNARC effect is observed when participants are asked to decide whether a number is even or odd, arguing that magnitude is automatically activated in parity judgements, although this is irrelevant to the task (Fias, 1996; Cipora et al., 2021). It thus corroborates the results obtained in the present study.

Although discrimination responses were observed in the None instruction, these responses, in contrast to what was found for Magnitude and Parity, were not significantly modulated by the distance between the base and the deviant numbers (fig. 2). This result is somewhat puzzling. Indeed, on the one hand, the observation of discrimination responses indicates that the brain was able to detect the periodic change of numerosity, despite the code variations. But, on the other hand, the absence of a significant distance effect suggests that the brain did not further process the magnitude information conveyed by the deviant numerosities. It is thus possible that a shared magnitude representation has been sufficiently activated to allow recognition of the common numerosity, but not enough to induce the emergence of a distance effect similar to that observed in Magnitude and Parity. A possible reason for this may be that participants devoted fewer cognitive resources in the absence of explicit instruction than when they were explicitly engaged in numerical processing. Therefore, the current data suggest that magnitude activation could vary according to the depth, but not the type, of the numerical processing involved in the task. To assess this potential explanation, it could be interesting in the future to test whether slowing down the presentation rate could enhance the emergence of a significant distance effect in the None instruction condition.

The present results underline the importance of using a reliable marker to examine a specific cognitive process with the FPVS technique. Difference in the markers chosen to evaluate magnitude processing might be the reason for the discrepancy between our results and those obtained by Guillaume et al. (2020). In their study, they indeed conclude that participants can spontaneously extract magnitude/parity information without any instruction directed towards numerical processing. However, the use of a small/large (or odd/even) contrast could possibly involve categorization processes based on non-numerical rules. Among those, one that is inherent to the FPVS paradigm relies on the relative frequencies of occurrence of the base and deviant stimuli (De Rosa et al., 2022). In the study of Guillaume and colleague (2020), each deviant digit was indeed presented 7 times less that base digits. Therefore, it seems highly possible that the brain successfully detected the rare nature of the deviant digit independently of its semantic category. To rule out this possibility, Guillaume et al. (2020) compared their magnitude/parity condition to a control condition in which digits were arbitrary allocated to the base/deviant categories. They observed peaks of response in that control condition supporting the brain’s ability to detect a difference in presentation rate and infrequent stimuli. Nevertheless, they found significantly greater discrimination responses in their experimental condition, suggesting that both magnitude/parity and item repetition rate influenced results. A major advantage of our design is that no control sequence was required to assess the reliability of our measure, since the distance effect is obtained by direct comparison of the two experimental conditions (close deviant *versus* distant deviant). We also reduced the difference in relative frequencies of occurrence so that the deviant numerosity was repeated only 4 times less than the base numerosity. Since the base and the deviant were presented under different notations, it allowed us to diversify the surface features of the stimuli and thus avoid categorization of the deviant based on low-level visual properties.

As it was already observed in the study of Marlair and colleagues (2022), the general visual responses (6 Hz) were not influenced by the distance condition, thus confirming that the neural distance effect was specifically induced by the occurrence of the deviant numerosity. Our results however showed that the amplitude of these brain responses depended on the instruction given to the participants in the right hemisphere. Larger right-lateralized responses were indeed observed in Magnitude, then in Parity, and finally in None instruction. This is likely to reflect the overall level of numerical awareness that was induced by the instructions: the closer the attentional focus was to magnitude processing (magnitude > parity > none), the more activated was the right hemisphere. Additionally, the influence of instruction on the difference between close and distant discrimination responses tended to be more pronounced in the right hemisphere than in the left. It thus seems that the right hemisphere plays a crucial role in the automaticity of magnitude integration. Previous neuroimaging studies examining the involvement of the left and right IPS in numerical processing already supported that the right IPS has a functional role in automatic magnitude processing (Jang & Hyde, 2020). Using transcranial magnetic stimulation (TMS), Cohen Kadosh and colleagues (2007) for example demonstrated that automatic processing of magnitude was impaired when disrupting the right, but not the left IPS (although both IPS were involved in magnitude processing). An fMRI adaptation study similarly highlighted a stronger cross-notation signal recovery in the right parietal cortex as compared to the one observed in the left hemisphere (Piazza et al., 2007).

To summarize, this study provides new insight into the brain's ability to spontaneously process numerical magnitude across Arabic digits, number words, canonical dot and finger configurations. Whether participant’s attention was explicitly oriented to number processing or not, they succeeded in detecting the periodic change of numerosity despite the code variation. We further showed that magnitude processing – adequately assessed by the presence of a distance effect on the discrimination responses – occurred even when participants’ attention was oriented towards the parity feature of numbers, but, we failed to observe such a distance effect when the participants were left without instruction. Taken together, these results suggest that the processing of magnitude at an abstract level is not completely spontaneous and may in fact depend on, and vary with, the cognitive resources engaged in number processing.

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Chapter 5. Quantities and digits activate a common distance-related representation of magnitude: evidence from a behavioral matching task

Abstract

Debate continues on whether number symbols (e.g., Arabic digits) and quantities (e.g., sets of dots) activate common or distinct magnitude representations. The presence of a distance effect – increasing difficulty in distinguishing two numbers as they get closer to each other – during symbolic number comparisons was often taken as evidence that symbols automatically activate their corresponding non-symbolic magnitude. However, alternative accounts have been put forward, suggesting that symbols are supported by a separate system which may produce similar effects to those observed in non-symbolic comparisons. The present study aimed to clarify this issue by relying on a same-different matching task. Participants were presented with arrays of digits organized in a canonical way (i.e., such as playing cards) and asked to decide whether the number of digits matched or mismatched the digit value (e.g., "2-2" = match; "2-2-2" = mismatch). Mismatched trials varied so that the difference between the quantity and the digit was either close (e.g., "2-2-2") or distant (e.g., "7-7-7"). Results showed that participants responded faster and more accurately to the distant mismatched trials than to the close ones, indicating the presence of a cross-notational distance effect. Therefore, these findings strongly support the idea that canonical quantities and Arabic digits are represented in a shared distance-related magnitude system.

Reference

Marlair, C., Lochy, A., & Crollen, V. (in preparation). Quantities and digits activate a common distance-related representation of magnitude: evidence from a behavioral matching task.

Quantities and digits activate a common distance-related representation of magnitude: evidence from a behavioral matching task[4]

1 Introduction

The distance effect is among the most frequently used markers of numerical processing, both at the behavioral (e.g., Holloway & Ansari, 2009, Van Opstal and Verguts, 2011) and cerebral level (e.g., Ansari and Dhital, 2006; Piazza et al., 2007). It is usually observed when participants have to perform magnitude comparison tasks and entails greater discrimination performance when the distance between two numerosities is large (e.g., 2 vs. 8), compared to when it is small (e.g., 2 vs. 3; Moyer & Landauer, 1967). The distance effect is commonly explained by the mental organization of magnitudes that resemble Gaussian distributions on a logarithmically compressed number line (Feigenson et al., 2004). As a result, close magnitudes have more overlapping distributions compared to distant magnitudes, which make them harder to discriminate (Van Opstal and Verguts, 2011). Because both symbolic (i.e., Arabic digits, number words) and non-symbolic (i.e., dot arrays) comparisons elicit a distance effect, it was taken as evidence that these numerical formats share a common magnitude representation (Dehaene et al., 1998). Indeed, since two abstract symbols should be as discriminable as two others, the occurrence of a distance effect suggest that numerical symbols automatically activate their corresponding non-symbolic magnitude.

However, this view has been challenged by several studies reporting a lack of correlation between the distance effects obtained in non-symbolic and symbolic magnitude comparison tasks (Holloway and Ansari, 2009; Maloney et al., 2010).

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Hence, it is possible that symbolic and non-symbolic numerosities are represented by distinct systems producing similar effects (Krajcsi et al., 2016; Reynvoet et Sasanguie, 2016). On the one hand, comparing non-symbolic magnitudes would generate a distance effect because of their mental organization on the number line (Feigenson et al., 2004). On the other hand, it was suggested that the distance effect observed during symbolic magnitude comparisons originates from the strength of associations between the stimuli and the response (e.g., in a simple comparison task, small numbers are strongly associated with the response "target smaller than standard"; see Van Opstal & Verguts, 2008, for full details). Close stimuli would therefore activate the response label with similar strengths, causing harder competition than distant stimuli. In this sense, Van Opstal and Verguts (2011) have assumed that the comparison of two ordinal positions would systematically generate a distance effect. Supporting this last assumption, a distance effect was indeed found during non-numerical order processing, such as comparing navy ranks, academic positions (Chiao et al., 2004), or alphabet letters (Van Opstal and Verguts, 2008).

To further explore the alternative accounts – common or distinct representational systems – several studies have investigated mixed-notation comparisons, with the hypothesis that, if numerical codes share a common magnitude representation, comparing mixed-notation pair of quantities (e.g., an Arabic digit and a dot array) should lead to similar performance than comparing single-notation pairs (e.g., two dot arrays; Lyons et al., 2012; Marinova et al., 2018; Marlair et al., 2022). For instance, Lyons and colleagues (2012) asked their participants to decide which of two numerosities was larger, with the numerosities presented either in single-notation (i.e., dots-dots, digit-digit, word-word), in mixed-notation within the same symbolic format (i.e., digit-word – Experiment 3) or in mixed-notation between the non-symbolic and symbolic formats (i.e., dots-digit – Experiment 1). They found that participants were slower to compare dots-digit pairs than pure dot pairs, but no such a difference was observed between digit-word comparisons and pure number word comparisons. The authors therefore argued that the "switch cost" emerging in dots-digit comparisons could not be due to the mixing of different visual notations (otherwise, a similar cost would have been observed for digit-word comparisons) but was rather evidence that non-symbolic and symbolic formats activate distinct magnitude representations (Lyons et al., 2012).

Contrasting with the results of Lyons et al., (2012), a recent study (Marlair et al., 2022) showed no difference in performance when participants had to compare within-format pairs of quantities (i.e., dots-fingers, digit-word) or between-format pairs (i.e., dots-digit, dots-word, fingers-digit, fingers-word). However, these inconsistencies could be due to methodological variations. The major one is that Marlair and colleagues (2022) used canonical configurations of dots (i.e., such as playing card patterns) and fingers (i.e., finger-counting configurations). These patterns are known to provide faster and more accurate magnitude representations than randomly structured arrays of dots and fingers, especially for the numerosities 4-9 (Kreilinger et al., 2021; Marlair et al., 2021). It was therefore assumed that canonical configurations possess an "in-between" status: on the one hand, they explicitly denote the cardinality of the set they represent (i.e., they can be counted), like non-symbolic quantities, but on the other hand, their familiar pattern allow for a more direct recognition of their magnitude, like symbols. As a result, it may be easier to integrate the numerical information of symbolic numerals and canonical, rather than non-symbolic, quantities since they share more similar representational acuity. However, the switch cost observed by Lyons and colleagues (2012) was also present for small non-symbolic quantities (1-4), which can be represented with very high precision (i.e., they can be subitized; Piazza et al., 2011). Hence, differences in representational acuity between the numerical codes chosen by the authors cannot fully explain the inconsistencies between the two studies.

Possibly, the conflicting findings and interpretations of Lyons et al. (2012) and Marlair et al. (2022) stem from the fact that both studies used comparative judgments (i.e., deciding which of two presented numerosities is smaller/larger), which are considered unreliable for assessing magnitude representations. As previously discussed, several findings indeed suggested that the numerical distance effect observed in comparison tasks originates from decisional processes rather than, or in addition to, magnitude activations (see Van Opstal and Verguts, 2008). Therefore, other tasks should ideally be used to address the common (or distinct) magnitude representation(s) of numerical codes. Van Opstal and Verguts (2011) proposed that a same-different matching task, in which participants have to judge whether two numerosities are equal or not, would be more suitable because it does not relate to an ordinal decision. Accordingly, Marinova and colleagues (2018) compared both types of tasks (i.e., comparison and matching) with single- and mixed-notations presentations. Similar to Experiments 2 and 3 of Lyons et al. (2012), in the comparison instruction, participants had to indicate which of two sequentially presented numerosities was larger. In the matching task, they had to indicate whether two sequentially presented numerosities were equal or not. At first sight, the results obtained in both instructions were in contradiction with the findings of Lyons et al. (2012). Indeed, there was no evidence for a switch cost when participants had to integrate non-symbolic (i.e., arrays of dots) and symbolic quantities (i.e., digits or number words). Nonetheless, after examining in more detail their data, the authors found that the presence of a switch cost may have been masked by differences in processing times of the second numerosity according to its notation (e.g., digits are processed faster than dot arrays).

