UNIVERSITE CATHOLIQUE DE LOUVAIN

Faculté de psychologie et des sciences de l’éducation
Unité de Neurosciences Cognitives

Interactions between fingers and numbers : Towards finger numeral representations

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Samuel DI LUCA

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There are two places in a thesis where you can actually be yourself: the conclusions, even if with some restriction of the case, in which one try to squeeze the maximum from his experiments, sometimes exaggerating, and the acknowledgements, in which, even if it is sometimes with a false humility, you understand that you couldn't have gone trough the thesis all by yourself.

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I would to give you all a strong and friendly handshake but exceptionally for this time, I'll use my hands to count!

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General introduction

Numerical information is extremely often used in daily-life activities. What time is it? How much does this object cost? How long does this take? Which size? How many times? How many days? How many thinks? How many questions! It is incredible “the quantity of numerical” information that humans (and animals) process in a day, and how fast it is carried by the conventional symbolic system of numbers.

Up to now, many models have tried to account for human abilities in the number domain. They can be grouped into two categories: those focusing on the link between numbers and space, and those focusing on the link between numbers and language. On the one hand, evidence supporting the link between symbolic numbers and space comes from shifts in spatial attention after the presentation of numerals (Casarotti, Michielin, Zorzi & Umiltà, 2007; Fischer, 2003), and from spatial biases in line bisection tasks (Calabria & Rossetti, 2005; Fischer, 2001; Fischer, Castel, Dodd, & Pratt, 2003). Moreover, a spatial compatibility effect has been observed between numbers and the side of response: small numbers are best associated with a left response, and the reverse for the large numbers (the so-called Spatial-Numerical Association of Response Codes; Dehaene, 1992; Dehaene, Bossini & Giraux, 1993). This spatial-numerical compatibility effect could be accounted for by the metaphor of an inner spatial number line on which numbers are represented, from small to large, from left to right (Dehaene, 1992; but see also Hubbard, Piazza, Pinel, & Dehaene, 2005, for a general review on the relationship between numbers and space). Even if the number line has been the object of many experiments in the last decade, and although various models of numerical representation have been proposed (for a review see Verguts, Fias, & Stevens, 2005), it has recently been shown that it is possible to account for the classically observed effects without the need of a numerical representation formalized on a spatial continuum (Verguts & Fias, 2004). On the other hand, research on the link between numbers and language mainly dealt with the acquisition of the number sequence and transcoding processes. The data, coming mainly from group and single case studies with brain-damaged patients, showed a strict isomorphism of lexical errors (concerning the individual elements constituting a given numeral: e.g., "hundred and twenty six" transcoded by "124"), and syntactical errors (the assembling of the components of a numeral; e.g., "hundred and thirty" transcoded in "10030") during the transcoding between verbal and numeral notations (Deloche & Seron, 1987; McCloskey, Sokol, & Goodman, 1986; but see also Lochy, 2001 for a general review). Aiming at unifying the spatial and linguistic components concerning the processing of numerals, Dehaene (1992, 2003) proposed an anatomical and functional model involving the intraparietal sulcus, especially its horizontal segment (HIPS) thought to provide the semantic representation of numbers (i.e., the analog number line), the posterior part of the superior parietal lobule (PSPL) associated with the manipulation of the visuo-spatial representation of numbers (Arabic Digits), and finally the angular gyrus (AG) for verbal number processing. However, even if the model is one of the most credited numerical models, able to account for many behavioural and functional data, it lacks to account for some pieces of functional evidence in which premotor areas are found activated during numerical tasks (Dehaene, Tzourio, Frak, Raynaud, Mehler, & Mazoyer, 1996; de Jong, Van Zomeren, Willemsen, & Paans, 1996; Rueckert, Lange, Partiot, Appollonio, Litvan, Le Bihan, & Grafman, 1996; Ghatan, Hsieh, Petersson, Stone-Elander, & Ingvar, 1998; Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Pinel, Le Clec'H, van de Moortele, Naccache, Le Bihan, & Dehaene, 1999; Pesenti, Thioux, Seron, & De Volder, 2000). Walsh (2003) hypothesized that the semantic representation of number magnitude information in the parietal cortex derives from visuo-motor functions involved in the quantitative processing of sensory information. This proposal has recently been supported by two experiments using a stroop paradigm in which judgements of the duration of dot sequences were influenced by the irrelevant numeral information conveyed by linear arrays of dots (Dormal, Seron & Pesenti, 2006), that in turn was found influenced by the processing of the spatial length (Dormal & Pesenti, 2007).

In the last few years, however, research efforts have been oriented towards another direction. Butterworth (1999a) proposed that at the origin of the parietal locus for the representation of numbers there was the human ability to count on fingers. Recent studies show that finger motor skills, more than language abilities, are best predictors of mathematical scores in children between 5 and 8 years (Fayol, Barrouillet & Marinthe, 1998, 2001). Could finger counting be the link between abstract, verbal, visual and motor representation of numbers? Several pieces of evidence support this hypothesis. Historical and cultural reports show that human beings counted on their fingers since the pre-historical epoch, and that aboriginal tribesmen still use their fingers and body parts as a language to express numerosities (Ifrah, 1981; Butterworth, 1999a). Moreover, children from many cultures start to familiarise themselves with numerosities through their fingers (Fuson, 1988). Adult humans show mathematical impairments after lesions in brain areas underlying finger and hands movements (Gerstmann, 1924, 1940). Finally, evidence of the link between finger movements and number processing can be found in a series of functional imaging experiments showing a coactivation of premotor and parietal areas during numerical tasks, a network thought to be responsible of the visual, motor and somatosensory information of fingers (Simon, 1999; Pesenti et al., 2000; Tommasini, Jbabdi, Klein, Behrens, Pozzilli, Matthews, Rushworth, & Johansen-Berg, 2007), and in comparative invasive electrophysiology techniques in monkeys (Schall, Morel, King, & Bullier, 1995; Rizzolatti & Luppino, 2001). There could thus be a functional link between fingers and numbers that has, so far, largely been overlooked by current research efforts in the domain of numerical cognition.

Scope and structure of this thesis

The aim of this thesis is to test the existence of a finger numeral representation, to establish how it could possibly interact with the processing of numbers, and to investigate its possible numerical semantic characteristics.

Chapter 1 will review the various streams of research supporting the idea of a link between finger and numbers that have been briefly sketched above: historical, cultural, developmental, neuropsychological, behavioural and functional data will be presented and discussed. The rest of this text will then present our empirical contribution to this issue.

We will first show that specific finger configurations corresponding to personal finger-counting habits can account for data that the metaphor of a simple but more credited left-to-right number line cannot easily integrate. Chapter 2 - *Finger digit-compatibility in Arabic numeral processin*g will present two experiments showing that personal finger-counting strategies interact with the identification of Arabic digits. In Arabic digit-to-finger mapping tasks, when participants identify Arabic digits by pressing appropriate keys with one of their ten fingers, they are faster and make fewer errors when the mapping is congruent with their own finger-counting habits than with other mappings.

Secondly, we will show that participants refer to finger numeral representations even when no motor responses are needed. We will show that canonical finger numeral configurations are processed faster than non canonical ones and that this higher processing speed stems from a direct access to number semantics. *Chapter 3 - Masked priming effect with canonical finger numeral configurations* will present two experiments in which first of all we empirically assess the canonical and non-canonical finger numeral configurations that will next be used to subliminally prime the participants during comparison to a standard task with Arabic numerals. Chapter 3 will end with a complementary analysis to exclude the possibility of visual, more than semantic, differences at the origin of the unequal processing between canonical and non-canonical finger numeral configurations. However, to completely exclude that some visuo-perceptual differences between canonical and non-canonical finger numeral configurations underlie their processing difference, we will test their low-level visual searching proprieties during a detection of an odd stimuli surrounded by distractors belonging to the same category. Chapter 4 - *Finger numeral representation and Pop-out effect* will show that during a visual searching task, the detection of an odd canonical finger configuration in a collection of non-canonical ones showing all the same numerosity, does not lead to a pop-out effect, and thus excludes that a peculiar visual salience difference between the two configurations underlies the differences observed in Chapter 3.

Next, we will investigate the qualitative difference between the canonical and non-canonical finger numeral representations by examining the patterns of priming activations generated by the two types of configuration. Chapter 5 - *Place coding for canonical finger numeral representations* will show that when the participants are primed with canonical finger numeral configurations, they activate a “place coding” numeral representation as for symbolic notations (i.e., Arabic digits), whereas when the participants are primed with non-canonical finger numeral configurations they activate a “summation coding” numeral representation, as non-symbolic notation (i.e., array of dots).

The final chapter will summarize the findings of this doctoral work. We will discuss them their implication to hot issues of the field and in light of recent findings, and we will offer some perspectives for the future research.

Chapter 1 – Numbers and fingers: A long/large-standing relationship

1.1. History in our hands

There was a time when human beings were unable to count, and the concept of number was nothing more than a visual and concrete feature of the objects that constituted the reality (Ifrah, 1981). For our ancestors, it was probably difficult, if not impossible, to conceptualise the numbers as specific entities, and sets as "night and day", "the ears" or "the eyes" did not share the common characteristic of “twoness”. “One” for example was perceived as “an entity” rather than the “quantity one”; “two” was looked as a distinction between “one” and “another one”, without order whom comes first; “three" and sometimes "four” were looked as a result of “two plus one” or “two times two” or “two and another time two”, rather than forming specific groups of numerosities. It is still possible to found concepts as “a lot”, referring to larger quantities, but without any further distinctions (Pica, Lemer, Izard, & Dehaene, 2004; Ifrah, 1981). However, even if there were no words to determine, to quantify, or to conceptualize such quantities, human beings used various strategies trying to handle them. Bones, sticks of wooden, pieces of strings, stones, and so on have been used to represent groups of entities and, eventually, to count (see Fig. 1-1). Body parts, including toes, knees, arms, elbows, shoulders, but also lips, ears, nose and eyes have mainly been and are still employed by some tribespeople (e.g., Islanders from Torres, Papuans, Elemis, Yupno and many others in New Guinea) to count, to handle, and to communicate numerosities (Ifrah, 1981; Butterworth, 1999a; see Fig. 1-2).