Consequently, it seems that paradigms using sequential presentations are not adequate to evaluate the integration of numerical magnitudes. In another study, Liu and colleagues (2015) avoided this issue by presenting simultaneously symbolic and non-symbolic quantities. Participants were instructed to decide whether pairs of symbols composed by two Arabic digits (e.g., “25”) or two letters (e.g., “QX”) were numeric or not, with the symbols superimposed on dot arrays that could either match or mismatch the magnitude represented by the double-digit numeral (e.g., digit “25” superimposed on 25 dots or on 38 dots). After adjusting for the estimation biases in the perception of dot arrays (i.e., systematic overestimation of small quantities and underestimation of large quantities), the authors reported a consistent advantage of matched numeric trials over mismatched numeric trials, in both speed and accuracy. They interpreted this cross-notation facilitation effect as evidence that symbolic and perceived non-symbolic magnitude are automatically integrated (Liu et al., 2015). However, whether the influence of irrelevant non-symbolic information on digit identification reflects a common magnitude system or an automatic associative relation between two distinct representations remains ambiguous (Marinova et al., 2018).

In conclusion, the current literature contains conflicting findings and interpretations regarding the existence of common or distinct magnitude representation(s). While some studies argued that symbolic and non-symbolic quantities activate separate representational systems, based on the presence of a switch-cost when integration between the two formats is needed (Lyons et al., 2012, Marinova et al., 2018), other findings supported a shared magnitude representation (Liu et al., 2015; Marlair et al., 2022). The aim of the present study was to further investigate this question while overcoming some methodological limitations of previous research. Participants were presented with canonical arrays of digits (i.e., such as playing cards on which the diamonds (♦) have been replaced by digits) and had to indicate whether the quantity of Arabic digits matched or mismatched the magnitude conveyed by the digit. By doing so, we carefully avoided the implication of ordinal decision processes that may arise in comparison tasks (Van Opstal and Verguts, 2008). Furthermore, both numerical information was simultaneously presented and thus, any difference observed between matched and mismatched trials could not be attributed to differences in processing times (Marinova et al., 2018). Finally, we decided to use canonical configurations rather than random structures of the arrays in order to minimize the perceptual biases in quantity estimations (Liu et al., 2015; Marlair et al., 2021).

The task included matched trials, where the Arabic digit was represented its exact number of times (e.g., 3-3-3) and mismatched trials, where the Arabic digit was depicted less or more times than its cardinal value (e.g., 3-3 or 2-2-2). Among the mismatched trials, the difference (the distance) between the quantity of elements and the digit magnitude could be either small (close; e.g., 3-3, difference = 1) or large (distant; e.g., 6-6, difference = 4). We hypothesized that if both notations readily activate a common magnitude representation, participants should take less time to identify the mismatch when the quantity and the digit are distant than when they are close. On the contrary, if these numerical representations are processed by two entirely distinct systems, or if they relate to each other through an associative relation that is independent of their magnitude, no distance effect should emerge.

2 Methods

2.1 Participants

Twenty-seven adults participated in the study (9 males, M_{age} = 23.3 years old, SD_{age} = 2.5). Three of them were left-handed and all had normal or corrected-to-normal vision. Participants did not present any neurological or psychological disorder. They gave their written informed consent and received a small monetary compensation for their participation. The procedure was in line with the Declaration of Helsinki and approved by the local Ethical Committee of the Cliniques universitaires Saint-Luc and the University of Louvain (2019/12SEP/400 – B403201941534).

2.2 Stimuli

Stimuli consisted in canonical arrays of single-digit numbers from 2 to 9. Canonical arrays were structured such as playing cards, but with the elements being replaced by a specific Arabic digit (fig. 1). The complete stimulus set consisted in three types of stimuli: matched (fig. 1a), close mismatched (fig. 1b) and distant mismatched (fig. 1c). Within the matched stimuli, each digit was represented its exact number of times (e.g., 2-2 or 5-5-5-5-5) whereas in the mismatched stimuli, the number of digits and the digit value were unequal (e.g., 3-3 or 4-4-4-4-4). Among the latter, the difference between the number of digits and the digit value could be either 1 (i.e., *close* mismatched trials; e.g., 3-3, number of repetitions = 2, digit value = 3) or 4 (i.e., *distant* mismatched trials; e.g., 6-6, number of repetitions = 2, digit value = 6). Furthermore, the number of digits could be either smaller than its cardinal value (e.g., 3-3) or larger (e.g., 4-4-4-4-4), evenly balanced within the mismatched conditions. Finally, each trial condition was composed of three stimulus series in order to control for the potential influence of low-level visual parameters (Mix et al., 2002) and a possible size congruency effect (Reike & Schwarz, 2017). In a first series, the size of the digits and the distance between them were kept constant across the stimuli. In a second series, the size of the digits increased as the number of digits increased, whereas in a third and final series, the digit size decreased with increasing number of digits (fig. 1).

2.3 Procedure

Participants were seated in front of a monitor and familiarized with the instruction. For each configuration, they had to indicate, as fast and as accurately as possible, whether the number of digits was equal or not to the value of the digit. Examples (not included in the stimulus set) were depicted and participants were instructed to give their response by pressing bimanually “s” or “l” on an AZERTY keyboard. Whether the left key “s” and right key “l” were associated with “same” or “different” responses was counterbalanced across participants. E-Prime 2.0 (Psychology Software Tools, USA) was used to execute the task and record participants’ accuracy and reaction time data. Whenever the participants felt ready to start, they pressed the space bar and the first stimulus appeared in the center of the screen (height x width = 4.2 x 3.0 deg of visual angle). As soon as a response key was pressed, the next trial began. Half trials presented matched configurations and half mismatched configurations, so that each possible response (i.e., same or different) had to be given 50% of the time. Thus, for mismatched trials, each stimulus of the close and distant conditions (fig. 1b, 1c) were presented once, while for matched trials, each stimulus of the matched condition (fig. 1a) was presented twice. In total, the task consisted of 96 trials randomly presented for each participant.

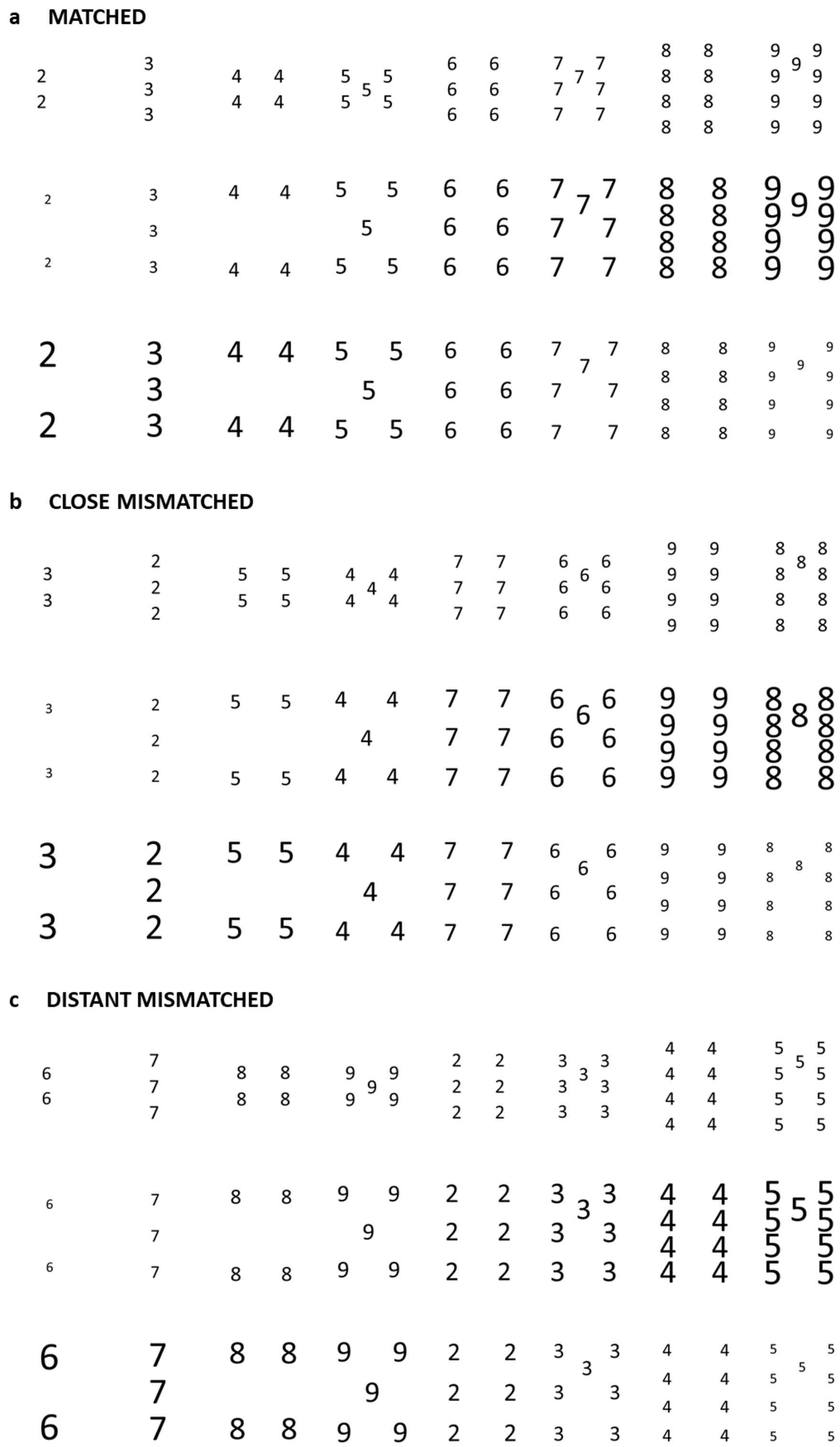
a MATCHED
b CLOSE MISMATCHED
c DISTANT MISMATCHED

Figure 1. Stimuli. Each array of stimuli was structured such as a playing card and contained a number of digits that could either match the digit value **(a)**, or mismatch the digit value **(b-c)**. When it mismatched, the difference between the number of digits and the digit value could either be 1 **(b. close mismatched)** or 4 **(c. distant mismatched)**. For each condition, 3 sets of stimuli were created. In the first one, the size of the digits and the distance between them was constant across stimuli (first lines). In the second one, the size of the digits increased as the number of digits increased (second lines). In the third and final one, the size of the digits decreased as the number of digits increased (third lines).

3 Results

The overall accuracy for the experiment was 96%. Trials with reaction times that were highly out of range (i.e., more than 3 standard deviations from the mean within an individual) were discarded from the analyses (max 2% per participant). Following this, inverse efficiency scores (IES) were calculated to combine speed and error measures by dividing the average reaction time (RT) by the percentage of accuracy (PCR) for each trial condition (i.e., matched, close mismatched, distant mismatched). Then, a repeated-measures ANOVA was conducted on Ln-transformed IES (but non-transformed IES are reported for the ease of comprehension) to compare the performance for the three trial conditions. Results from this analysis revealed a significant effect of *Condition*, $F(2,52) = 7.43$, $p = .001$, $\eta_p^2 = 0.22$, indicating that participants' performance was influenced by the type of trials (fig. 2). Post-hoc pairwise comparisons, with a Bonferroni correction applied, further showed that participants were significantly worse to respond to close mismatched trials ($M \pm SD = 996.3 \pm 228.9$ ms) as compared to distant mismatched trials ($M \pm SD = 920.1 \pm 187.6$ ms; $p = .002$), but there was no significant difference between the mismatched trials and the matched condition ($M \pm SD = 936.2 \pm 180.2$ ms; $p_s > .05$). This difference between close and distant mismatched trials therefore support the presence of a distance effect on participants' performance. Moreover, a look at individual data revealed that 23 participants out of 27 exhibited the typical distance effect while only four of them showed an inverse distance effect (i.e., better performance for close than distant trials, fig. 2).

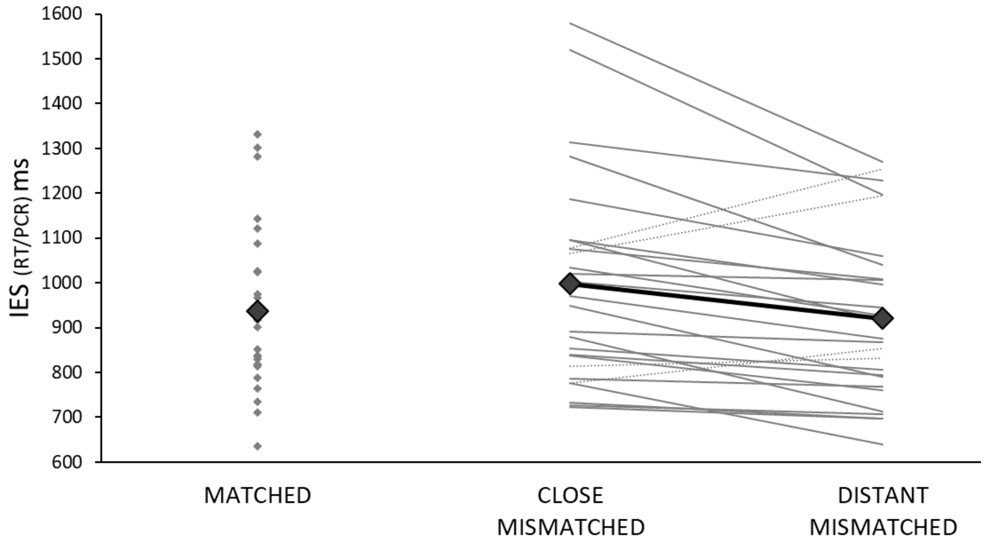

Figure 2. Results. Participants' inverse efficiency scores for matched, close and distant mismatched trials. Black diamonds represent the mean of the group and grey diamonds/lines represent individual data. Dotted lines indicate the participants showing a reverse distance effect.