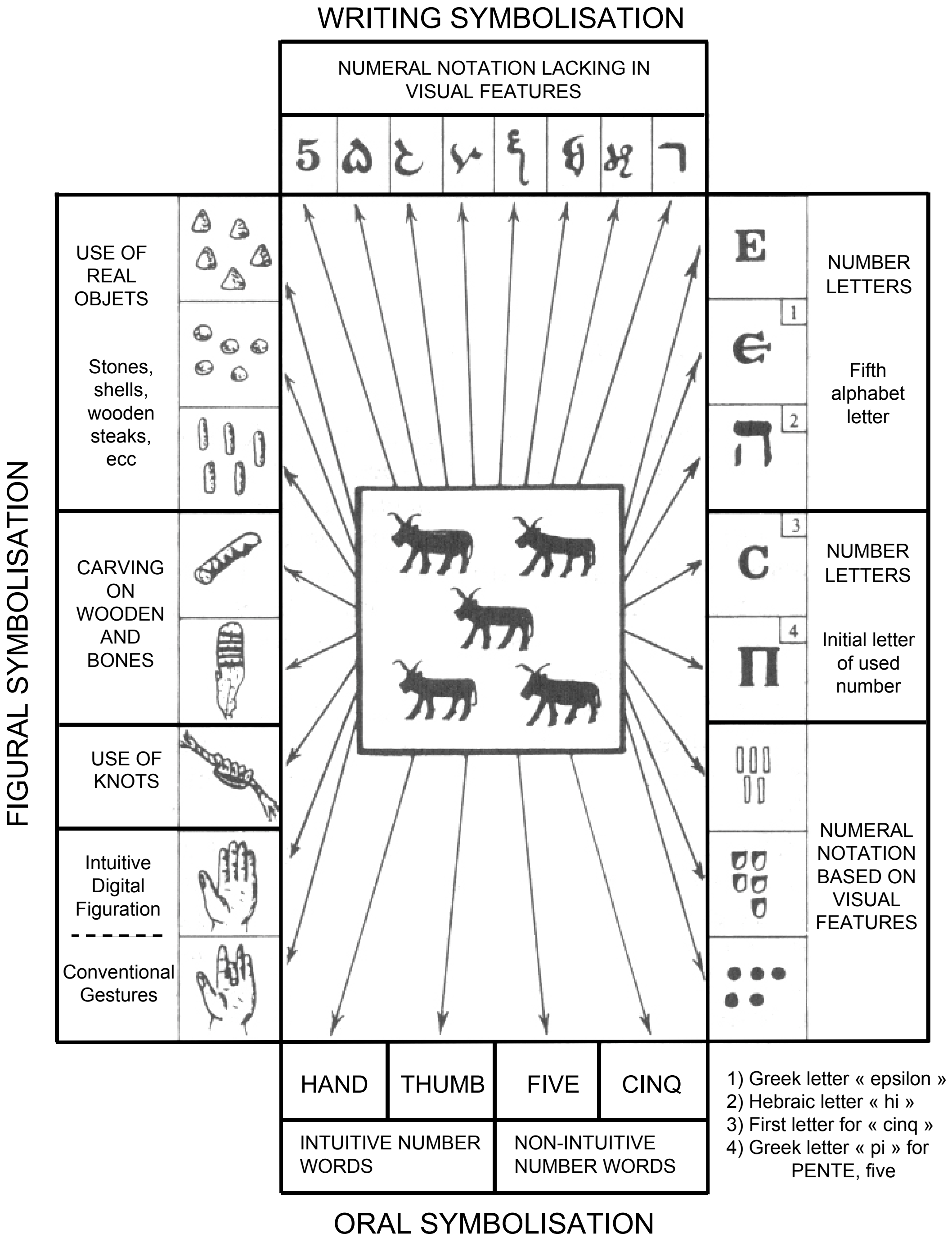


Figure 1-2. Writing, oral and figural symbolisation used by human beings referring to the numerosity information (adapted from Ifrah, 1981).

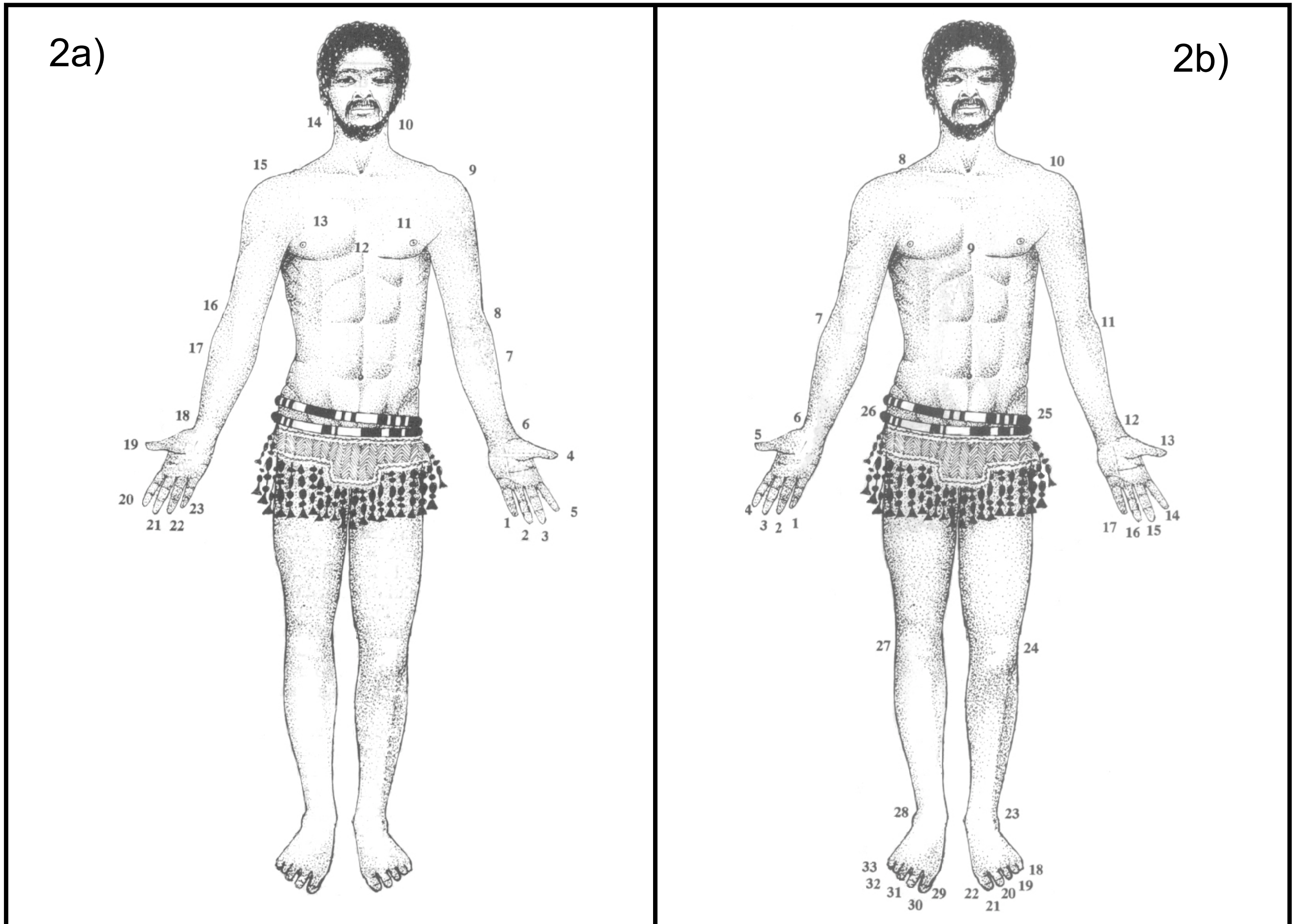


Fig. 1-2) Shows body counting strategies used by the Elemis in New Guinea (2a), and by Islanders from Torres (2b), which extend the body counting to the feet and to the legs (adapted from Ifrah, 1981).

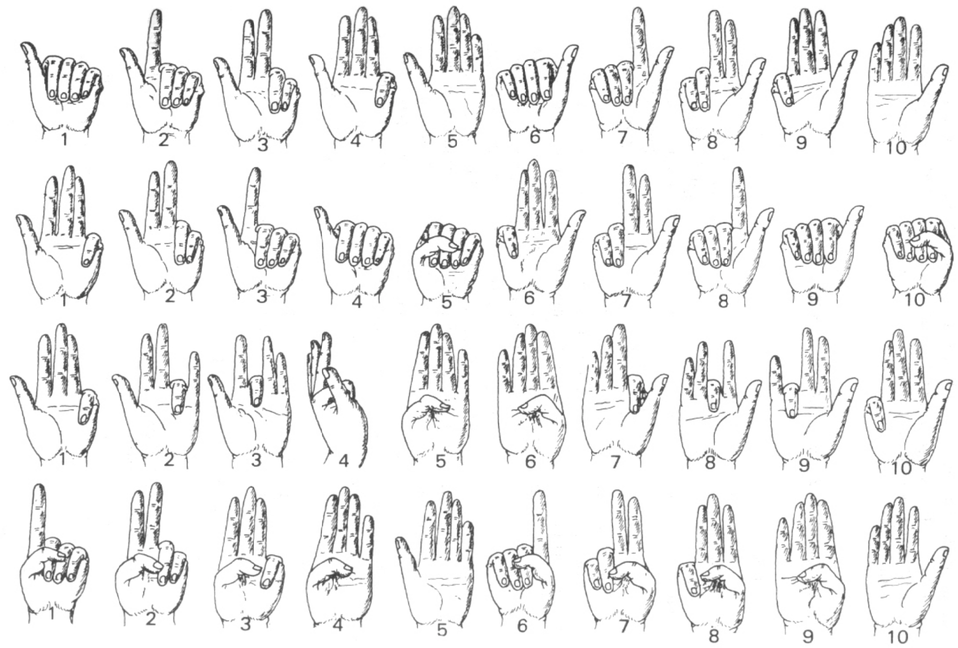
Among these different kinds of body counting and different ways to represent numerosities, there is a common and fruitful body instrument used by most cultures and at every epoch: the fingers. Fingers have been used to conceptualise, to enumerate, to communicate, to represent and to keep in mind numerosities, long before understanding that the "numerosity" could be a separated feature of the entities (Ifrah, 1981). The first proofs of finger-counting strategies can be found for Sumerians and Babylonians in early Mesopotamian regions, as well as in ancient Mayan and Aztec populations in pre-Columbian South America. Finger-counting was extremely basic, starting with the thumb or the little finger and raising or lowering a finger every time a unit was added. Later, it gained more sophistication and, in daily-life activities, specific finger configurations were used to express numerosities larger than ten. Such finger configurations were found in Asia, Arabia and North Africa, regions with strong commercial activities, in which tradesmen used to touch the fingers of customers in specific sequences to communicate the quantities sold and the prices to pay. An alternative method was developed by the Egyptians, and then adopted by the Romans, in which fingers could take specific configurations to communicate numerosities up to ten thousand using not only the whole finger but also its parts, such as the phalanges, top of fingers and knuckles. At that time, finger-counting was considered as one of the most important pedagogic tools for teaching and learning arithmetic (see Fig. 1-3). The most developed finger-counting method is perhaps the one used in China, and described in the book *Suan Fa Tong Zong* (Dawei, 1593), which, with the use of phalanges and finger joints, could be used to count up to ten billion (see Fig. 1-4).