3.1 Follow-up analyses: size congruency

As mentioned in the methods section, the stimuli used in each trial condition varied according to the size of the elements (i.e., the digits): in a first "neutral" set, the size of the digits was kept constant across the stimuli; in a second "size congruent" set, the size of the digits increased as the quantity increased; in a third "size incongruent" set, the size of the digits decreased as the quantity increased (fig. 1). An additional two-way repeated-measures ANOVA was computed to investigate the effect of size congruency on IES and its potential interaction with trial condition. Results from this 3 (condition: matched, close mismatched or distant mismatched) x 3 (size: neutral, congruent, incongruent) repeated-measures ANOVA showed a main effect of *Condition*, $F(2, 52) = 7.82$, $p = .001$, $\eta_p^2 = 0.23$, no main effect of *Size*, F(2,

52) = 0.23, p = .797, η_p^2 = 0.009, but a significant interaction between *Condition* and *Size*, F(4,104) = 3.13, p = .028, η_p^2 = 0.11. To further investigate the *Condition* x *Size* interaction, repeated-measures ANOVAs were first computed to examine the effect of size congruency on participants' IES within each trial condition. None of them showed a significant main effect of *Size* (all p_s > .05). Then, repeated-measures ANOVAs were conducted separately for each size category. Results highlighted a significant effect of *Condition* for neutral size, F(2, 52) = 8.08, p = .001, η_p^2 = 0.24, for congruent size, F(2, 52) = 7.69, p = .001, η_p^2 = 0.23, but not for incongruent size, F(2, 52) = 1.28, p = .29, η_p^2 = 0.047 (fig. 3). Post-hoc pairwise comparisons with Bonferroni correction revealed a significant distance effect (i.e., better performance for distant mismatched than close mismatched trials) in both neutral and congruent size categories, but it did not reach the significance level in the incongruent size trials (table 1).

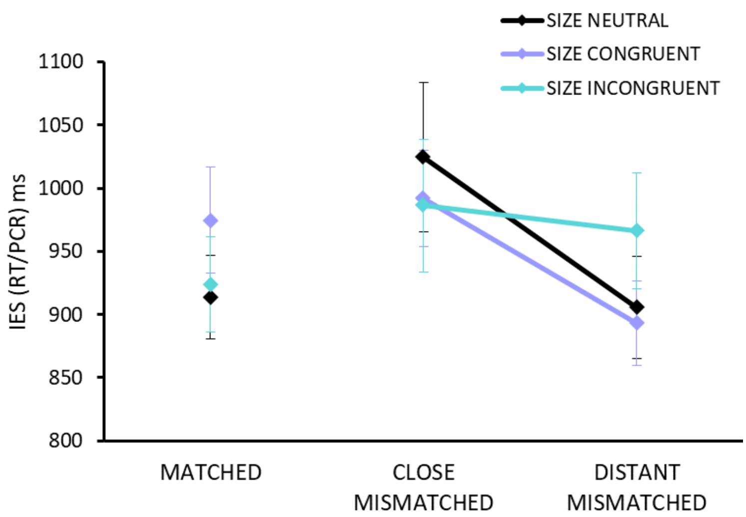

Figure 3. Results from size congruency analyses. Participants' IES for matched, close and distant mismatched trials within each size category: neutral in black, congruent in light purple and incongruent in green. Diamonds represent the mean of the group and bars show standard errors of the mean.

Table 1. Post-hoc pairwise comparisons with Bonferroni correction for the interaction between trial condition and size congruency. Significant ($p < .05$) mean differences between trial types (matched, close mismatched and distant mismatched) are marked by an asterisk (*).

Size Congruency	**Trial Condition**			**Mean Dif**	**SE**	***p-value***
Neutral	Matched	*vs*	Close Mis.	-110.6*	40.7	.025
	Matched	*vs*	Distant Mis.	8.45	26.7	1.000
	Close Mis.	*vs*	Distant Mis.	119.0*	36.4	.002
Congruent	Matched	*vs*	Close Mis.	-17.5	35.8	1.000
	Matched	*vs*	Distant Mis.	81.5*	28.9	.011
	Close Mis.	*vs*	Distant Mis.	99.0*	24.3	.001
Incongruent	Matched	*vs*	Close Mis.	-62.2	38.5	0.333
	Matched	*vs*	Distant Mis.	-42.3	34.8	0.879
	Close Mis.	*vs*	Distant Mis.	19.8	41.5	1.000

One should note, however, that the size (in)congruency was defined according to the quantity (i.e., the size increased or decreased with the number of elements). If we consider also the size congruency according to the digit value (i.e., bigger font size for larger digits = congruent; smaller font size for larger digits = incongruent), it appears that the close and distant mismatched trials were not equivalent (fig. 4). Possibly, difference in digit size congruency may have influenced the comparisons between close and distant IES.

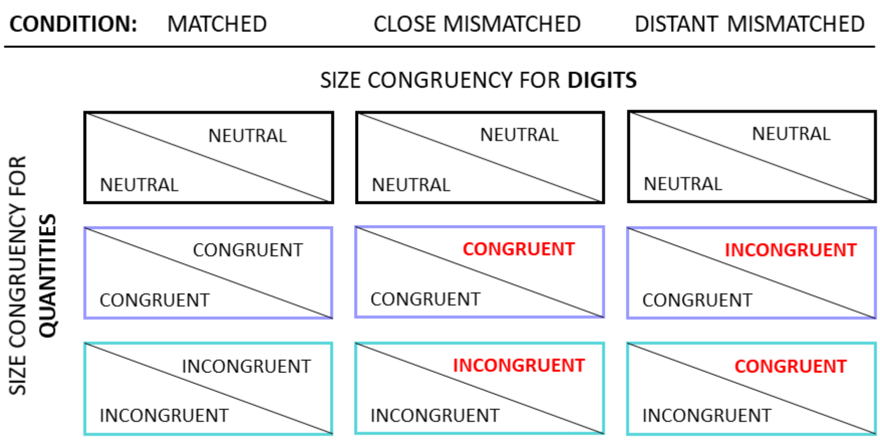

Figure 4. Size congruency for quantities and digits. For each trial condition (i.e., matched on the left, close mismatched in the middle, distant mismatched on the right), size congruency was determined according to quantities: neutral, in black, corresponds to the first lines of stimuli depicted on fig. 1, congruent, in light purple, corresponds the second lines and incongruent, in green, to the third one. This figure shows, for each category, the corresponding digit size congruency and highlights, in red, the resulting differences between close and distant mismatched conditions.

3.2 Follow-up analyses: digit smaller vs. larger than quantity

An additional two-way repeated-measures ANOVA was also performed to compare the effect of close *versus* distant mismatch on IES when 1) the digit was larger than the quantity (e.g., digit "3" represented twice) and 2) the digit was smaller than the quantity (e.g., digit "2" is represented 6 times). Results from this 2 (condition: close mismatched or distant mismatched) x 3 (digit value: smaller or larger than quantity) repeated-measures ANOVA showed a main effect of *Condition*, $F(1, 26) = 15.7$, $p = .001$, $\eta_p^2 = 0.38$, a main effect of *Digit value*, $F(1, 26) = 13.2$, $p = .001$, $\eta_p^2 = 0.34$, and no interaction between these two factors, $F(1, 26) = 0.33$, $p = .571$, $\eta_p^2 = 0.01$. Participants' IES were indeed lower (better performance) when the digit was larger than the quantity ($M \pm SD$ = 916.0 ± 33.8 ms) than when the digit was smaller than the quantity ($M \pm SD$ = 1004.4 ± 47.3 ms), but difference between close and distant mismatched trials was present in both cases (fig. 5).

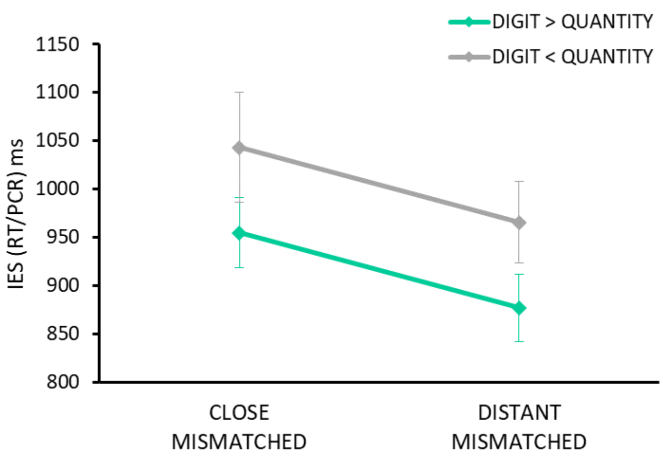

Figure 5. Results from the analysis of digit smaller *vs.* larger than quantity. Participants' IES for close and distant mismatched trials when the digit was smaller than the quantity, in grey, and when it was larger, in green. Diamonds represent the mean of the group and bars show standard errors of the mean.

As a possible explanation, difference in performance when the digit is larger *vs.* smaller than the quantity may be due to the coding mechanisms of digits and quantities. It was indeed assumed that digits would be encoded following a "place coding" scheme, where the digit activates its cardinal value with a maximal strength and also its direct neighbor numbers with a decreasing strength (Roggeman et al., 2007). In contrast, the canonical quantity may follow a "summation coding" scheme that activates the entire range of quantities up to the target quantity with equivalent strength (fig. 6). Consequently, when the quantity is larger than the digit value, there would be an overlap in the representations of the quantity and digit magnitudes that make them more difficult to differentiate, compared to when the quantity is smaller than the digit value (where no such an overlap occurs, fig. 6).

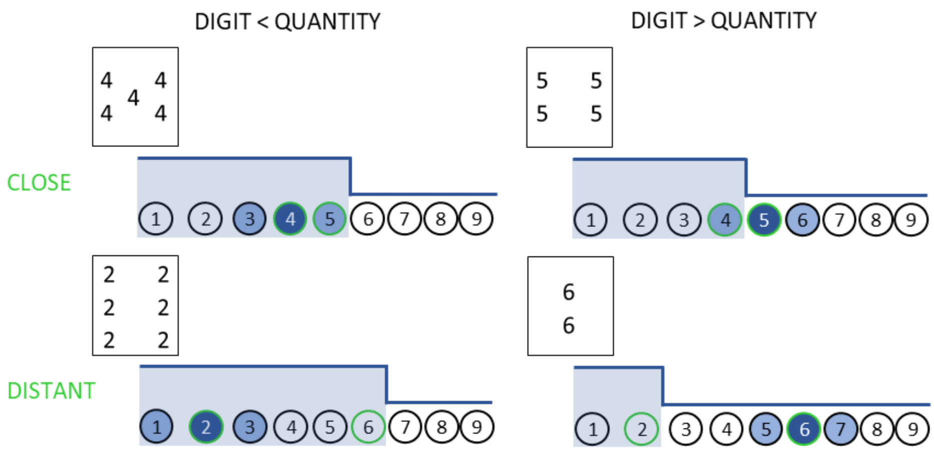

Figure 6. Illustration of the coding schemes for digits and quantities. The target digit and quantity are highlighted in green, with either small (close) or large (distant) difference between them. According to the place coding scheme, a digit activates its cardinal value with a maximal strength (dark blue) and also its neighbors with

decreasing strength (lighter blue). If the target quantity follows a summation coding scheme, it will activate all the quantities below it with the same strength (light blue rectangle), creating an overlap with the digit representation when the digit is smaller than the quantity (on the left) but not when the digit is larger (on the right).

4 Discussion

To date, there is still no consensus on whether different numerical formats, such as dot arrays and Arabic digits, are integrated into a common magnitude representation or processed by distinct systems. On the one hand, some researchers claimed that the observation of similar distance effects in symbolic and non-symbolic numerical tasks (i.e., better performance in discriminating two numerosities that are distant *versus* close to each other) was evidence that symbols and quantities activate a shared representation (Dehaene et al., 1998). On the other hand, it was argued that these numerical codes could rather be processed by distinct systems exhibiting similar effects (Krajcsi et al., 2016). The aim of the current study was to clarify this issue and overcome some methodological limitations of previous studies. We used a same-different matching task in which participants had to decide whether canonical arrays of digits contained a number of digits equal or not to the magnitude conveyed by the digit (e.g., "4-4-4-4" is equal, "4-4-4" is unequal). Canonical configurations were chosen to avoid discontinuity in the representational accuracy of small (1-4) and large (5-9) numerosities (Krajcsi et al., 2013). Crucially, when the quantity mismatched the digit, difference between these two numerical values could be either small (e.g., "3-3") or large (e.g., "6-6"). Participants were found to respond faster and more accurately when the mismatch between the digit value and the quantity was larger than smaller.

Our findings therefore provide evidence of a cross-notation distance effect, which strongly supports the existence of a common magnitude representation for canonical quantities and digits. It was indeed argued that the distance effect in a same-different task originates from number representations rather than decisional processes (Van Opstal and Verguts, 2011). Hence, we can reasonably assume that the presence of a distance effect in the current matching task stems from overlapping representations of the quantity and digit magnitudes, implying that both numerical formats are encoded within a common representational system. These findings corroborate the results obtained by Liu and colleagues (2015) who showed a cross-format facilitation effect. In their study, participants were found to identify Arabic digits faster when they co-occurred with irrelevant dot arrays that matched (*versus* mismatched) their magnitude. It is however possible that this facilitation effect resulted from associative links between symbolic and non-symbolic information, without necessarily implying access to their common magnitude. In the current study, responses to mismatched trials were modulated by the distance between quantities and digits. If an associative relationship was the only parameter contributing to the mismatched identification, one could expect that close and distant mismatched trials would be processed similarly because the quantity information is not correctly associated with its symbolic label. Therefore, the presence of a distance effect on mismatched trial identification allows us to provide a more robust argument in favor of a common magnitude representation for canonical quantities and digits.

Some limitations of the current study should nevertheless be acknowledged. Firstly, it cannot be excluded that certain parameters other than the numerical magnitude might have contributed to the observed findings. Although preliminary, results from the follow-up analyses indeed suggest that the stimulus size congruency have influenced participants' performances. While a distance effect emerged when the physical size of the elements (i.e., the digits) was neutral and congruent to the quantity (i.e., bigger digit size when the quantity was larger), it did not when the size was incongruent (i.e., smaller digit size when the quantity was larger). Taking a closer look at the data (see fig. 3), it seems that performances for distant mismatched trials with incongruent size were worse than in the two other size categories (albeit not significantly). As a possible explanation, we tentatively suggest that there might have been an interference between the size congruencies regarding the quantity and the digit value (see fig. 4). Indeed, in that specific condition, the physical size of digits was incongruent with the global quantity (i.e., large quantities were composed of small fonts), but it was congruent with the local digit values (i.e., large digits were written in large fonts). Previous studies have already reported that the physical size of digits could modulate the processing of symbolic numerical meaning (Reike & Schwarz, 2017). Hence, it might be that when the size of digits was congruent with the digit value, it was more difficult for participants to identify the configuration as a mismatched trial. One should note, however, that this hypothesis is in contradiction with the classical effects observed in Navon’s paradigm (Navon, 1977). Indeed, evidence usually suggests that, when processing both the global and local levels, it is the global information that dominates and interferes with the local information (Gerlach & Poirel, 2018). Since the current task did not include a proper control of the digit size congruency, any interpretation should be made cautiously. Future studies may seek to examine more closely the interference of global and local size congruency effects. An interesting follow-up could be to create other configurations were the quantity would be presented at the local level and the digit at the global level.

A second limitation to be raised is that, in the current task, participants were forced to compare the magnitude of both notations to give the correct answer. Other tasks could be proposed to implicitly examine the access to magnitude representation across numerical formats. For example, using the same configurations, participants could be asked to judge whether the quantity or the digit value is smaller/larger than 5, enabling examination of how the remaining information influences performances. Recently, a similar study (Sokolowski et al., 2022) investigated the relation between digits and quantities using a stroop-like paradigm. Participants had to compare adjacent arrays of digits (e.g., “4-4-4-4” *versus* “3-3-3”) and were instructed to indicate which side contained either the greatest quantity of digits (i.e., non-symbolic task), or the largest digit value (i.e., symbolic task). The authors were thus able to evaluate how the relevant dimension (i.e., the one that participants had to judge) was influenced by the irrelevant numerical information (i.e., the one that participants had to ignore). Quantities and digits were both found to influence the processing of each other, although the comparison of quantities was more impacted by irrelevant symbolic information than the opposite. Sokolowski and colleagues (2022) therefore suggested that non-symbolic and symbolic numerical magnitudes are processed simultaneously at some stage of processing, which nicely complements the results of this study where both digits and quantities constituted relevant information. Additionally, their findings also revealed an asymmetry in the way participants processed quantities and digits, supporting more automatic processing for symbolic than non-symbolic numerical magnitudes.

Taken together, our results and those of Sokolowski et al. (2022) fit well with a computational model suggesting that non-symbolic and symbolic magnitudes are coded into a common representational system, but through different processes (Verguts & Fias, 2004). Non-symbolic quantities would indeed activate their cardinal representation via an intermediate step called “summation coding”. This additive process implies that the number of units being summed proportionally increases with larger quantities, resulting in increasingly noisy magnitude representations. In contrast, the summation step is not required for processing the cardinality of symbolic magnitudes. Humans would thus benefit from using symbols because it allows for a more precise and straightforward magnitude representation. However, because the final output still bears traces of how it was originally shaped by non-symbolic experience, symbolic magnitudes come to inherit some of the properties of non-symbolic representations (Verguts & Fias, 2004). Consequently, symbols would thus be represented with more, but not absolute, precision. This could explain why digit comparisons still exhibit a distance effect, despite the fact that symbols should, in principle, allow for a sharp representation of a given numerical magnitude that is clearly distinct from that of other symbols (Verguts & Fias, 2004). Interestingly, results from the current study suggest that canonical quantities would not be exempt from the summation coding step. Although this hypothesis needs further investigation, it seems consistent with the finding that performances were worse when the digit was smaller than the quantity (see fig. 6). Indeed, these lower performances might possibly be due to an overlap between the digit representation and the noise produced by the summation coding of the quantity. On the contrary, no such overlap would occur when the digit is larger than the quantity, resulting in better performances.

To conclude, this study provides evidence that canonical quantities and digits activate a common and distance-dependent magnitude representation. Although the current data do not allow us to specify *how* or *when* this shared representation develops, we argued that the use of the quantities-digits matching task would be ideally suited to address the developmental trajectory of this numerical integration in children. Our findings also raise important questions regarding the functional role of an integration between canonical quantities and digits. How is it related to mathematical performances and does this relation change during development? One might indeed consider that children at the beginning of mathematical learning would strongly rely on this common magnitude representation. Yet, as a convergent body of evidence suggest that adults process symbols more automatically than quantities, it is possible that the gradual shift from a common representation to the specialization of the symbolic system contributes to better mathematical performance in adulthood.

5 References

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Chapter 6. General Discussion

Numerosities can be represented in many different ways, such as non-symbolic quantities (e.g., collections of randomly spaced dots), canonical patterns (e.g., dot arrays organized like playing cards and culture-typical finger configurations) or symbolic numerals (e.g., Arabic digits and number words). Over the course of their numerical development, humans will progressively learn to establish correspondences between these different codes. In the literature of numerical cognition, the association between non-symbolic quantities and numerical symbols has been the focus of much research and debate. However, only a few studies have examined the specific status of canonical finger and dot configurations. Hence, the aim of the current PhD thesis was to investigate the cerebral bases of canonical number representations, their specificity relative to non-symbolic quantities and their integration with symbolic numbers. This final chapter first gives a summary of the theoretical background and the research objectives. It then provides an overview of the main findings and discusses them in light of the current literature. Future research directions are also proposed.

1 Summary of the research context and general aims

The development of mathematical competencies begins early in childhood and predicts later academic achievement and professional success (Jordan et al., 2009; National Mathematics Advisory Panel, 2008). Mathematical knowledge is thought to be grounded in children's innate ability to manipulate (e.g., compare, estimate) non-symbolic quantities (e.g., set of items) that are perceived in the environment (Feigenson et al., 2004). This capacity would be supported by two core systems: a parallel individuation system (PIS) for small sets of items and an approximate number system (ANS) for larger numerosities. While the former allows for the exact representation of up to four objects (i.e., the subitizing process), the latter follows the Weber-Fechner law, causing two effects in individuals' numerical representation

(Dehaene, 2003): the size effect – decreased representational accuracy as the quantity increases (e.g., 19 is less precise than 9) – and the distance effect – increased difficulty in distinguishing two quantities as they get closer to each other (e.g., 9 and 10 are more difficult to discriminate than 9 and 19). Because of the PIS's capacity limit and the ANS's imprecision, these systems alone cannot fully support the development of mathematical thinking. Therefore, children will have to acquire a sophisticated and abstract symbolic code (e.g., Arabic digits, number words) to achieve higher mathematical expertise. In contrast to the PIS and ANS, this cultural construct must be learned and it will take several years for children to master it (Carey & Barner, 2019).

Past research has revealed a key role of canonical number representations in children's early acquisition of symbol cardinal meaning. Canonical numerosities can be represented in the form of dot patterns, such as those found on dice faces and playing cards, or in the form of finger configurations, such as those typically used in a culture while learning to count. Because of their "in-between" status – i.e., they can be counted like non-symbolic quantities, but at the same time, their familiar patterns can be automatically recognized like symbolic representations – canonical number configurations were assumed to facilitate the association between non-symbolic and symbolic numerical magnitudes (Kreilinger et al., 2021). Three recent longitudinal studies provided evidence in favor of this assumption. First, the processing of canonical dot patterns was found to be predictive of children's counting and cardinal understanding (Kreilinger et al., 2022). In addition, children's ability to quickly recognize canonical finger configurations was found to predict their symbolic representation accuracy (Van Rinsveld et al., 2020a) and finally, children's mastery of both canonical dot and finger structures were shown to predict their later arithmetic performance (Kreilinger et al., 2021). In sum, these behavioral findings clearly suggest a specific (and beneficial) role of canonical number representations, which may be to facilitate the correspondence between non-symbolic and symbolic quantities at the beginning of numerical development.

Neuroimaging studies have also provided significant insights into the underlying mechanisms of magnitude representation and integration across numerical codes. Activity within the parietal cortex, and more specifically the intraparietal sulcus (IPS), was consistently observed during the comparison of non-symbolic or symbolic numerical magnitudes (Dehaene et al., 2003). In recent years, a growing set of studies have relied on an electrophysiological (EEG) paradigm called fast periodic visual stimulation (FPVS; Rossion, 2014) to examine the implicit processing of numerical information. These studies demonstrated the brain's ability to spontaneously and automatically discriminate non-symbolic quantities (Guillaume et al., 2018; Van Rinsveld et al., 2020b), as well as to extract magnitude and parity information from symbolic digits (Guillaume et al., 2020). Furthermore, this paradigm has been used to address the neural signature of magnitude integration across non-symbolic dot arrays, Arabic digits and number words (Marinova et al., 2021a). Findings reported in this study supported the existence of a direct association between dots-number words and number words-digits, but suggested only an indirect link between dots and digits. To date, however, no study has used FPVS to explore the processing of canonical dot and finger configurations or to examine whether these numerical codes can be automatically integrated with other symbolic representations. From a broader perspective, it appears that studies investigating the cerebral bases of canonical number representations, especially of canonical dot patterns, are very scarce.

The goal of the current thesis was twofold: first, it aimed to provide insight into the implicit processing of canonical dot patterns and canonical finger configurations. To address this question, FPVS was used to explore whether canonical number representations could be automatically discriminated from non-canonical number configurations. This first study, described in *Chapter 2*, was conducted among 10-year-old children, who also performed a behavioral naming task (i.e., they had to indicate as fast and accurately as possible the numerosity that was presented either canonically or non-canonically). In addition, a second aim of this thesis was to explore the automatic integration of canonical number representations and symbolic magnitudes. The study reported in *Chapter 3* also relied on an FPVS paradigm, but this time combined with a multi-code presentation of quantities (i.e., Arabic digits, number words, canonical dot and finger patterns) and the distance effect (i.e., greater ease in distinguishing between two distant rather than close numerosities) as a marker of semantic access. After having established the existence of a shared magnitude representation among young adults, the spontaneous nature of this integration process was evaluated in a study reported in *Chapter 4.* To do so, the same multi-code FPVS design was used but while varying the attentional focus of the participants (*Chapter 4*). Finally, the last study of this thesis (*Chapter 5*) aimed at proposing a reliable behavioral paradigm to assess the integration of canonical dot patterns and Arabic digits, addressing several methodological limitations that previous studies had faced.

2 Overview of the main findings

In line with previous research suggesting that canonical dot and finger configurations provide a more automatic access to magnitude (Benoit et al., 2004; Di Luca & Pesenti, 2008), the behavioral findings reported in *Chapter 2* showed that children identified canonical dot and finger representations faster and more accurately than non-canonical patterns. At the cerebral level, the periodic occurrence of canonical configurations within a stream of non-canonical patterns led to significant discrimination responses over bilateral posterior regions. These FPVS discrimination responses therefore support the brain’s ability to spontaneously recognize the canonical nature of number representations and to generalize it across numerosities (i.e., 4-9). Although the brain activity could not be precisely localized with EEG, responses elicited by canonical dot and finger configurations showed a topography compatible with parieto-occipital regions. Hence, it seems to coincide with the brain areas identified as representing magnitude information from symbolic and non-symbolic numerical formats (Dehaene et al., 2003). Some differences were nevertheless observed between the processing of canonical dot and finger configurations. Indeed, the discrimination response elicited by canonical dots was much larger than the one elicited by canonical fingers. It is however very likely that numerical processing in the dot condition has been confounded with a shape recognition effect, due to the fact that all canonical configurations had a rectangular shape whereas the non-symbolic patterns had more variable and random shapes. In contrast, such a clear distinction between shapes was not present in the finger condition. One could thus argue that the FPVS response elicited by canonical finger configurations, compared to canonical dot patterns, more reliably measured the access to numerical magnitude representation. Accordingly, a positive correlation between children's right-lateralized brain responses and behavioral canonical gains was observed in the finger condition only. Based on a recent meta-analysis showing that the left and right IPS may be preferentially engaged in effortful and automatized processes respectively (Arsalidou et al., 2018), this finding suggests that a more automatic neural processing of canonical finger configurations was associated with a greater facilitation effect in children's behavioral performance.