Fingers are also at the origin of the modern number words in many cultures and languages as oral counting was originally referring to body parts (e.g., finger, hands, etc.), and only secondarily to the numerosity to which it referred (Ifrah, 1981). In English, for example, the word *five* comes from a root common to *finger* and *fist*, and the word *digit* means at the same time *number* and *finger*. In some Slavic languages, the word *pet* (five) originates from the word *pest* (hand). Other examples can be found in other non Indo-European languages. It is the case for the Ali language, in middle Africa, in which the number words *five* and *ten*, are respectively pronounced as *moro* (meaning hand), and *mbouna* (from a contraction of *moro* (five) and *bouna* = two), literally *two hands* (Ifrah, 1981).

Fingers most probably also underlie base 10 in our mathematical positional number system. There is no mathematical or arithmetical reason for that, because a base 12 for example would be far preferable, as it is divisible by 2, 3, 4 and 6, whereas a base 10 is divisible only by 2 and 5. The hour system moreover refers more directly to a base 12 than a base 10 and, finally, base 12 seems even to have inspired number words in some European languages (e.g., specific number words up to "twelve" in English, "thirteen" been composed of words referring to "3" and "10" respectively).

Finally, with the invention of specific dedicated symbolic numerals, the use of finger gestures underwent an inevitable decline, yet without completely disappearing. Indeed, even among technologically advanced populations, one can find villages in which habitants still use their fingers to make multiplications between 5 and 10, or 15 and 20 (Ifrah, 1981-2000; Brissiaud, 2003: see Fig. 1-5) and, of course, most of human adults use their fingers in various daily-life activities, probably because it represent a reminiscent practice tool to which they have dealt with mathematical, arithmetical and numerical issues in childhood.

(a)



(b)

Figure 1-3) Shows the Elementary finger linear counting (a) and the Figural finger counting (b) methods (adopted from Ifrah, 1981).

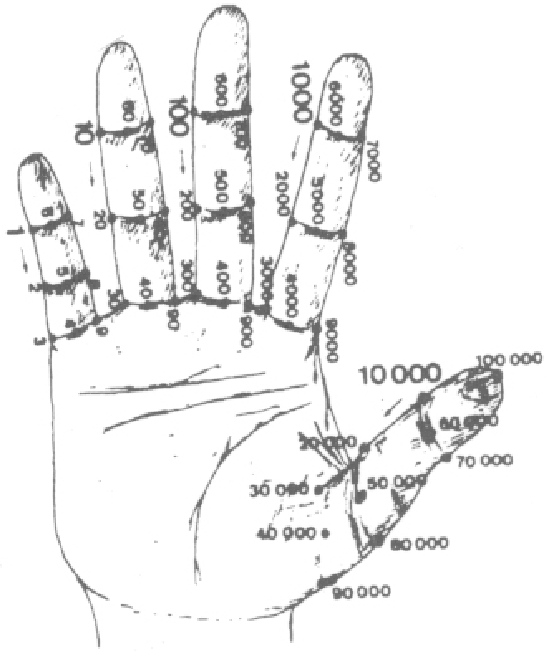


Figure 1-4. Method of finger counting described in the book *Suan Fa Tong Zong (1583),* allowing on to count until one hundred million on one hand only, and until ten billion by using both the hands (from Ifrah, 1981).

Finger multiplication of Arabic digits between 5 and 10 Fig. 5)

Example: 7 x 8

Close: (7 – 5) fingers in one hand and
(8 – 5) fingers in the other

Result: 5 fingers closed in all,
3 fingers closed in one hand and
2 fingers closed in the other

So: 7 x 8 = 5 x 10 + 3 x 2 = 56

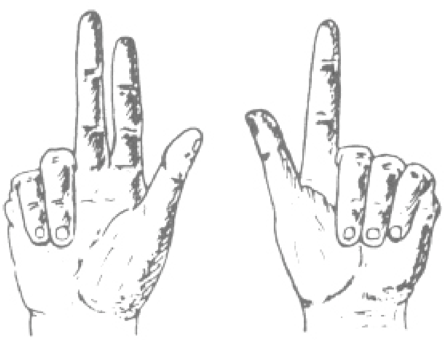


Figure 1-5. Method used by some village people in the south of France to perform simple multiplications (from Ifrah, 1981).

1.2. From personal to general numerosities

1.2.1 Cultural evidence

Many children spontaneously use their fingers when faced to numerosities and basic mathematical issues, and various are the ways they do that: as a pointer to assess the one-to-one correspondence during enumeration tasks, to keep track of the verbal sequence during counting, to show numerosities to other people (an activity that we will name "montring"; see Chapter 3), like a pincer during precision and power grasping, or as an indicator for continuous magnitudes. Practice increases performances in all human beings activities. Counting motionless objects is not as a simple task, and it requires the counter to establish a strict correspondence between words, having time but not spatial location, and objects, located in space but no differentiable in time. The correspondence by using an indicating act, the pointing, relating a spatial located object and a serial sequence of number words is named one-to-one correspondence (Fuson, 1988; Gelman & Gallistel, 1978). The number word –object correspondence derives from two correspondences made by the indicating act: the word-pointing correspondence made in time, and the pointing-object correspondence made in space. Spatial and temporal levels yield different kinds of errors. Observations with children aged between 3 and 6 years old showed three types of errors: object skipped, in which an object receives neither a word nor a pointing, multiple counts in which an object receives repetitive number words and pointing, and pointing-no-word, in which an object receives a pointing but no word (Fuson, 1988). Interestingly, one-to-one correspondence enumeration seems to be an exception to the fact that preschool children encounter problems in coordination with two concurrent streams of activities because two continuous sequence of actions (pointing and saying a word) are performed better than a spatial distributed action sequence (pointing once and only once at each object) alone (Fuson, 1979b; Luria, 1959, 1961). This seems to confirm that the verbal enumeration activity is based onto, or at least is greatly helped by pointing, thanks to which the children apply a motor control to the objects to be enumerated. Differently, during counting, children use their fingers as visual and motor support to the verbal sequence. Fuson and colleagues (1982) describe that children apply an appropriate counting procedure by passing through five steps of counting development. At the first one, the string level, the number words are pronounced as a single expression and the children perceive the sequence as a unit. At the unbreakable chain level, children understand that the sequence is constituted by units, but they are unable to start counting from an arbitrary point, a skill that is developed at the breakable chain level. At the numerable chain level, children understand the mathematical meaning of the number words and they get used to count and to keep track segments of connected words (i.e. to solve 4 + 2, they start to count until 4 and after keep track with fingers the following two number words: "four … five and six"). Finally, at the bidirectional chain level, children are able to count in both upward and downward directions. This gradual understanding of the verbal sequence and counting rules, whatever the respective of inborn contribution abilities, leads the children to detect the regularities that are at the basis of mathematical competences, and to naturally interiorize cardinality and ordinality features of numbers. Moreover, with the practice of a stable order in finger counting, children familiarize with those finger configurations that are frequently used and that, as other iconic system, will give a direct access to their semantics (Wiese, 2003a, 2003b). This has been recently supported by a study in which, by presenting 7-year-old children with photos of typical and atypical finger-counting configurations from 2 to 9, children enumerated faster the configurations conformed to their personal finger counting habits, confirming the holistic representation of numbers expressed by familiar hand configurations (Noël, 2005).

1.2.2 Behavioural and empirical data

Recently, a study conducted with 5- and 6-year-old children showed that finger abilities, evaluated by various neuropsychological tests including single finger recognition, finger discrimination, simultagnosia and graphestesia, were the best predictors of mathematical skills one (Fayol, Barrouillet & Marinthe, 1998) and even three (Fayol, Barrouillet & Marinthe, 2001) years later. This predictive power of finger gnosia tests appeared to be specific to mathematical performance (and equally for numerical tasks that do or do not rely heavily on finger representation or on magnitude representation) as these tests were not found to be predictive of reading skills (Noël, 2005). On the same wave of research, it has recently been shown that training finger gnosis abilities improved consequently mathematical skills (Gracia-Bafalluy & Noël, 2008). In that study, 33 children with low scores in finger gnosis tests were randomly divided in two groups: the "action group" received training in finger differentiation, while the "control group" received training in reading comprehension; a third group of children with high scores was used as a measure of the numeral development of the first two groups. After 8-weeks of training, two times per week, the action group showed improved scores in various mathematical skills (e.g., subitizing, counting raised fingers and ordinality judgement), resulting in a mathematical significant performance differentiation with the control group, and in the disappearance of the mathematical performance differences with the high level scores group.