The following study (*Chapter 3*) aimed at using FPVS to explore the automatic association between canonical numerosities and other symbolic representations (i.e., Arabic digits and number words). During one-minute sequences, young adults were visually stimulated with a stream of one base numerosity (e.g., "2") presented at 6 Hz and in randomly mixed codes (i.e., digit, word, canonical dots and fingers). Periodically, every fifth base stimulus, a deviant numerosity (e.g., "3") was inserted in the stream, also presented in randomly mixed codes. As reported in *Chapter 3*, significant discrimination responses were observed at the periodic change of numerosity (i.e., 6/5 = 1.2 Hz), which implies that the brain successfully generalized magnitude information over the deviant's representation codes. In support to the claim that these discrimination responses reliably assessed magnitude processing, their amplitude was found to be sensitive to the numerical distance between the base and the deviant: greater responses were elicited when the deviant numerosity was distant than close from the base (e.g., "2-8" *versus* "2-3"). This neural distance effect was furthermore correlated to its behavioral measure from an independent comparison task. Hence, these findings provided evidence that digits, words, canonical dot and finger patterns activate a shared numerical representation. This common activation was mainly concentrated over bilateral parieto-occipital sites, consistent with the idea that the two parietal lobes hold an abstract representation of magnitude containing semantic knowledge about numerical quantities (such as proximity and larger-smaller relations; Dehaene & Cohen, 1998). Nevertheless, the data indicated that the right hemisphere was more sensitive to the distance effect than the left, suggesting a possible asymmetry in the way the left and right parietal cortex process abstract magnitude information.

The FPVS design proposed in *Chapter 3* appears to be successful in measuring the automatic integration of canonical numerosities and symbolic numerals. Yet, a clear limitation of this study is that participants were instructed, before the start of the stimulation, to determine the smallest or largest numerical value that would be presented during the sequences. Hence, although participants did not have to perform any explicit task *during* the EEG recordings, we cannot preclude that the instruction directed their attentional focus towards the processing of magnitude, thereby promoting it. Consequently, the question of whether canonical quantities and symbolic numbers can spontaneously (i.e., automatically *and* unintentionally) activate a shared magnitude representation remained open. To address this issue, the study reported in *Chapter 4* aimed at using the same multi-code FPVS paradigm as presented in *Chapter 3* to explore abstract magnitude processing under different attentional contexts. In a first condition, participants were not given any specific instruction other than to look at the stimulation whereas in a second condition, they were instructed to determine the odd or even numerosities that would be presented during the sequences. All conditions led to significant discrimination responses associated with the periodic change of numerosity, suggesting that canonical dot patterns, canonical finger configurations, Arabic digits and number words spontaneously converged to a shared neural representation. More surprisingly, however, the sensitivity of discrimination responses to the distance effect was similarly observed when participants' attention was pre-oriented towards magnitude and parity, but not when participants were left without instruction. On the one hand, these findings indicate that abstract (or shared) magnitude information can be automatically processed even when the attentional focus is directed to another semantic feature of numbers, such as parity. On the other hand, this seems to depend on the cognitive resources involved in numerical processing.

Finally, the last study reported in this thesis (*Chapter 5*) investigated the integration of canonical dot configurations and Arabic digits with a new behavioral approach. Past research addressing whether quantities and number symbols are represented commonly or distinctively have led to inconsistent findings (Lyons et al., 2012; Liu et al., 2015), possibly due to some methodological differences regarding the task (e.g., magnitude comparison or matching) and the presentation mode (e.g., sequential or simultaneous). In the study of *Chapter 5*, participants were presented with canonical arrays of Arabic digits (i.e., such as playing cards on which the symbols have been replaced by digits) and asked to indicate, as fast and accurately as possible, whether the quantity of digits matched or mismatched the digit value (e.g., "3-3-3" = match, "3-3" = mismatch). Crucially, when the quantity and the digit mismatched, difference between the two numerical magnitudes was either small (e.g., "3-3" = *close* mismatched configurations) or large (e.g., "6-6" = *distant* mismatched configurations). The idea behind this approach was that, if canonical quantities and Arabic digits are indeed processed by a common distance-related representational system, participants should be better (i.e., faster and more accurate) at indicating the mismatch of distant than close configurations. The results confirmed our expectations by showing a significant cross-numerical code distance effect, which thus strongly supports the claim that canonical quantities and digits are integrated in a shared distance-related magnitude system.

3 Discussion and future research directions

3.1 The way of canonical configurations

Canonical configurations have played a leading role throughout this thesis. Those refer to specific arrangements of items that are perceived frequently and repeatedly in the same configurations, such as the dot patterns on a dice face and a playing card, or the cultural finger-counting (e.g., thumb, index and middle finger represent “3”) and finger-montring gestures (e.g., index and middle finger show “2”). At the behavioral level, canonical configurations of both dots and fingers were found to facilitate the enumeration of sets above four elements (i.e., above the subitizing range 1-4; Krajcsi et al., 2013; Di Luca & Pesenti, 2008). The results obtained in *Chapter 2* first replicated these findings. In addition, *Chapter 2* demonstrated that canonically arranged dot arrays and finger patterns were spontaneously categorized by the brain, granting them a unique connection with the magnitude they represent. In the following section, we discuss what might explain or support this advantage of canonical configurations over non-canonical ones.

With regard to the dots, two factors have been put forward that could underpin the facilitation effect of canonical structures in numerosity estimation: a pattern recognition theory and a “groupitizing” process. The pattern recognition theory was first introduced by Mandler and Shebo (1982), who suggested that small sets of dots could be recognized as simple shapes (e.g., point, line, triangle or square) enabling fast and accurate numerosity estimation (i.e., subitizing). If subitizing indeed results from some kind of pattern recognition, one might expect that subitizing performance would be sensitive to the arrangement of items. Accordingly, Krajcsi and colleagues (2013) demonstrated that the size of the subitizing range was extended to 6-7 elements when using canonical (dice-like) patterns instead of random arrays. While below 4 performance were not sensitive to the arrangement of items, beyond 4 all numerosities (5-9) were enumerated faster and more accurately in their canonical structure, a finding also reported in the behavioral results of *Chapter 2*. Furthermore, distortion of the regular canonical shapes negatively impacted the response latencies, suggesting that less recognizable patterns start to rely more on counting processes (Krajcsi et al., 2013). The pattern recognition theory was also supported by recent neuroimaging findings. Combining ERPs and functional microstates, Gheorghiu and Dering (2020) explored the interplay between shape recognition and numerosity estimation. In their first experiment, the authors compared ERP responses to numerosity when represented as dot arrays forming simple shapes (e.g., 3 dots placed on the vertices of a triangle) *versus* randomly arranged. Shape number configurations led to an increased amplitude of several ERP components: N1 (160-220 ms), N2 (250-400 ms) and LMF (400-650 ms). In addition, their microstate analyses indicated that shape coding was initiated prior to numerosity estimation, thereby suggesting that pattern recognition can facilitate number processing (Gheorghiu & Dering, 2020). These findings strengthen the hypothesis that a shape-related confounding factor may have impacted the discrimination response of canonical dot configurations (described in *Chapter 2*). Given that a temporal distinction could not be made in the FPVS analyses, it is indeed possible that the cerebral responses reported in that study reflected a mix of early shape coding and later numerical processes.

A second factor that may account for the facilitation effect of canonical dot patterns in numerosity estimation is a process called “groupitizing”. This process involves two subsequent steps: first, a dot array is separated into smaller subsets containing a number of dots that can be subitized (Starkey & McCandliss, 2014). Right after, the subitized values are mentally summed or multiplicated (or a combination of both) to retrieve the total magnitude of the set (Ciccione & Dehaene, 2020). Groupitizing has been found to improve rapid estimation of numerosity and to be a good predictor of later mathematical achievement (Guillaume et al., 2021). Because of their symmetrical shapes, canonical dot patterns can be easily separated in subsets of 3 or 4 elements (e.g., a canonical pattern of 6 dots is represented by 2 rows of 3 dots), which may thus facilitate the groupitizing strategy and lead to faster enumeration. Recently, the neural mechanisms underlying groupitizing has been examined with fMRI (Maldonado Moscoso et al., 2021). In that study, participants were scanned while performing numerosity estimation of dot arrays that were either spatially grouped or randomly organized. The results showed that estimations of ungrouped and grouped arrays commonly activated a right lateralized frontoparietal network, suggesting that they both relied on the approximate number system. However, spatially grouped dot arrays additionally and uniquely recruited regions in the left hemisphere, known to be involved in calculation procedures (Maldonado Moscoso et al., 2021). A similar pattern of results was reported in the first study of this thesis (*Chapter 2*). The processing of canonical dot arrays was indeed associated with bilateral brain responses over posterior sites. Hence, this activation seems compatible with the hypothesis that groupitizing could have been automatically induced by the canonical configurations. Based on the findings of Maldonado Moscoso et al. (2021), one could expect that children showing greater activation of the left hemisphere would more strongly rely on the groupitizing strategy to process canonical dot patterns, whereas those showing greater activation of the right hemisphere would directly retrieve the magnitude associated with the canonical array. Consequently, a right-lateralization response could have been associated with a greater canonical gain in children’s enumeration performance. However, results from the study reported in *Chapter 2* failed to show such a correlation. The fact that our findings did not support this relation may be explained by the contribution of other non-numerical factors in the discrimination of canonical dot patterns, such as the shape coding process mentioned previously.

Although the data reported in *Chapter 2* does not allow to distinguish between the two strategies (i.e., pattern recognition and/or groupitizing) possibly involved in canonical dot processing, future studies may wish to investigate this question further. For instance, it could be interesting to compare the processing of canonical configurations to that of spatially grouped dot arrays (similar to the grouped stimuli used by Maldonado Moscoso et al., 2021). Because the latter would not form specific shapes, they would prevent the involvement of pattern recognition processes but enable groupitizing. Another possibility could be to compare the neural processing underlying regular shapes and distorted shapes (such as those used by Krajcsi et al., 2013) to further explore the neural mechanisms of shape recognition in numerical processing.

By contrast with dots, the advantage of canonical finger configurations in numerosity estimation is unlikely to originate from a shape recognition process. Using a visual-detection task (i.e., find the target among distractors), Di Luca & Pesenti (2010) indeed showed that canonical finger patterns enjoyed no perceptual saliency among non-canonical configurations (i.e., no pop-out effect). Although the task did not involve processing numerical information, it strongly argues that visuo-perceptual differences between canonical and non-canonical finger configurations could not account for better identification of canonical patterns. Some authors have suggested that, due to their frequent use during the development of early numerical and mathematical abilities, canonical finger representations have come to acquire a specific status in long-term memory (Di Luca et al., 2010; Soylu et al., 2018). As a result, canonical finger configurations would facilitate magnitude access by reactivating the connections established with other numerical representations (i.e., the non-symbolic and symbolic codes) in long-term memory, whereas non-canonical configurations would still require subitizing or counting to extract their magnitude information. This assumption was supported by a recent electrophysiological study that compared the ERP correlates of processing finger-counting, finger-montring and non-canonical finger configurations (Soylu et al., 2019). A higher positivity in the late P3 range (250-500 ms) was found over parieto-occipital sites for both canonical configurations, which was interpreted as evidence for a more automatic access to numerical information for finger-counting and finger-montring configurations compared to non-canonical ones. According to the authors, this difference in the later semantic processing stage could be explained by differences in the strategy used: memory recall for canonical *versus* counting for non-canonical configurations (Soylu et al., 2019). These findings therefore support the idea of a progressive internalization of finger numeral representations during development, which appear to persist in adulthood. The results reported in *Chapter 2* are consistent with this view, as they indicate that 10-year-old children can already spontaneously recognize the canonical nature of finger patterns across numerosities (4-9).

Canonical finger configurations have also been assumed to convey basic relationships between quantities, such as (de)composing numbers (e.g., adding 2 fingers to 3 fingers makes 5), or quantifying the exact difference between two numerosities (e.g., 3 fingers and 5 fingers are separated by 2 fingers; Roesch & Moeller, 2015). Furthermore, canonical finger patterns beyond 5 inevitably include a full hand, which implies that large numerosities (6-9) come to be represented as 5 *plus* something, whereas below five all numerosities can be represented as 5 *minus* something. In this view, some sort of groupitizing process may also be involved in the representation of canonical finger configurations. However, in contrast to the dots' groupitizing strategy, only additions and subtractions would be used to retrieve the total magnitude of the configuration, and not multiplications. Supporting this hypothesis, an fMRI study in adults provided evidence that the brain regions underlying finger representations were also involved in arithmetic operations, albeit more importantly for subtractions than for multiplications (Andres et al., 2012). In that study, brain activity was measured while participants solved subtraction and multiplication problems, or performed a finger discrimination task (i.e., identify the position of fingers). Mental arithmetic and finger representation activated common areas in different regions of the parietal cortex bilaterally. However, the similarity of activation patterns was higher between finger discrimination and subtractions, compared to multiplications, and also more important for the left than for the right hemisphere. Consistent with the results of Andres and colleagues (2012), findings in 8- to 13-year-old children revealed that subtractions, but not multiplications, significantly activated finger motor areas, suggesting an automatic reliance on finger representations to solve subtraction operations (Berteletti & Booth, 2015). Finally, two other studies indicated that canonical finger configurations facilitated adults' performance in solving addition problems (Badets et al., 2010; Van den Berg et al., 2021). Taken together, these considerations give some strength to the idea that canonical finger configurations may automatically activate number relations involved in additions and subtractions, which in turn would favor the development of these arithmetic skills.