However, the use of fingers does not stop after the acquisition of more performing symbolic numeral notations and, in various circumstances, finger numeral representations can be used by adults doing specific numerical tasks (as will be shown in Chapter 2). Also, a recent work conducted in young adults has shown that finger-counting habits can be at the basis of compatibility effects between numbers and space. Thanks to a questionnaire study determining which is the hand with which participants start to count, it has been found that a group of 53 “left-starters” but not a group of 47 “right-starter” exhibited the SNARC effect in a parity judgement task (Fischer, 2008).

1.3. Neuropsychological evidence

The link between fingers and numbers has been acknowledged since the dawn of the days, but it is only with the modern neuropsychological approach that research scientists have tried to understand their functional interactions. The pioneer of those streams of research has been the neurologist J. Gerstmann who unified in the 1924 in a syndrome still bearing his name four specific symptoms jointly presented by some patients: left-right disorientation, dysgraphia, finger agnosia and acalculia. In the left–right disorientation, the patients failed to indicate either their own and the examiner’s left-right body parts (Varney, 1984; Levine, Mani, Calvanio, 1988; Mazzoni, Mazzoni, Pardossi, Cantini, Giorgetti, & Arena, 1990; Mayer, Martory, Pegna, Landis, Delavelle, & Annoni, 1999) or left-right objects along the horizontal axis (Gold, Adair, Jacobs, & Heilman, 1995), whereas the vertical axis (i.e., up-down) was preserved (Stengel, 1944; Tucha, Steup, Smely, & Lange, 1997). The dysgraphia resulted from a loss of, or a failure to access to, motor graphic patterns in memory yielding misaligned and scrawled letters (Jung, Yeo, Sibbitt, Ford, Hart, Brooks, 2001; Zesiger, Martory, & Mayer, 1997), or from a deficit at the allographic level where letter identity is accessed for motor production and yielding omissions, perseverations or substitutions in writing (Roeltgen, Sevush, & Heilman, 1983; Strub & Geschwind, 1974; Tucha et al., 1997), mainly with similar letters (Levine et al., 1988; Rapp & Caramazza, 1997). Patients suffering from finger agnosia are unable to recognise their own (Jung et al., 2001, Levine et al., 1988; Moore, Saver, Johnson, & Romero, 1991) or the examiner’s fingers (Mayer et al., 1999; Carota, Di Pietro, Ptak, Poglia, & Schnider, 2004) without visual control (Strub &

Geschwind, 1974; Mazzoni et al., 1990). Patients with Gerstmann's syndrome also failed in all the tasks assessing finger integration information (i.e., to indicate the number of fingers between two fingers touched by the examiner; Tucha et al., 1997). Finally, the acalculia, that is generally described as an impairment in performing simple numerical tasks, is here observed with a large pattern of patient profiles. One can find problems in writing, comprehension and production of Arabic digits (Kinsbourne & Warrington, 1962; Tucha et al., 1997; Varney, 1984; Martory, Mayer, Pegna, Annoni, Landis, & Khateb, 2003; but also Granà, Hofer, & Semenza, 2006, a case of "spatial acalculia"), preserved (Dehaene & Cohen, 1997; Cohen, Dehaene, Chochon, Lehericy, & Naccache, 2000) or impaired (Strub & Geschwind, 1974; Toeltgen et al., 1983; Vernay, 1984; Levine et al., 1988) facts retrieval, and preserved but unable to apply arithmetical facts (Delazer & Benke, 1997). In line with the above mentioned hypothesis asserting that the use of finger-counting strategies in childhood may lead to a common representation of numbers and fingers in the adult brain, Gerstmann (1957) argued that the focal point of the syndrome was the loss of a "sense of fingers", because fingers were somehow involved in all the other disrupted skills, and he pointed to the left parietal lobe, specifically the angular gyrus, as the critical site for lesions that produce this syndrome. A few years later, the incidence of finger agnosia and aphasia on the other symptoms of the Gerstmann's syndrome was studied (Kinsbourne & Warrington, 1962). Data showed that whereas aphasia was not linked to fingers agnosia or to the others symptoms, when Gerstmann's symptoms were present finger agnosia was present too. Although the existence of the syndrome has regularly been questioned (see, for example, Poeck & Orgass, 1966), and despite the fact that it has occasionally been described after various cortical and subcortical lesions (Santos, Cope & Keller, 1991; Jung et al., 2001), it is mostly found after left angular lesions. Brain-damaged patients studies have not been able to disentangle alternative interpretations of the syndrome, and a visual origin is still supported by some researchers (Mayer et al., 1999; and see also Gold et al., 1995; Martory et al., 2003; Carota et al., 2004) although a series of experiments using focal cortical stimulation have shown that stimulation of the left angular gyrus disrupts performance on finger recognition, writing, and calculation tasks (Roux, Boetto, Sacko, Chollet & Trémoulet, 2003). Even very focal angular lesions may lead to the co-occurrence of finger agnosia and numerical disorders (Mayer, et al., 1999) without additional language or intellectual deficits. Similarly, repetitive transcranial magnetic stimulation (TMS) applied over the angular and supramarginal gyrus disrupts both calculation and finger selection (i.e., speeded key press with the same or opposite finger after tactile stimulation) tasks (Rusconi, Walsh & Butterworth, 2005). Importantly, the angular gyrus is also responsible for the initiation of bimanual finger movements (De Jong, Willemsen & Paans, 1999).

1.4. Functional evidence

Several pieces of evidence supporting a functional link between fingers and numbers come from human brain-imaging studies (Simon, 1999; Pesenti et al., 2000; Tommasini et al., 2007) and from comparative invasive electrophysiology techniques in monkeys (Schall et al., 1995; Rizzolatti & Luppino, 2001). It is well known that various visuo-motor functions such as orientation of attention in space and time (Coull & Nobre, 1998), object manipulations (Binkofski, Buccino, Posse, Seitz, Rizzolatti, & Freund, 1999; Grefkes, Weiss, Zilles, & Fink, 2002), reaching (Cohen & Andersen, 2002), grasping (Culham, Danckert, DeSouza, Gati, Menon, & Goodale, 2003; Raos, Umiltà, Gallese, & Fogassi, 2004) and visual pointing (Connolly, Andersen & Goodale, 2003; Frey, Vinton, Norlund, & Grafton, 2005) rely on parieto-premotor networks. The same networks are co-activated during various numerical tasks such as addition, substractions, multiplications, and comparisons (Dehaene et al., 1996; de Jong et al., 1996; Rueckert et al., 1996; Ghatan et al., 1998; Dehaene et al., 1999; Pinel et al., 1999; Pesenti et al., 2000). Importantly, the intraparietal sulcus (IPS), mainly in the left but also in the right hemisphere, has been found activated during all the above mentioned tasks, and it is thought to reflect number semantic processing. This area being part of the above-mentioned fronto-parietal network, the contribution of visual and motor components, specifically for fingers and fingers movements, in the concept of numbers has been suggested (Pesenti, Zago, Crivello, Mellet, Samson, Duroux, Seron, Mazoyer, & Tzourio-Mazoyer, 2001).

The functional contributions of the use of fingers for the development of the concept of numbers can be detailed through three different finger strategies used during numerical tasks: a) pointing, i.e., detecting stimuli to be explicitly or implicitly counted; b) grip index-thumb aperture, during the tasks with analogue magnitude representations; and c) finger counting, supporting explicit or implicit verbal numeral sequence and small arithmetical operations.

1.4.1. Pointing

Dorsal premotor (PMd) F2 area is involved in programming and controlling proximal movements based on somatosensory information while rostro-ventral F2 neurons use both somatosensory and visual information (Shen & Alexander, 1997). Additional evidence shows that, when multiple visual targets are presented, directionally tuned neurons discharge if one of the targets is near their preferred direction, leading to a representation of multiple reach options at the population level (Cisek & Kalaska, 2005). Moreover, F2 neurons are also involved in reaching decisions on the basis of arbitrary simulus-response associations. Increased PMd activity has been found during addition (Menon et al. 2000), subtraction (Chochon, Cohen, van de Moortele, & Dehaene, 1999; Burbaud, Camus, Guehl, Bioulac, Caille, & Allard, 2000), and comparison tasks (Chochon et al., 1999; Fias, Lammertyn, Reynvoet, Dupont, & Orban, 2003). Even if no correlation was found with the distance between numbers to compare, notation and response side determined the pattern of activation found in the PMd during comparison tasks (Pinel et al. 1999). F2 areas hold specific connections with medial intraparietal (MIP) areas in the horizontal IPS region. MIP is part of the parietal reach region; it is involved in preparation, execution and monitoring of reaching movements (Colby & Duhamel, 1991; Cohen & Andersen, 2002), and it is found activated during visual guidance of a cursor to a target using a joystick, but not during the watching of a play-back version of the trial (Eskandar & Assad, 1999, 2002). This finding indicates that MIP integrates visual and somatosensory informations and that it is critical to coordinate hand movements towards visual targets (Battaglia-Mayer, Caminiti, Lacquaniti, & Zago, 2003). This findings support the hypothesis that, during number processing tasks, the MIP-F2 circuit contribute to maintain specific associations between numbers and motor responses (Göbel, Johansen-Berg, Behrens, & Rushworth, 2004). PMd has been found activated during the comparison of numerical and non-numerical magnitudes, such as spatial length and angle amplitude (Fias et al., 2003). The MIP-F2 circuit is supposed to play a dominant role in coding arbitrary stimulus-response associations, as corroborated by a study in wich TMS applied over the PMd yielded an impearement in the choice of answer (Harrington, Rao, Halland, Bobholz, Mayer, Binderx, & Cox, 2000). Also a recent study using TMS applied over the primary motor (M1) cortex to monitories corticospinal (CS) excitability during counting of visual presented stimuli shows an increased CS excitability. This was true for dot enumeration irrespective of the use of numbers or letters to enumerate. It proves first of all that visual scanning necessary to enumeration is followed by finger motor-related movements as pointing and one-to-one correspondence, and secondly, that the visuo-motor contribution to enumeration may be extended to any ordered series (Andres, Seron, & Olivier, 2007: see Fig. 1-6).