Similar to the results observed for the canonical dot condition, the findings reported in *Chapter 2* revealed a bilateral activation of posterior sites associated with the automatic discrimination of canonical finger configurations among non-canonical ones. Based on past research, it is possible that the involvement of the left hemisphere reflects the automatic implication of calculation procedures in the processing of canonical finger patterns (Andres et al., 2012), whereas the activation of the right hemisphere would reflect automatic access to the magnitude representation stored in long-term memory (Van den Berg et al., 2022). In line with this hypothesis, data of the study described in *Chapter 2* highlighted a positive association between children’s right-lateralized brain response and their canonical facilitation effect in the behavioral naming task. Hence, a plausible explanation for this relation may be that children who relied more on computational strategies to retrieve the magnitude of the canonical finger patterns took less advantage of these configurations, as compared to the children who directly retrieved the magnitude associated with the canonical pattern in long-term memory.

In conclusion, *Chapter 2* has fulfilled the first objective of this thesis by shedding new light on the implicit processing of canonical dot and finger configurations. Although several studies have considered canonical number representations in the same way as non-symbolic quantities (e.g., Benoit et al., 2013; Kaufmann et al., 2008; Venkatraman et al., 2005), it is now clear that canonical configurations are processed distinctively from non-canonical (i.e., non-symbolic) number representations. Findings presented in *Chapter 2* have indeed demonstrated the spontaneous discrimination of canonical patterns among non-canonical ones, supporting the claim that canonical configurations may provide a fast access to magnitude representation. However, despite the fact that canonical dot and finger patterns enjoy more representational accuracy than non-symbolic quantities, these configurations should not be considered in the same way as symbolic numerals neither. Support for this last assumption can be found in the appendix of *Chapter 3*. In that study, participants were presented with a base numerosity (e.g., "2") at 6 Hz and a deviant numerosity (e.g., "3") was periodically appearing at 1.2 Hz. Within different conditions, both base and deviant numerosities could be presented in single code (i.e., canonical dots, canonical fingers, Arabic digits or number words) in mixed-code within the same format (i.e., dots-fingers or digits-words) and finally in mixed-format combining the four different codes (main data of *Chapter 3*). Results from the single code analyses, reported in the appendix of *Chapter 3*, highlighted qualitatively different processing for the two canonical and the two symbolic codes. While larger FPVS discrimination responses were found when contrasting distant (e.g., 2/8) *versus* close (e.g., 2/3) base/deviant numerosities in the canonical dot and finger conditions, such a neural distance effect did not emerge in the FPVS responses associated with Arabic digit and number word presentations. Although these results should be interpreted with caution, due to the strong possibility of low-level visual confounds in the discrimination responses (discussed in *Chapter 3*), it nevertheless suggests that canonical number representations automatically exhibit some shared properties with the non-symbolic format. Hence, these findings are well in line with previous research suggesting that canonical configurations of dots and fingers possess an "in-between" (or iconic) status (Di Luca & Pesenti, 2011; Van Rinsveld et al., 2020a; Kreilinger et al., 2021).

3.2 A role for canonical representations in the acquisition of numerical symbols?

As mentioned in the *General Introduction*, a complete comprehension of numbers implies that children must acquire the meaning of symbolic representations, such as number words and Arabic digits, which represents a crucial step in their mathematical development (Carey and Barner, 2019). Extensive research has been devoted to the question of how symbols gain their meaning, referred to as the "symbol grounding problem", and at least two major accounts are currently confronted in the literature: the ANS mapping account and the symbol-symbol association account (see Reynvoet & Sasanguie, 2016 for a review). On the one hand, the *ANS mapping account* assumes that symbols acquire their meaning by being mapped onto their pre-existing non-symbolic representations (Dehaene, 2001). Several empirical findings (albeit disputed, see Reynvoet & Sasanguie, 2016) have been taken as evidence for this non-symbolic-symbolic integration: as examples, non-symbolic and symbolic comparisons both show a distance effect (Moyer & Landauer, 1967), their processing is supported by the same brain region (i.e., within the parietal cortex, Dehaene et al., 2003) and the precision of the mapping is predictive of later mathematical abilities (Libertus et al., 2016). On the other hand, the *symbol-symbol association account* assumes that the PIS, rather than the ANS, allows children to acquire the cardinal meaning of the first number words by mapping them onto their exact non-symbolic representations, within the subitizing range (1-4). Once this initial mapping has occurred, children will come to understand several numerical principles (such as ordinal relations and the successor function, see Carey and Barner, 2019), that will progressively lead to the development of a distinct symbolic system where numerical symbols are represented through associations with each other (Reynvoet & Sasanguie, 2016).

Several developmental studies explicitly compared both accounts by investigating how young children develop the correspondence (mapping) between non-symbolic quantities, number words and Arabic digits (Hurst et al., 2017; Lira et al., 2017; Marinova et al., 2021b). These studies were based on the idea that the ANS mapping account (or the quantity account, see Hurst et al., 2017) and the symbol-symbol associations account (or the symbolic account) would differently predict the order of acquisition of these mappings. According to the quantity account, children would indeed start to map number words to quantities, and may acquire Arabic digits' meaning in the same way (i.e., by mapping them onto their non-symbolic quantities). Only after mastering these two symbolic representations would children learn the correspondence between them, by understanding that the Arabic digit "3" represents the same quantity as the number word "three" (Hurst et al., 2017). In contrast, the symbolic account predicts that children would first acquire the meaning of Arabic digits by making an asemantic correspondence with the number words and only after would children understand that Arabic digits represent the same quantities as the number words do. In all three studies, results were in favor of the symbolic account, showing that children first learn to map words-dots and words-digits, before they acquire the digits-dots mapping (Hurst et al., 2017; Lira et al., 2017; Marinova et al., 2021b). Furthermore, Lira and colleagues (2017) complemented their research with a path analysis exploring the relations between children's mapping abilities and their performances in several magnitude comparison tasks. They found that children's digits-dots mapping was predictive of their capacity to compare two symbolic numbers, with an indirect effect of the words-dots and words-digits mappings. These findings led the authors to assume that the development of children's numerical skills is based on the capacity to integrate all the representations together (i.e., dot quantities, number words and Arabic digits).

An intriguing question that we aimed to explore in the current thesis is how and when canonical number representations would be integrated in the interconnected model of early numeracy acquisition proposed by Lira and colleagues (2017). Recent behavioral studies have suggested that both canonical dot and finger configurations may support the mapping between non-symbolic quantities and symbolic numerals, through facilitating the acquisition of the cardinal principle (Kreilinger et al., 2021, 2022, Orrantia et al., 2022; Van Rinsveld et al., 2020a, more details for these studies are provided in the *General Introduction*). As such, canonical patterns would thus play an intermediate role in the mapping between words and quantities and between digits and quantities. Accordingly, while investigating how children develop their ability to map between canonical (dice-like) dot arrays, spoken number words and Arabic digits, Benoit and colleagues (2013) observed a different pattern of results than those reported in studies using non-canonical representations of dots (Hurst et al., 2017; Lira et al., 2017; Marinova et al., 2021b). Four-year-old children were indeed found to perform equally well when mapping between canonical dots and number words and between canonical dots and digits, but they performed more poorly when mapping between number words and digits. Hence, contrasting with the results reported earlier, these findings are more in favor of a (canonical) quantity account which assumes that the mapping between canonical quantities and symbols occur before the mapping between symbolic representations. With regard to the fingers, it was found that children who have not yet acquired the cardinal principle were more accurate in representing set of 2 or 3 items with their fingers than with number words (Gunderson et al., 2015). As discussed by the authors, these findings raise the possibility that children first map sets of items to finger configurations by taking advantage of their shared item-based (non-symbolic) nature, and then gradually map these learned (canonical) finger patterns to number words, taking advantage of their shared representational and communicative properties to eventually grasp the cardinal principle (Gunderson et al., 2015). Taken together, these previous studies strongly suggest that the use of canonical dot and finger configurations is a crucial milestone in children's numerical development. Hence, the integration of canonical quantities, number words and Arabic digits may constitute a central component when developing models of early numerical acquisition such as the one proposed by Lira et al. (2017).

To the best of our knowledge, the study reported in *Chapter 3* was the first to explore the neural bases underlying the integration of canonical configurations and symbolic number representations. In that study, significant brain responses were observed at the periodic change of numerosity despite its code variation (i.e., numerosities were presented as digits, words, canonical dot and finger configurations, randomly mixed). Based on the FPVS principles, these results indicate that the brain could successfully generalize over the deviant's magnitude irrespectively of its notation. Hence, for the first time, the study presented in *Chapter 3* provided evidence that the brain is able to automatically integrate magnitude information from canonical number representations and symbolic numerals. Another FPVS study had examined the integration of numerical codes before, with an experimental design involving pairwise combinations of non-symbolic dot arrays, number words and Arabic numerals (Marinova et al., 2021a). While their findings supported an automatic integration of number words and dots, and number words and digits, they did not provide conclusive evidence for an automatic integration of digits and dots. As discussed by the authors, these results possibly indicate the existence of a direct cognitive link between both number words and non-symbolic quantities and number words and digits, but suggest only an indirect link between Arabic digits and non-symbolic dots. Although the data were collected in adults, this pattern of results seems to fit with the developmental trajectory of early numerical acquisition showing that children first learn to map number words on quantities and digits on number words, before they can make the association between digits and quantities through the knowledge of how number words relate to both information (Hurst et al., 2017; Marinova et al., 2021a, 2021b). Following the same rationale, the finding of an automatic integration between canonical number representations, Arabic digits and number words, as reported in *Chapter 3*, appears to be consistent with the pattern of results obtained by Benoit and colleagues (2013). These authors indeed suggested a direct association between canonical dot arrays and symbolic numerals, that would presumably occur before the association between number words and digits. Hence, it could be argued that the acquisition of the canonical quantities-symbolic number mapping plays a foundational role in the process by which children learn the correspondence between number words and digits. As a result, the automatic integration of canonical number representations and symbolic numerals may persist in adulthood, as reflected by the results obtained in our FPVS study.

Taken together, these behavioral and neural findings raise the interesting, albeit speculative, possibility that the integration of canonical quantities and other symbolic representations may pave the way for the development of an abstract magnitude representation, enabling the gradual establishment of correspondences between all numerical codes. Further research is needed to explore this hypothesis. For instance, it would be interesting to use the multi-code FPVS paradigm in young children to determine *when* the common activation for canonical quantities and symbolic number emerges, and *how* the development of this shared magnitude representation may be related to the mapping acquisition. One should also consider the possible contribution of other educational or demographic factors (e.g., language, instruction, culture) in the acquisition of canonical quantities-symbols mapping. As an example, it was found that home numeracy activities (i.e., daily interactions between parents and children that promote experiences with numerical content, e.g., singing counting songs, naming numbers, playing dice games, etc.) were positively related to children's mapping skills (Marinova et al., 2021b). Thus, a complete model of early numeracy acquisition should also take the influence of these different factors into account. Finally, given that the mastery of canonical number representations was found to predict children's arithmetic skills (Kreilinger et al., 2021) and that children's abilities in mapping digits to non-symbolic quantities was shown to predict their symbolic magnitude comparison performance (Lira et al., 2017), it would be of great interest to determine how the acquisition of canonical quantities-symbols mapping relates to later mathematical achievement.