1.4.2. Grip Aperture

The anterior intraparietal region (AIP) properties have mainly been investigated in monkeys trained to reach and grasp objects of different sizes and shapes, showing that neurons mostly discharged during the grasping of specific objects. Contrary to posterior areas in the IPS, of which MIP is part, the AIP activity is not influenced by the spatial location of objects, which suggests that it is concerned in hand and finger movements but not in proximal arms movements (Sakata, Taira, Murata & Mine, 1995; Hoshi & Tanji, 2006). AIP neurons can be divided in visual or 'object type' neurons, activated during specific object manipulations in light conditions, and motor or 'non-object type' neurons, discharging above all during object manipulation in the dark, and visuo-motor neurons show an intermediate response with less activation in the dark than in the light (Murata, Gallese, Luppino, Kaseda, & Sakata, 2000). AIP are connected with F5 areas in premotor ventral regions (PMv) to which they form the AIP-F5 circuit (Murata, Fadiga, Fogassi, Gallese, Raos, & Rizzolatti, 1997). F5 area has comparable categories to those recorded in AIP but it has recently been shown that its activity is determined by the handgrip used to grasp the object more than the object shape (Raos et al., 2004). Finally the AIP-F5 circuits are conceived as responsible of the object manipulations depending on the visual and physic characteristics of the objects (Jeannerod, Arbib, Rizzolatti & Sakata, 1995). Theses functional pieces of evidence are supported by two recent studies. In the first one, participants have been tested in a parity judgement task on Arabic digits visually presented, while the elctromyographic (EMG) activity of the intrinsic hand muscles was recorded. Participants had to open or close (depending of the randomisation) their hand grip indicating if Arabic digits were odd or even. Results showed that large digits boost opening grip aperture, whereas the reverse was true for small digits (Andres, Davare, Pesenti, Olivier & Seron, 2004). In the second experiment, participants were presented with rods differing in length and primed by Arabic digits. The participants had to decide if they virtually could or not grasp the rods, depending on their maximum hand grip aperture. Results showed that small digits yielded an overestimation of the participants' grasping capabilities, the reverse for the large digits. Two control experiments showed that the effect didn't originate from a simple perceptual effect, or from order properties of the digits (Badets, Andres, Di Luca & Pesenti, 2007). Both studies corroborate the hypothesis of a common magnitude processing information between numbers and grasping movements (see Fig. 1-6).

1.4.3. Finger counting

Links between supramarginal (GSM) and angular Gyri (AG), and premotor areas have only recently been found in the human brain. The difficulty is that these regions are not present in monkeys, and the GSM and AG, as well as fine differentiations in the HIPS, are a peculiarity of the human brain. However, a recently developed imaging technique using Diffusion-Weight magnetic resonance imaging (MRI) and tractography now makes it possible to quantify long-range connectivity *in vivo* (Catani, Howrd, Pajevic, & Jones, 2002; Mori & Zhang, 2006; Aron, Behrens, Smith, Frank, & Poldrack, 2007). In a recent work, using multiple-fibre diffusion tractography (Behrens, Johansen-Berg, Jbaldi, Rushworth, & Woolrich, 2007), connections between the IPS and ventral and dorsal PM areas have been found (Jeannerod et al., 1995; Murata et al., 1997; Raos et al., 2005; Tommasini et al., 2007), as well as between left and right AG and PMv areas (Tommasini et al., 2007). The AG is known to be responsible for the initiation of bimanual finger movements (De Jong et al., 1999) as well as higher-order aspects of motor control that allows one to consciously access different aspects of one's own actions (Farrer, Frey, Van Horn, Tunik, Turk, Inati, & Grafton, 2007). However, the entire supramarginal regions, and above all AG, SMG, both linked to PMv areas (correspondent of F5 monkey areas), are found activated during fine control of hands and finger movements, and the SMA is particularly related to hand gestures (Hermsdörfera et al., 2002) in coactivation with left parietal inferior regions (B40) for gestures imitations (Mühlaua et al., 2005). It has been hypothesized that mirror neurons offer a neural basis for preverbal communication, by relating the behaviour observed in others to internal representations of motor acts (Rizzolatti & Arbib, 1998; Rizzolatti & Craighero, 2004). If true, this hypothesis could explain how language comes to develop in the inferior frontal gyrus, which is the human homologue of area F5, where mirror neurons for gestures are found. Likewise, a neuronal system matching finger movements execution and observation could also provide a neural substrate for digital representations of numbers. Because children learn to count on their fingers by observing others and replicating the counting trials on their own (Fuson, 1988), the recurrent association between the visual-motor configuration of fingers and the related movements may prompt the creation of internal representations for number-related actions (Pesenti et al., 2001). In support of this view, mirror neurons in F5 mainly receive afferences from the rostral part of the IPL (Luppino, Murata, Govoni, & Matelli, 1999) but also from the AG and SMG, thought to be the responsible areas for starting and controlling finger movements, as well as activated during the manual language for dumb and deaf patients (Neville et al., 1998: see Fig. 1-6).

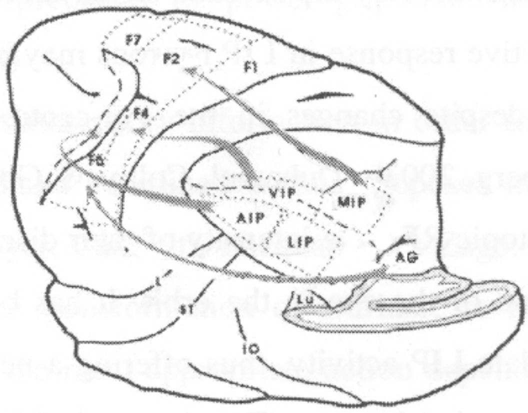


Figure 1-6. Parietal projections from areas located in the lateral bank and in the fundus of the intraparietal sulcus. In order to show these areas, the intraparietal sulcus has been opened and the occipital lobe removed. From Rizzolatti et al., 1998.

1.5. Contribution of the thesis

In this chapter, we have presented many pieces of evidence of the semantic relationship between fingers and numbers. We have reported proofs that the use of fingers to express numerosities is an historical and possibly even pre-historical aptitude of human beings. A system for finger-number representation may thus have been gradually developed, from merely using fingers (and body parts) as referring to specific numerosities (30/33 units; primitives in Papua and New Guinea), through a conventional numerical attribution to gestures (until 9000 units; Bede, 672-735), to expressing numerosities up to ten billion with the use of phalanges, knuckles and top of fingers (Suang Fa Tong Zong, 1583). If primitives populations witness the origins of the human numerical concepts by the use of fingers, children finger-counting aptitudes corroborate the link between fingers and numbers by the fact that children spontaneously develop pointing, grasping, and, with the help of their parents and teachers, fingers-counting and finger-montring strategies when confronted to numerical problems, as if it was a natural pathway for every human being. However, even if the above mentioned finger numerical strategies have been the object of studies during childhood (see Fuson, 1982-1988; Gelman & Gallistel, 1978; Weise, 203a,b; Noël, 2005; Fayol et al., 1998-2001), little is known about how the finger-counting and finger-montring habits could interact with the abstract and more general semantic representation of numbers. Neuropsychological, behavioural and functional imaging data suggest that even in adults, fingers keep a special role on the semantic representation of numbers. However, no empirical investigation has been carried out so far on finger-counting habits on adult humans, and especially on how these finger representations could interact with the semantic representation of numbers.

In this thesis we will focus on the canonical aspects of the finger-counting and finger-montring strategies. Firstly, we will show that, under specific conditions (all ten fingers used as response modality), participants refer to finger counting numeral representations more than to an analog, number-line like, representation of numbers. Subsequently, we will determine which is/are the finger canonical representation(s) of numerosities and we will use it/them to subliminally prime the processing of Arabic numerals, showing that the semantics of numbers is automatically accessed by finger canonical representation(s). Next, we will exclude that canonical and non-canonical finger numeral representations differ only because of low-level visual differences and we will show that these representations refer to two distinct ways of processing the numerosity.

Chapter 2 Finger-digit compatibility in Arabic numeral processing[1]

ABSTRACT

Finger-digit response compatibility was tested by asking participants to identify Arabic digits by pressing one of ten keys with all ten fingers. The direction of the finger-digit mapping was varied by manipulating the global direction of the hand-digit mapping as well as the direction of the finger-digit mapping within each hand (in each case, from small to large digits, or the reverse). The hypothesis of a left-to-right mental number line predicted that a complete left-to-right mapping should be easier whereas the hypothesis of a representation based on finger counting predicted that a counting-congruent mapping should be easier. The results show that when all ten fingers are used to answer a mapping congruent with the prototypical finger-counting strategy reported by the participants leads to better performance than a mapping congruent with a left-to-right oriented mental number line, both in palm-down and palm-up postures of the hands, and demonstrate that finger-counting strategies influence the way numerical information is mentally represented and processed.

[1] This section is a modified version of an article with identical title by Di Luca, Granà, Semenza, Seron & Pesenti, which has been published in the Quarterly Journal of Experimental Psychology, 2006, 59(9), 1648-1663.

1. Introduction

Differences in the speed and accuracy with which a stimulus elicits a given response are called stimulus-response compatibility effects. In the domain of numbers, there seems to be a natural association between the response large and the right side, and between the response small and the left side. Indeed, it has been found that small numbers are preferentially responded to with the left-hand key, whereas the reverse is true for large numbers. This phenomenon has been termed the Spatial-Numerical Association of Response Codes effect, or SNARC effect (Dehaene, Bossini, & Giraux, 1993; see also Bächtold, Baumüller, & Brugger, 1998; Brysbaert, 1995). It was found to be stronger with single-digit Arabic numerals, but weaker or absent with numerals composed of 2 digits and with written verbal numerals; it did not reverse in left-handed individuals or in right-handed individuals crossing their hands, but it was significantly weaker in participants who had a right-to-left writing system[2]; finally, it was determined by the relative magnitude of the numbers within the interval used, the same numbers being preferentially associated with a right or left response depending on whether they were the largest or the smallest numbers in a given series (Dehaene et al., 1993). Interestingly, the SNARC effect has also frequently been observed in tasks that do not require evaluating number magnitude such as identity judgements (Dehaene & Akhavein, 1995), phoneme monitoring (Fias, Brysbaert, Geypens & d'Ydewalle, 1996), or orientation judgements (Fias, Lauwereyns & Lammertyn, 2001). Yet, all tasks with numbers do not automatically lead to a SNARC effect. For example, irrelevant magnitude information does not affect the processing of colours or shapes whereas it does affect the processing of the orientation of Arabic digits (Fias et al., 2001). This was interpreted in terms of degree of

[2] For example, Iranians (Dehaene et al., 1993). This suggests a relationship between the direction of writing and the direction of the SNARC effect. Note that there was no evidence of a complete reversal of the spatial-numerical association as a function of the direction of writing. However, in Iranian immigrants, the slope of the SNARC effect was a function of the time spent away from Iran: the longer the Iranian participants had stayed in a left-to-right writing system, the more the slope of their SNARC effect was similar to that of occidental participants.

neural overlap of the brain structures underlying the relevant and irrelevant judgements: a SNARC effect would emerge when the relevant task and the irrelevant magnitude information share the same (or, at least, close to the same) brain areas in the parietal cortex (e.g., in the above-mentioned example, shapes and colours processing would rely on the ventral occipito-temporal stream, whereas orientation and magnitude processing would rely on the dorsal occipito-parietal stream).

Classically, the SNARC effect has been interpreted as revealing a natural mapping of a mental numerical continuum representing numerical magnitudes by distributions of activations onto extracorporeal physical space (Dehaene, 1992; Dehaene, Dehaene-Lambertz & Cohen, 1998). This view is supported by recent brain-imaging studies showing robust and highly replicable activations in the parietal cortex - known to be involved in space processing- along the intra-parietal sulcus, when numerical processing is involved (Pinel, Le Clec'H, van de Moortele, Naccache, Le Bihan & Dehaene, 1999; Simon, Mangin, Cohen, Le Bihan & Dehaene, 2002). Yet, brain-imaging studies also suggest an alternative interpretation as another very robust joint activation is observed in the precentral gyrus (Dehaene, Spelke, Pinel, Stanescu & Tsivkin, 1999; Dehaene, Tzourio, Frak, Raynaud, Mehler & Mazoyer 1996; de Jong, van Zomeren, Willemsen & Paans, 1996; Ghatan, Hsieh, Petersson, Stone-Elander & Ingvar, 1998; Pesenti, Thioux, Seron & De Volder, 2000; Pinel et al., 1999; Rueckert et al., 1996). This joint activation of parietal and precentral areas may reflect the involvement of a finger movement representation network (Pesenti et al., 2001). Such a network would apparently underlie finger counting and numerosity quantification as well as representation during childhood (Butterworth, 1999a; Simon, 1999), and, by extension, become the substrate of some numerical knowledge and processes in adults. Various findings support this interpretation. Several developmental (Fuson, 1988) and cross-cultural (Butterworth, 1999b) studies show that spontaneous finger-counting strategies are developed and used by children in almost all human cultures, and that results of finger discrimination tests are the best predictor of arithmetic performances in 5- to 6-year-old children (Fayol, Barouillet & Marinthe, 1998). Moreover, neuropsychological studies show a link between acalculia and finger agnosia (Gerstmann, 1940). Finally, brain-imaging studies show that precentral activations similar to the ones observed during numerical tasks are observed not only with overt finger/hand movements but also during covert movements (i.e., without actual motor realization as during mental imagery tasks; Grafton, Fadiga, Arbib & Rizzzolatti, 1997; Thompson, Abbott, Wheaton, Syngeniotis & Puce, 2004).

In the present paper, we tested how the way fingers are used to represent numerosities and support counting may have an impact on how numbers are mentally processed. Participants were asked to identify visually presented single Arabic digits by pressing one of ten keys with one of their ten fingers. In the first experiment, we tested the respective strength of the mental number line and the finger-representation accounts by systematically varying the direction of the finger-digit mapping to evaluate the effect of various possible finger-counting strategies on the presence or absence of a left-small/right-large bias. In the second experiment, we tested whether the preferred finger-digit mapping was related to implicit visuo-spatial cues or if it truly reflected a finger-digit association by comparing palm-up and palm-down postures of the hands.

2. **Experiment** 1

In this experiment, three different sources of left-to-right (in)congruence that could lead to a measurable facilitating or interfering effect in Arabic digit identification were manipulated: (1) the global orientation of the hand-digit mapping (with the left hand [LH] responding to small numbers and the right hand [RH] to large ones, or the reverse, whatever the specific finger-digit mapping within the hands), (2) the finger-digit mapping of the LH (from little finger to thumb from small to large digits, or the reverse), and (3) the finger-digit mapping of the RH (from little finger to thumb from small to large digits, or the reverse). When combined, these three variables give eight different finger-digit mappings displayed in Fig. 2-1, with different possible predictions. Should a left-to-right oriented mental number line produce a strong extracorporeal association between numbers and space, then a strict SNARC-congruent left-to-right mapping of fingers and digits (mapping 1 in Fig. 2-1) would lead to the fastest and less error-prone identification, whereas a totally SNARC-incongruent right-to-left mapping of fingers and digits (mapping 8 in Fig. 2-1) would lead to the slowest and more error-prone identification. Alternatively, if finger counting plays a role in the way numerical representations are built and contributes to some stimulus-response compatibility, then counting-congruent mapping(s) should have stronger facilitation effect(s) on identification whereas counting-incongruent mappings should have interference effects. Since the participants of this study were native Italians who were raised and went to school in Italy, they had the typical Italian finger-digit mapping where counting starts with the right thumb and proceeds to the little finger from one to five, and then from the left thumb to the little finger, from six to ten. This would make mapping 7 in Fig. 2-1 the fastest and least error-prone. Mapping 3 is another instance of a possible finger-counting mapping starting with the LH. The other mappings were included to test the possible main effects of the three sources of congruence (for example, if the only factor that matters for the SNARC effect is to respond to small digits with the LH and to large digits with the RH, whatever the specific within-hand finger-digit mapping, then mappings 1 to 4 should be globally faster and less error prone than mappings 5 to 8, without any difference among them, etc.).

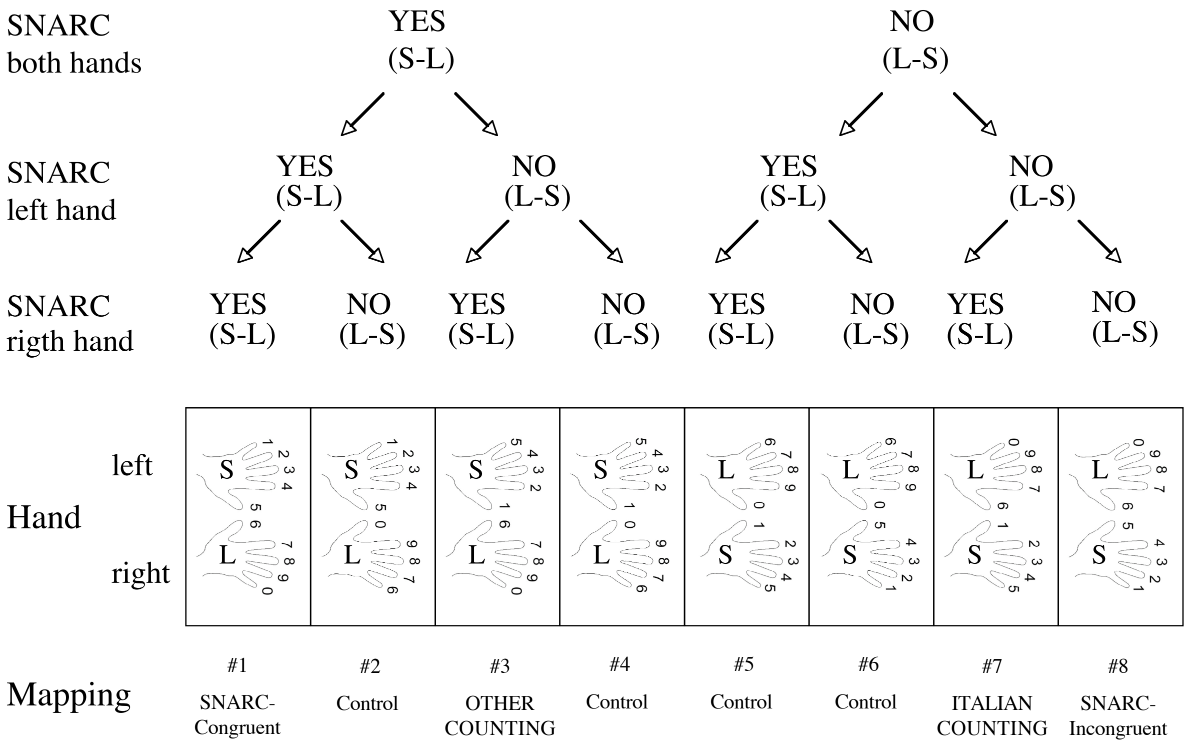


Figure 2-1. Experimental design and finger-digit mappings of experiment 1. The bottom part of the figure shows the eight mappings obtained by combining the three variables (upper part) related to the orientation of the mapping, as well as their relationship with Hand and Magnitude (see text for details; S= Small, L= Large, S-L= Small on the left and large on the right, L-S= large on the left and small on the right).

2.1 Method

2.1.1 Participants

One hundred and twenty-two right-handed Italian participants took part in this experiment. Six were excluded because they had misunderstood the instructions and four because they applied an erroneous association for two fingers (in mappings 2, 6, 1 and 3 respectively). Among the 112 remaining participants, 78 were females. One hundred and nine participants were students at the Psychology Faculty of Trieste and three came from other universities, all without specific mathematical background[3]. Ages ranged from 21.1 to 34.1 years (mean±sd age: 25.1±2.9 years).