3.3 Hemispheric asymmetry in the neural underpinnings of magnitude processing

Although EEG does not allow for a precise localization of the brain activity underlying magnitude representations, it can nevertheless provide powerful insight into the hemispheric specialization of numerical processing. When examining the lateralization pattern of brain responses elicited by the individual code presentations (*Chapter 2 & Chapter 3 – appendix*), results are in line with those reported by previous studies involving dot patterns or symbolic numbers (Guillaume et al., 2020; Lochy & Schiltz, 2019; Marinova et al., 2021a). As already discussed above, the study described in *Chapter 2* demonstrated that the discrimination of canonical dot and finger configurations activated bilateral regions over parieto-occipital sites. The findings reported in *Chapter 3 (appendix)* slightly differ from that of *Chapter 2*, by showing a larger distance effect on the brain activity supporting canonical dot and finger processing within the right hemisphere. However, these two studies fundamentally differ in the way they were designed: while in *Chapter 2* canonical and non-canonical numerosities were contrasted, only canonical patterns were used in *Chapter 3* and direct comparison of the brain responses induced by close base/deviant numerosities and distant base/deviant numerosities was made (i.e., the neural distance effect). Hence, one may conclude that canonical configurations of dots and fingers can be represented in both hemispheres, but that their underlying magnitude processing is mainly supported by the right hemisphere. The lateralization patterns of Arabic digit and number word discrimination (*Chapter 3 – appendix*) were highly consistent with that reported in a previous FPVS study (Marinova et al., 2021a). That is, for Arabic digits, significant discrimination responses were obtained predominantly over right parieto-occipital regions, whereas number words responses were mostly left-lateralized. These findings seem to perfectly fit with the influential triple code model of number processing proposed by Dehaene (TCM; 1992). The TCM posits that numerical processing involves three distinct mental representations of numbers: an Arabic number form, thought to be situated in the right hemisphere (see Yeo et al., 2017 for a review), a verbal word frame in the left hemisphere (Dehaene et al., 2003), and a non-symbolic magnitude representation in bilateral intraparietal sulci (IPS). Under the assumptions of the TCM, neither the Arabic number form nor the verbal word frame contain any semantic information. Thus, these two codes converge onto the magnitude system, where the quantity associated with a given symbol can be retrieved and put in relation with other quantities (Dehaene & Cohen, 1995). Fully in line with this assumption, the findings reported in *Chapter 3 (appendix)* highlighted that neither the digit nor the word discrimination responses were modulated by the distance effect when tested in separate conditions (i.e., the “uni-code” conditions). Quite impressively, however, the combination of both codes (i.e., the “intra-format” condition) resulted in a significant distance effect over right parieto-occipital regions, suggesting that the integration of Arabic digits and number words automatically activate their underlying magnitude representation (Dehaene & Akhavein, 1995).

An overlapping finding in the studies reported in *Chapter 3 & 4* was that the right hemisphere may be superiorly engaged in the automatic processing of quantities than the left hemisphere. According to the TCM, both hemispheres possess a magnitude representation system (Dehaene & Cohen, 1995). The results obtained in the current thesis do not reject this assumption, as a trend towards distance sensitivity was consistently observed in the left hemisphere, though it only reached significance in the right hemisphere. A recent meta-analysis of studies using an adaptation paradigm (i.e., passive viewing, Grill-Spector & Malach, 2001) to investigate numerical processing indicated that both non-symbolic and symbolic formats consistently activated bilateral IPS (Escobar-Magariño et al., 2022). In addition, this study included an analysis of the lateralization index of IPS activation, which revealed a clear difference in the way brain activity is lateralized according to the numerical format: a right hemispheric dominance was found in studies using non-symbolic quantities and a left hemispheric dominance was found in studies involving symbolic numerals (Escobar-Magariño et al., 2022). Previous research suggested that hemispheric specialization for numerical formats emerges over the course of development. By comparing the brain activity of children and adults during symbolic and non-symbolic comparisons, Holloway and Ansari (2010) showed that the right parietal cortex undergoes a developmental specialization for the abstract representation of numerical magnitude. They indeed found that the right hemisphere, but not the left, exhibited significant age-related increases in the activation related to the conjunction of symbolic and non-symbolic numerical magnitude comparisons. Using a similar approach, another study suggested a specialization of the left parietal cortex for the semantic representation of Arabic digits (Vogel et al., 2015).

The results reported in *Chapter 3* are more in line with the hypothesis that both left and right parietal lobes hold an abstract representation of magnitude (Dehaene

& Cohen, 1995). Indeed, analyses performed on the FPVS responses elicited by the multi-code presentation of numerosities (i.e., combination of digits, number words, canonical dot and finger configurations) did not lead to a significant effect of lateralization, supporting the ability of both hemispheres at integrating numerical magnitude. However, an interaction between the distance factor (i.e., close *versus* distant base/deviant numerosities) and the lateralization was found, indicating a significant distance effect only in the right hemisphere (*Chapter 3*). It is thus possible that abstract magnitude information may be more precisely represented within the left hemisphere. Similar findings were reported in a fMRI adaptation study, in which greater distance-related cross-notation fMRI recovery was observed in the right compared to the left parietal cortex when deviant non-symbolic dots were presented amongst Arabic digits (Piazza et al., 2007). Taken together, these data raise the possibility that the left parietal representation has been affected by the acquisition of number symbols. As a result, the right parietal cortex would have kept a coarse representation for both symbolic and non-symbolic notations, whereas the left hemisphere may have acquired a refined precision (Dehaene, 2007; Piazza et al., 2007). Support for this last assumption was also provided by another fMRI adaptation study in adults (Piazza et al., 2004). Indeed, the authors observed that although both left and right intraparietal regions adapted to non-symbolic numerosities (i.e., dot arrays), the precision of the representation (measured by the Weber fraction in recovery of adaptation) tended to be higher in the left than in the right IPS (Piazza et al., 2004). Finally, several behavioral studies have suggested that the acquisition of symbolic number representations can enhance the precision of non-symbolic processing (Matejko & Ansari, 2016; Mussolin et al., 2014). While there is thus available support for a difference in the precision of left and right magnitude coding, further research will be needed to directly address the question of the hemispheric asymmetry in numerical processing.

Another meta-analysis on brain activity related to numerical processing in children have proposed that the left and right IPS might be differently engaged depending on the task complexity (i.e., a process-driven lateralization hypothesis; Arsalidou et al., 2018). Taking a constructivist developmental perspective (Arsalidou & Pascual-Leone, 2016), the authors argue that the right hemisphere would be involved in automatic number processes (e.g., simple magnitude comparisons), whereas the left hemisphere would be implicated in more effortful problems, that require operation rules applied to numbers (e.g., calculation tasks). As such, the involvement of the left and right parietal cortices in numerical processing would follow a trade-off between the individuals' mental-attentional capacity and the tasks' mental demand: when the task is very easy (automatized), that is, when the mental capacity is well above the mental demand, it would favor the right hemisphere. In contrast, a novel (effortful) task involving larger mental capacity would rather favor the left hemisphere. Additionally, as the task becomes more familiar with experience (overlearned processes), there would be a progressive transfer from the left to the right hemisphere (Arsalidou et al., 2018). As it was discussed earlier, the finding of a correlation between right-lateralized brain response associated with the processing of canonical finger configurations and children's performance in the behavioral naming task (*Chapter 2*) seems to fit well with this process-driven lateralization hypothesis. Indeed, children showing more activation in the left and right hemispheres would respectively involve more effortful and automatized strategies to process canonical finger representations, which in turn may influence their ability to enumerate these number configurations. Results reported in *Chapter 4* also suggest a specific role of the right hemisphere in the automatic processing of magnitude information. By varying the instruction given to the participants before the administration of the multi-code FPVS paradigm (*Chapter 3*), this study explicitly addressed the conditions under which abstract magnitude processing can occur. Findings highlighted that the sensitivity of discrimination responses to the distance effect, considered as a reliable marker of semantic processing, varied according to the instruction: it was significantly present when participants' attention was explicitly oriented to magnitude and to parity features, but not when participants were passively viewing numerosities. While the influence of instruction was found in both hemispheres, it tended to be more pronounced in right posterior regions, thus supporting the idea that the right parietal cortex is more implicated than the left in automatic numerical processes. In the same line, a transcranial magnetic stimulation (TMS) fMRI study showed that although automatic magnitude processing was supported by both IPS, it was only impaired when right IPS neuronal activity was disrupted (Cohen Kadosh, 2007). Taken together, these results thus indicate that the right, but not the left, IPS may be functionally necessary for automatic magnitude processing.

3.4 Fast Periodic Visual Stimulation, a powerful paradigm to measure automatic numerical processing?

One methodological aim of this PhD thesis was to capitalize on the increasingly popular FPVS technique in order to measure the automatic (implicit) processing of number representations (*Chapter 2-4*). As reviewed in the *General Introduction*, brain activity within the IPS, which is believed to underly magnitude representation, has also been related to response selection demands (Culham & Kanwisher, 2001; Gobel et al., 2004; Jiang & Kanwisher, 2003). This confound has led some authors to argue that the similar patterns of activation found during non-symbolic and symbolic comparisons may result from similar response selection demands associated with the different numerical codes, rather than from a common representational system (Cohen Kadosh & Walsh, 2009). Therefore, the FPVS paradigm can be used to overcome this methodological issue, as it allows the measurement of brain activity involved during numerical processing in the absence of response selection. In *Chapter 3 (and 4)* this EEG technique was used to show the automatic integration of numerical representations. To recap, participants were visually presented with a stream of one numerosity (e.g., “2”), presented at 6 Hz (i.e., 6 stimuli/s) and in randomly mixed codes (i.e., Arabic digit, number word, canonical dot and finger configurations). Every fifth stimulus, a deviant numerosity (e.g., “3”), also presented in randomly mixed codes, was inserted within the stream (i.e., at 6/5 = 1.2 Hz). Significant discrimination responses were found at the frequency of the deviant presentation (i.e., 1.2 Hz) over a period of only 1-minute simulation, which indicates that FPVS can provide a rapid and yet sensitive (i.e., with a high signal-to-noise ratio) measure of numerical processing. Although impressive, one major question remains: how do we know that the observed response reflects the process we intended to measure? Several factors, other than the one being intentionally manipulated, may indeed contribute to the discrimination of the deviant stimuli (e.g., differences in the low-level perceptual features or in the frequencies of occurrence of base/deviant, those will be further described in the following section). To address this question, most of the previous FPVS studies involved the use of control sequences, in which the same stimuli as those included in the experimental condition were presented but randomly assigned to the base/deviant categories. As an example, in the study of Guillaume et al. (2020), their magnitude condition contrasted small (1 2 3 4) and large digits (6 7 8 9) as base/deviant whereas the corresponding control sequence contrasted two arbitrary categories of digits (i.e., 1, 4, 6, 9 *versus* 2, 3, 7, 8). As a result, differences in activation between the experimental and control conditions should reflect the processing of the target feature manipulation over and beyond potential stimulus-driven factors. However, it cannot be excluded that variations between the two conditions other than those explicitly manipulated could stem for significant differences in activation. Studies reported in *Chapter 3 & 4* of the current thesis relied on the use of the distance effect (Moyer & Landauer, 1967) as a marker of magnitude processing. It was expected that the discrimination of a distant deviant numerosity (e.g., base “2” – deviant “8”) would produce larger response amplitudes than discrimination of a close deviant (e.g., base “2” – deviant “3”; Piazza et al., 2004). As predicted, the results of the study described in *Chapter 3* indicated significant distance modulation on the discrimination responses, which was furthermore correlated to participants’ behavioral measure of the distance effect. Hence, we showed for the first time that the combination of FPVS and numerical distance effect can provide a reliable and implicit measure of magnitude integration across numerical codes.

In a FPVS study, the frequencies of interest, that is, the base and deviant stimulation rates, are thus defined in advance. While it provides a great advantage in terms of objectivity (i.e., the resulting responses will be obtained as these exact predefined frequencies), it also implies that the stimulation rates must be chosen *a priori* by the experimenter. What stimulation frequency could (or should) be used to adequately assess numerical processing? On the one hand, stimuli should be presented enough time so that each numerosity (irrespective of its format) can be processed sufficiently deeply before the next one appears in the stream. If the frequency rate is too high, it may lead to the measurement of early perceptual processes only (Rossion, 2014). On the other hand, the stimulation rate should be fast enough to avoid the involvement of conscious decisional aspects in numerosity processing. Previous FPVS studies in numerical cognition have used a relatively high visual stimulation rate of 10 Hz, meaning that each base and deviant numerosity was presented on the screen for 100 ms (non-symbolic – Guillaume et al., 2018; Van Rinsveld et al., 2020b; symbolic – Guillaume et al., 2020; both – Marinova et al., 2021a). While these studies found significant discrimination responses associated with the presentation of the deviant numerosity, it is possible that such a high frequency rate would fail to capture the process underlying magnitude integration across formats. Indeed, a recent ERP study exploring the time course of the implicit integration between non-symbolic quantities and Arabic digits reported a significant effect starting around 130 ms post-stimulus (Liu et al., 2018). As discussed by Marinova and colleagues (2021a), this may possibly explain why the latter did not find significant FPVS responses in their mixed digits-dots condition. In line with the findings of Liu et al. (2018), a previous ERP study obtained significant voltage differences associated with the distance effect for dot arrays and Arabic digits spanning around 130-240 ms after stimulus onset (Temple & Posner, 1998). Hence, taken together, these results suggest that a stimulation frequency of 6 Hz (i.e., 6 stimuli/s, so that each stimulus is presented for 166.67 ms), as used in the multi-code FPVS paradigm of *Chapter 3 & 4*, could be more suitable (compared to 10 Hz) to evaluate magnitude integration and to assess the presence of a neural distance effect.