2.1.2. Apparatus

Stimuli were presented on a 15” Macintosh LCII screen and answers were given by key presses on a standard Apple Desktop Bus keyboard. In most of the previous experiments showing the SNARC effect, participants used either two fingers of one hand or one finger of each hand. To better evaluate the mental number line and the finger-counting accounts, all ten fingers were used in this experiment. Participants adopted a typical typing position on the keyboard to ensure a comfortable posture for the hands and arms and a good in-line positioning of the fingers, except for the thumbs that were lowered slightly (see Fig. 2-2).

Figure 2-2. Position of the hands on the keyboard. The top row shows the position of the little, ring, middle, index, index, middle, ring and little fingers of the left and right hands, respectively; the bottom row shows the position of the left and right thumbs.

2.1.3. Stimuli and procedure

Stimuli were 1.5 cm high Arabic digits ranging from 0 to 9 presented inside an 11.5 x 11.5 cm^2 white square at the centre of a black background screen. Each trial started with an asterisk lasting for 500 msec, followed by the stimulus that remained on the screen until the

[3] Informal testing after the experiment confirmed that at least 82% of the participants used the typical Italian association when counting with their fingers. This aspect was formally assessed in experiment 2.

participant answered, then ended with a blank screen lasting for 500 msec before the next trial started (see Fig. 2-3a). Eight mappings were obtained by combining three dichotomous variables related to the orientation of the finger-digit association. Each mapping was (1) compatible or not with a global SNARC orientation (for the two hands), with small digits associated with the LH and large digits with the RH, or the reverse, (2) compatible or not for the LH, from small to large digits, or the reverse, and (3) compatible or not for the RH, from small to large digits, or the reverse (see Fig. 2-1). Participants had to press the key corresponding to the displayed digit as indicated by the specific finger-digit mapping; during the training phase, a figure showing the finger-digit mapping to be used (as at the bottom of Fig. 1) was placed beside the keyboard to help the participant remember the current association. In order to test some of the main effects and interactions within subject (see Results section), each participant received 2 out of the 8 possible finger-digit mappings in two different blocks. Each finger-digit mapping was administrated as a first mapping to 14 participants, and as a second mapping to 14 other participants. The 56 possible orders of the two mappings (i.e., 1-2, 2-1, 1-3, etc.) were randomly assigned to two participants. A block was composed of 20 (not analysed) practice and 100 experimental trials. The order of presentation of the stimuli was pseudo-randomly determined (no more than four consecutive responses with the same hand, at least three items before the repetition of the same digit).

To control possible motor speed differences among the fingers, a baseline reaction time task was also applied after the two blocks with digits. Stimuli were line drawings of a LH and a RH taken from the neuropsychological MODA test (Milan Overall Dementia Assessment; Brazzelli, Capitani, Della Sala, Spinnler & Zuffi, 1994). The drawings were 9 x 7.5 cm^2 and were presented inside an 11.5 x 11.5 cm^2 white square at the centre of a black background screen. Each trial started with a drawing lasting for 500 msec, followed by the same drawing with a finger pseudo-randomly darkened and remaining on the screen until the participant answered, then ended with a blank screen lasting for 500 msec before the next trial started (see Fig. 2-3b). This task was composed of 20 (not analysed) practice and 100 experimental trials. Participants responded with one hand at a time (50 trials per hand, in a counterbalanced order) in order to keep a central presentation of the stimuli, decrease visual inspection of the screen and, most importantly, to avoid discarding the critical hand selection component from the experimental task.

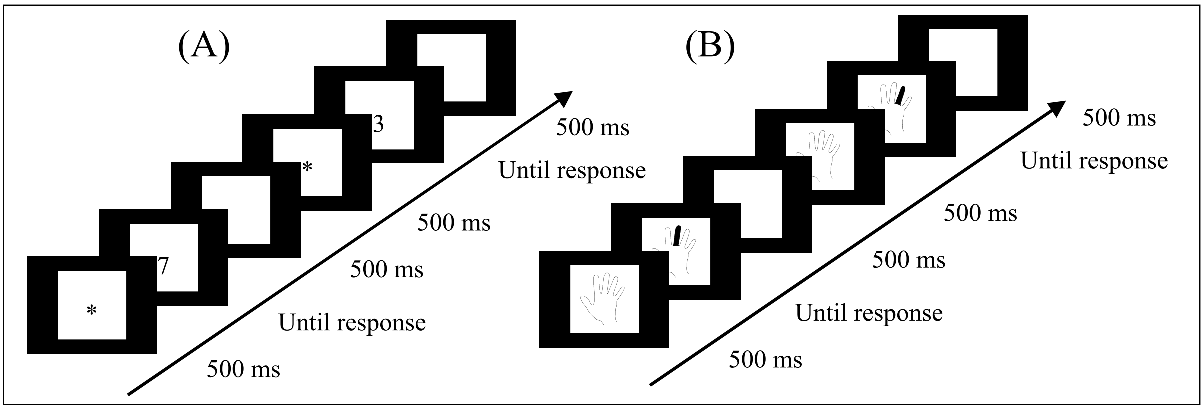


Figure 2-3. Sequence of events during (A) the blocks with digits and during (B) the block with hands.

2.1.4. Preliminary control analyses

The first preliminary analysis was carried out to check possible motor differences in the baseline task. Error rate averaged over participants was 2.39%. There was no speed-accuracy trade-off as indicated by the absence of negative correlation between response latencies (RLs) and number of errors, computed over 20 couples [ten fingers separated for gender; r = + .604; n = 20; $p < .005$]. An ANOVA on RLs of correct responses with gender as a between variable and hands and fingers as within variables showed no significant gender difference [mean±sd RLs for females: 459±82 msec; for males: 435±93 msec; $F(1,110) = 1.888$; $p > 0.1$], but a significant difference between hands [mean±sd RL for LH: 460±96 msec; for RH: 434±79 msec; F (1,110) = 37.09; $p < 0.001$] and between fingers [F (4,440) = 33.386; $p < 0.001$]. There were also interactions between hands and fingers [F (4,444) = 7.831; p < 0.0001] as well as between hands, fingers and gender [F (4,440) = 2.507; p < 0.05]. For these reasons, the RLs for digit identification were corrected prior to analyses by subtracting for each participant the median RL observed in her/his baseline task for each corresponding finger.

The second preliminary analysis was carried out to test possible practice or training effects in the digit blocks. There was globally no significant difference between the first and second block [mean±sd RL for block 1: 447±139 msec; for block 2: 439±136 msec; F (1,208) = 0.166; p = ns]. Within blocks, there was a difference between the first five and the last five responses, with the latter always slightly faster [mean±sd RL for the first 5: 486±190 msec; for the last 5: 431±168 msec; F (1,432) = 8.003; $p < 0.005$]. This effect suggests a simple practice effect as shown by the absence of interaction between the first five/last five responses and the experimental variables [F (1,432) = 0.419; p = ns].

Note that a single*0* was used in place of *10* to avoid using a 2-digit number mixed with single-digit numbers. The instructions explicitly mentioned that *0* was to be understood as *10*, but a few subjects complained during the post-experiment debriefing that they sometimes hesitated. Therefore, *0* was not entered in subsequent analyses[4]. Finally, in all subsequent analyses, RLs (corrected by the finger speed as measured in the motor task) were converted to 1/RLs to avoid any problem of asymmetric distribution (Tabachnick & Fidell, 1989). Only latencies of correct responses were analysed.

[4] All the analyses were also run without discarding *0* and the results were virtually similar.

2.2. Results

Four series of analyses with different aims were carried out. Since each participant was only subjected to 2 out of the 8 mappings, both or only the first one were used in the analyses, depending on the aim of each analysis and its between- or within-subjects rationale; therefore, the number of participants included in the analyses varied (details are given where appropriate). We first started by testing differences across the eight mappings. We then ran a global analysis taking into account the three variables related to finger-digit orientation, to which Hand and Magnitude were added in separate analyses. A third analysis assessed a possible within-subject interaction between Magnitude, Hand and Orientation. Finally, a fourth analysis pointed out the best associations between fingers and digits.

2.2.1. Mapping differences

Mean error rates and corrected RLs for mappings 1 to 8 are given in Table 2-1. There was no speed-accuracy trade-off as indicated by the absence of negative correlation between RLs and the number of errors [$r = +.843$; $n = 8$; $p < 0.004$].

To test if there was a difference between the eight mappings, a one-way between-subject ANOVA was performed on RLs, only on the first block of all 112 participants. There was a significant difference between the mappings [$F(7,104) = 3.795$; $p < 0.001$]. The three fastest mappings were the typical Italian counting, the complete SNARC-incongruent and the complete SNARC-congruent mappings (respectively mappings 7, 8 and 1). T-tests, with *p*-level set at 0.02 using the Bonferroni correction for multiple comparisons, showed no difference between mappings 8 and 1 [$t(14) = 0,602$], but a marginally significant difference between mappings 7 and 1 [$t(14) = 2,09$; $p < 0.05$]: participants tended to respond faster with the prototypical Italian counting mapping than with the SNARC-congruent mapping. The same analysis carried out on errors highlighted a significant difference between the mappings [F (7,104) = 2.545; p < 0.02], but no difference between mappings 1, 7 and 8 on the t-tests.

	Mean		LH/Small		RH/Large	
Mapping	Errors	RLs (sd)	Errors	RLs (sd)	Errors	RLs (sd)
1	5.0	427 (137)	3.6	370 (94)	6.4	499 (203)
2	8.8	434 (121)	6.6	387 (93)	7.9	491 (162)
3	8.3	480 (114)	5.5	448 (154)	6.9	519 (94)
4	7.8	568 (137)	7.1	508 (133)	8.1	644 (152)
			LH/Large		RH/Small	
5	7.4	468 (148)	8.3	552 (199)	6.4	401 (139)
6	8.2	461 (149)	6.9	504 (170)	7.4	427 (160)
7	3.6	340 (97)	5.5	400 (133)	3.1	291 (80)
8	4.9	367 (142)	5.2	386 (142)	4.6	352 (148)

(LH = left hand, RH = right hand; RLs = response latencies)

Table 2-1. Mean error rates (%) and response latencies (msec) for each mapping, globally and separated for hand and magnitude in experiment 1.