Despite its numerous advantages, the FPVS paradigm also faces some methodological issues that should be carefully considered when designing an experiment and interpreting data. As mentioned earlier, a first major concern relates to the involvement of low-level perceptual parameters in the discrimination responses, as clearly illustrated by the uni-code data reported in *Chapter 3 (appendix)*. To limit the influence of these perceptual biases, a frequently used solution is to control for the non-numerical visual cues (e.g., total area, item size, density) of non-symbolic representations (Guillaume et al., 2018), or to add some variability in the visual features of the stimuli (e.g., by varying the font type and size of the Arabic digits and number words; Lochy & Schiltz, 2019). Nonetheless, low-level perceptual differences between two quantities, digits or number words will always remain and thus contribute, at least to some extent, to the discrimination of the deviant numerosity. Using a multi-code presentation, such as in *Chapter 3 & 4*, offers a great solution to this methodological issue. Indeed, because both base and deviant stimulus categories contained a high level of variability in their visual features, it substantially reduced (if not eliminated) the possibility that the brain could rely on visual cues to discriminate the deviant numerosity from the base. This assumption was further reinforced by the individual sequence analysis, which did not show any significant difference in close or distant response amplitudes (e.g., close base/deviant sequences “2/3” and “8/9” yielded similar response amplitudes). Thus, besides its theoretical purpose which was to investigate magnitude processing across numerical codes, the multi-code FPVS paradigm also allowed us to overcome the limitation faced in the uni-code presentations regarding low-level perceptual biases.

As already mentioned, a second unwanted factor that might significantly contribute to the FPVS discrimination responses is the relative frequency-of-occurrence difference of the base and deviant categories (de Rosa et al., 2022). For instance, a typical 60-s stimulation sequence with a base frequency of 6 Hz and a deviant stimulus embedded every fifth item (i.e., at 1.2 Hz), includes a total of 288 base stimuli and only 72 deviants, thus featuring the former as frequent (standard) and the latter as infrequent (rare) stimuli. Differences in the frequency with which bases and deviants are presented in a given stimulation sequence seem inherent in the nature of FPVS. Crucially, a recent study demonstrated that the brain can elicit a discrimination response associated with the occurrence of deviant stimuli in the absence of any pre-existing difference between the base and deviant categories (e.g., deviant words were periodically appearing in sequence of words with no semantic distinction between them; de Rosa et al., 2022). Hence, the discrimination response obtained in that study was only due to the relative frequency-of-occurrence difference of base and deviant stimuli. Evidence for the claim that the brain is able to categorize the rare nature of deviant stimuli was also found in the study of Guillaume and colleagues (2020). While participants were presented the control sequences, in which Arabic digits were randomly assigned to the base and deviant categories (i.e., no semantic distinction between them), some peaks of response emerged at the frequency of the deviant occurrence, albeit not statistically significant. Although this frequency-based neural mechanism may also have contributed to the discrimination of the multi-code numerosity in the study of *Chapter 3*, the finding of a significant correlation between the cerebral and behavioral measures of the distance effect comfort us in the fact that our FPVS paradigm mainly and reliably assessed numerical processing. Nevertheless, future studies could try to minimize the influence of this statistical confound by reducing the relative difference in the frequency of occurrence of base and deviant stimuli. For instance, it might be worthwhile to add some variability in numerosities assigned to the base category, so that base and deviant magnitudes would occur with the same probability.

Finally, the findings reported in *Chapter 4* highlighted that attention may also modulate the neural responses associated with automatic magnitude processing. Before being presented with the multi-code FPVS paradigm (described above), participants were instructed to focus their attention either on the magnitude or parity feature of numerosities, or to passively look at the stimulation. Results showed significant discrimination responses elicited at the frequency of the deviant presentation in all three conditions. Interestingly enough, while a significant distance modulation was found on the responses obtained in magnitude and parity instructions, we did not find conclusive evidence for the presence of a distance effect during simple viewing. The fact that a distance effect was observed when participants were instructed to focus their attention on parity, but not when passively attending the stimulation, suggests two conclusions. First, consistent with previous behavioral findings (Fias, 1996; Cipora et al., 2021), our data support that magnitude can be automatically processed irrespective of the numerical feature that is explicitly triggered (i.e., magnitude or parity). Second, while the neural encoding of numerosities seems to occur spontaneously, the processing of this shared magnitude appears to require a sufficient level of attentional resources. In view of this last assumption, we tentatively suggest that magnitude integration may be a process involving multiple stages: seeing and recognizing numerosities (early perceptual stage), encoding magnitudes (intermediate integrative stage) and then relating them to each other (late processing stage producing the distance effect). Hence, our findings suggest that this later comparative stage would be strongly modulated by attention. The idea that numerical processing passes through successive stages was already proposed in earlier research (Dehaene, 1996). During a comparison task with symbolic numbers (i.e., Arabic digits and number words), ERPs showed neural signatures associated with three consecutive steps: a first occipito-temporal activation related to numerical identification, then a right-lateralized parieto-occipital activation affected by the distance effect (but not by notation) and finally, a late activation in the motor cortex associated with response execution. To our humble knowledge, the study reported in *Chapter 4* was the first to investigate how attention and task instruction can influence FPVS responses in the numerical cognition field. Two other studies had previously examined the role of these two parameters in modulating the neural responses associated with speech processing (Ding et al., 2018; Niesen et al., 2020). It would be important for future research to continue investigating the relation between numerical processing and attentional mechanisms.

In conclusion, the studies reported in *Chapter 2-4* demonstrated that FPVS is a powerful technique to examine the automatic processing of numerical representations and magnitude integration. As discussed above, several methodological factors, such as stimulus parameters, stimulation frequency or the instruction given to participants, need to be carefully considered before running a FPVS experiment. Nevertheless, this paradigm offers a number of significant advantages over alternative neuroimaging techniques. Given that the discrimination responses can be obtained in a very short period of time (only a few minutes of stimulation), the FPVS technique would be ideally suited to conduct research on populations with a lower attention span, such as newborns and young infants. Furthermore, since the task is usually very simple (i.e., not involving high cognitive abilities), it could also be used with atypical participants, such as people suffering from developmental dyscalculia or intellectual impairment.

3.5 Can we use the distance effect as a marker of magnitude access?

Since the seminal work of Moyer and Landauer (1967), the numerical distance effect has been considered as one of the most reliable metrics to index magnitude processing (Maloney et al., 2010). According to the most popular view, it originates from overlapping distributions of the Gaussian curves representing quantities on a compressed internal scale (the mental number line; Dehaene, 2007). As a result, the closer two magnitudes are, the more similar their coding schemes are and the harder it is to distinguish them (Piazza et al., 2004). The fact that both non-symbolic and symbolic processing show behavioral and neural signatures associated with the distance effect has been a major argument in favor of a shared magnitude system. For instance, combining fMRI adaptation with a distance metric, Piazza and colleagues (2007) found common neural populations activated for non-symbolic dot arrays and Arabic digits within the parietal cortex. In their study, participants were repeatedly exposed to a certain quantity in order to create adaptation. They were then introduced with a deviant numerosity that could be either close or distant from the habituated quantity, and could be presented in the same or in different notation. The results showed a distance-dependent signal recovery (i.e., larger recovery for distant than close deviants), irrespective of the format change. Hence, it appears that neural populations that were adapted to one numerical format generalized their activation to the other numerical format, supporting their ability to encode both symbolic and non-symbolic magnitudes (Piazza et al., 2007). These findings fit nicely with the neural model of number representations proposed by Verguts and Fias (2004). Concretely, this model postulates that the same neurons initially involved in non-symbolic quantity processing learn to represent the magnitude of numerical symbols. By doing so, symbolic representations come to inherit certain properties of the originally available non-symbolic system, explaining the presence of a distance effect in both formats. However, the model also predicts that the tuning curves would be narrower for symbolic than for non-symbolic magnitudes, suggesting that numerical symbols could be represented with more, but not absolute, precision (Verguts & Fias, 2004). This last prediction was supported in the current thesis by the finding of smaller distance effect in the neural responses associated with symbolic numerical codes as compared to that found in our iconic (canonical) FPVS condition (*Chapter 3 – appendix*).

The behavioral results reported in *Chapter 3* also indicated the presence of a significant distance effect on participants' performance, when completing comparison tasks that involved canonical number representations (i.e., mix of canonical dot and finger patterns), symbolic numerals (i.e., mix of Arabic digits and number words), or both (mix of all numerical codes). Participants were indeed found to respond faster and more accurately in deciding which of two simultaneously presented numerosities was larger (or smaller) when they were separated by a greater distance (e.g., comparing "2-8" led to better performance than comparing "2-3", irrespective of the numerical code). In line with the prediction of Verguts and Fias (2004), the distance effect observed in symbolic comparisons was smaller than that observed in iconic comparisons (*Chapter 3 – appendix*). Crucially, we did not find any difference in performance when analyzing separately the inter-format comparisons (i.e., digit-dots, digit-fingers, words-dots, words-fingers) and the intra-format comparisons (i.e., digit-digit, digit-word, word-word, dots-dots, dots-fingers, fingers-fingers). Therefore, contrasting with previous behavioral results which showed that mixed-format comparisons required an additional processing time compared to pure non-symbolic and symbolic conditions (Lyons et al., 2012), such a cognitive cost was not highlighted in our data. While it is tempting to conclude that canonical quantities and symbolic numbers rely on a shared magnitude representation system, one could argue that these results stem from other, non-numerical, aspects related to the task. It was indeed suggested that a distance effect observed in comparison tasks may originate from response-related decisional processes rather than the internal representations of numerosities (Van Opstal et al., 2008). As explanation, if the task is to choose the larger of two numbers, it has two output nodes, i.e., *left larger* and *right larger,* that will be connected with the two input nodes, i.e., *larger number on the left* and *larger number on the right*. These connections from the stimuli (input) to the response (output) nodes monotonically increase: large numbers on the left input are strongly connected to the left output node and weakly connected to the right output node. In reverse, large numbers on the right input node have respectively strong and weak connections with the right and left output nodes. Consequently, the distance effect could result from the monotonic connection weights: when the numbers to be compared are close to each other (e.g., “8-9”), they activate almost as strongly the left larger and right larger response nodes; whereas when the numbers are distant from each other (e.g., “2-8”), the activation of the correct response node (in this example, larger right) increases, resulting in faster reaction times and greater accuracy (Van Opstal et al., 2008). Hence, the monotonic connection view calls into question the idea that the comparison distance effect is indicative of numerical representations.

To overcome this methodological issue, the last study reported in this thesis (*Chapter 5*) introduced a same-different matching paradigm to assess the integration of canonical quantities and symbolic magnitudes. In contrast to the numerical comparison task, only the value of the numerosities, but not their ordinal position, is relevant to decide whether two magnitudes are equal or not. Consequently, it was assumed that the distance effect observed in a same-different task would directly result from the internal representations (the tuning curves) of numerosities (Van Opstal & Verguts, 2011). In *Chapter 5*, participants were presented with canonical arrays of digits and asked to determine, as fast and as accurately as possible, whether the magnitudes conveyed by the digit and the canonical configuration were the same or not. As an example, if the digit "4" was represented four times, participants should respond "same" (i.e., matched trial); but if it was represented five times, they should respond "different" (i.e., mismatched trial). To assess the presence (or absence) of a numerical distance effect, mismatched trials were created so that the difference between the quantity and the digit value could be either small (e.g., digit "4" represented 5 times, distance = 1) or large (e.g., digit "4" represented 8 times, distance = 4). The results reported in *Chapter 5* demonstrated that participants were faster and more precise to decide that a configuration mismatched when the difference between the numerical magnitudes was large as compared to small. Hence, this cross-notation distance effect indicates that adults readily activated a common representation of canonical quantities and Arabic digits, supporting their ability to integrate both information in a shared magnitude system. This same-different paradigm offers several advantages, including the non-involvement of ordinal decisions (Van Opstal and Verguts, 2011). By presenting both numerical information as a single configuration, we have also avoided a potential cost of switching between different perceptual input streams (Lyons et al., 2012) and thus provided a straightforward measure of magnitude integration. It could also be interesting to combine the stimuli used in this study with a FPVS design. For instance, contrasting matched and mismatched configurations as base and deviant stimuli would allow us to examine whether the brain can spontaneously detect when there is a mismatch between the canonical quantity and the digit magnitude. Similar to *Chapter 3 & 4*, discrimination responses for close and distant mismatched could be compared to measure a neural distance effect and see if it relates to the distance effect obtained in the behavioral task.

4 Conclusions

The current thesis aimed to explore the interconnection between numerical codes using behavioral and neurophysiological approaches. While non-symbolic and symbolic numerosities have been widely investigated, canonical number representations have received considerably less attention. Yet some studies have suggested that canonical dot and finger configurations might play a pivotal role in human numerical development (Kreilinger et al., 2021, Orrantia et al., 2022; Van Rinsveld et al., 2020a). The findings reported in the present thesis support this assumption, revealing that canonical number representations enjoy a specific status distinct from that of non-symbolic and symbolic numerical codes. Across the studies, discrimination and integration mechanisms of non-symbolic, iconic (canonical) and symbolic numerosities were highlighted. Using both fast periodic visual stimulation EEG recordings and behavioral paradigms, we have shown that humans are capable to automatically discriminate canonical number representations from non-canonical patterns, and to integrate canonical quantities and symbolic numbers in a shared distance-related magnitude system. These findings suggest that canonical number configurations should be integrated into models of numerical development. Future research could help to determine when the integration process starts and how it relates to later mathematical achievements.

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