2.2.2. Global analysis

This second series of ANOVAs matches the experimental design with the three variables related to the orientation as between-subject variables, to which two other within-subject variables of interest were added: the Hand (LH *vs*. RH) and the numerical Magnitude of the digits (Small: *1* to *5* *vs*. Large: *6* to *9*). These last two variables cannot be entered simultaneously in the same analysis because they are confounded within mappings (e.g. in mappings 1 to 4: Small=LH and Large=RH; in mappings 5 to 8: Small=RH and Large=LH). They were thus entered in two distinct analyses where only the first out of the two experimental blocks was used, for the 112 participants.

Error rates and corrected RLs are given in Table 1. There was no speed-accuracy trade-off as indicated by the absence of negative correlation between RLs and number of errors, computed over 16 couples [8 mappings, separated for LH and RH, with Hand as fourth variable: r = + .834, n = 16, < .000; 8 mappings, separated for Small and Large digits, with Magnitude as fourth variable: r = + .067; n = 16; ns].

The ANOVA revealed a main effect of the Orientation of both hands [mean±sd RL for Small-Large: 477±127 msec; Large-Small: 409±134 msec; F (1,104) = 7.494; $p = 0.007$], reflecting a preference for global anti-SNARC orientation: the mappings with the small digits associated with the RH and the large digits associated with the LH were faster than the reverse (small on the left and large on the right). There were no main effects of the Orientation of the LH [F (1,104) = 0.177; $p = 0.675$] nor of the Orientation of the RH [F (1,104) = 1.171; $p = 0.282$]. A two-way interaction between Orientation of both hands and Orientation of the LH was observed [F (1,104) = 16.769; $p < 0.001$]: participants were faster in the global anti-SNARC mappings (small on the RH and large on the LH) when the orientation of the LH was anti-SNARC too. Conversely, in the global SNARC mappings (small on the LH and large on the RH), the participants were faster when the LH was SNARC oriented. As for the errors, only the 2-way interaction between Orientation of both hands and Orientation of the LH was observed [F(1,104) = 7.373; p < 0.01]: the participants produced fewer errors in the global SNARC-incongruent mappings when the orientation of the LH was anti-SNARC too. Conversely, in the global SNARC mappings, the participants produced fewer errors when the LH was SNARC congruent.

With Hand as fourth variable, an interaction with the Orientation of the hands was found [F (1,104) = 87.880; $p < 0.001$]: the LH was as fast with small as with large digits, whereas the RH was slower when associated with the large digits. There was also an interaction with the

Orientation of the RH [F (1,104) = 4.822; $p < 0.03$] showing that the RH was slower if anti-SNARC oriented, whereas the orientation had no effect on the LH. With regard to the errors, only the interaction between Hand and Orientation of the hands was found [F (1,104) = 4.533; p = < 0.04]: for the LH, the number of errors was equal, whatever the Orientation, whereas the RH produced fewer errors when associated with the small digits.

When Magnitude was the fourth variable, its main effect was significant [mean±sd RL for Small: 398±139 msec; for Large: 499±173 msec; F (1,104) = 87,188; $p < 0.001$]: participants responded faster to small numbers than to large ones. There was a 3-way interaction between Magnitude, Orientation of both hands and Orientation of the RH [F (1,104) = 4.822; $p < 0.03$]: besides the general Magnitude effect, the difference between small and large digits was smaller in the global L-S orientation when the RH was anti-SNARC oriented. As for the errors, only a main effect of Magnitude was found [F(1,104) = 4.533; p < 0.04]: subjects produced fewer errors with small as opposed to large digits.

*2.2.3. Magnitude*Hand*Orientation interaction*

To evaluate the interaction between the variables Hand and Magnitude, a third series of analyses was carried out with the Hand (LH *vs*. RH) and the Magnitude (Small *vs*. Large) as between-subject variables and the Orientation (Small-Large *vs*. Large-Small) as a within-subject variable. To test this triple interaction within subjects, the two experimental blocks were used but only in the 48 participants for whom the direction of one hand was reversed and the other kept constant from the first to the second block (i.e. subjects who underwent a test with one of the following pairs of mappings: 1 and 3, 1 and 4, 2 and 3, 2 and 4, 5 and 6, 5 and 8, 6 and 7, 6 and 8, 5 and 7, 1 and 2, or 3 and 4). There was no speed-accuracy trade-off as indicated by the absence of negative correlation between RLs and number of errors [r = + .789; n = 8; p < 0.02].

There was no main effect of Orientation [F (1,44) = 0.418; *ns*]. A main effect of Magnitude was observed [mean±sd RL for Small: 409±151 msec; for Large: 508±156 msec; F (1,44) = 8.082; $p < 0.007$]: participants responded faster to small numbers than to large ones. Despite the correction for motor differences, a main effect of Hand was found [mean±sd RL for LH: 423±sd: 136 msec; for RH: 493±181 msec; F (1,44) = 3.996; $p = 0.052$]: the LH was faster than the RH. These main effects were qualified by a Hand by Magnitude interaction [F (1,44) = 11.222; $p < 0.002$]: the response to large digits was slower with the RH whereas magnitude had no effect on the LH. Finally, there was a 3-way interaction [F (1,44) = 4.860; $p < 0.033$]: whatever the global orientation, the response to small digits were always faster with the RH, whereas with the LH the response was faster in the global SNARC-orientation, but slower in the anti-SNARC (Fig. 2-4). The analysis of errors showed a Magnitude by Hand interaction [F(1,44) = 4.453; p < 0.04]: the RH responded better to small digits whereas the LH response to large digits was better. There was also a Magnitude by Orientation interaction [F(1,44) = 3.839 p < 0.051] showing that a better response was obtained with small digits in the global S-L orientation and with large digits in the global L-S orientation.

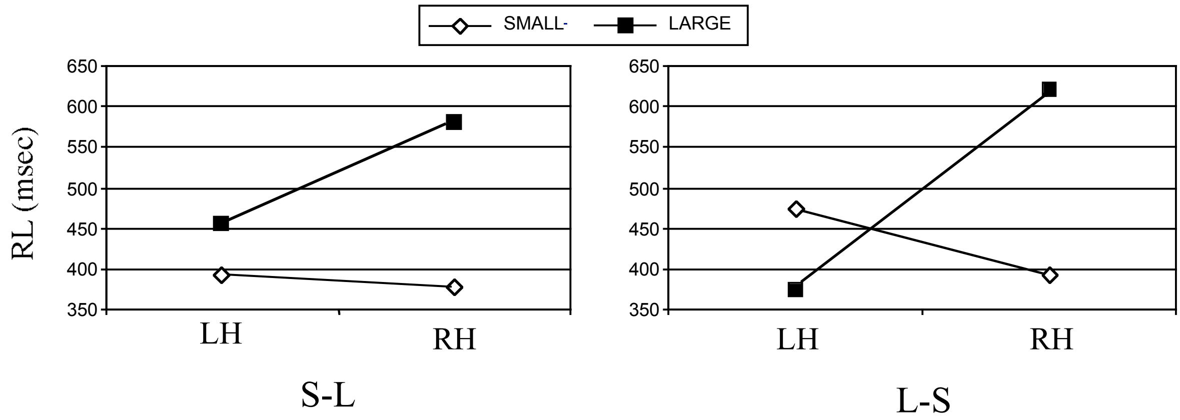


Figure 2-4. Mean response latencies (RLs) as a function of the magnitude, the hand and the orientation (diamonds: small digits, squares: large digits; LH=left hand, RH= right hand; S-L= Small on the left and large on the right, L-S= large on the left and small on the right).

2.2.4. Optimal finger-digit and digit-finger mappings

Finally, a fourth series of ANOVAs and t-tests revealed the best digit-finger association (i.e., the significantly fastest finger for each digit) as well as the best finger-digit associations (i.e., the significantly fastest digit for each finger)[5]. The RL differences between the two critical mappings (SNARC-congruent and typical Italian counting) and the fastest associations across mappings were directly compared. For these last series of analyses, only the first block for the 112 participants was used, and the *p* level was set at 0.005 for the ANOVAs and at 0.001 for the t-tests by using the Bonferroni correction for multiple comparisons.

Error rates and corrected RLs for each mapping are given in Table 2-2. There was no speed-accuracy trade-off as indicated by the absence of negative correlation between RLs and

[5] Zero was re-entered in these analyses to test its possible best associations.

the number of errors, computed over 36 couples [eight fingers separated for four possible digits; and two fingers separated for two possible digits; r = + .77; n = 36; p < 0.001].

DIGIT	HAND										
	LEFT					RIGHT					
	little	ring	middle	index	thumb	thumb	index	middle	ring	little	
1	236 *1,07*				450 *6,61*	358 *6,61*				313 *3,21*	7,009 *0,0002*
2		300 *3,39*		428 *5,54*			465 *5,00*		420 *4,82*		5,104 *0,0020*
3			485 *8,39*					387 *6,07*			4,005 *0,05*
4		525 *7,32*		448 *5,18*			332 *6,25*		315 *4,29*		8,681 *<0,0001*
5	476 *4,46*				452 *6,61*	423 *8,57*				350 *3,04*	2,748 *0,050*
6	531 *5,89*				397 *5,54*	496 *5,89*				568 *6,96*	5,036 *0,003*
7		577 *11,61*		409 *8,21*			578 *7,68*		656 *11,43*		5,024 *0,003*
8			464 *8,66*					538 *10,18*			7,875 *0,006*
9		319 *2,32*		458 *5,89*			478 *5,00*		338 *3,39*		7,61 *<0,0001*
0	300 *1,79*				390 *6,25*	395 *7,68*				354 *4,82*	2,802 *0,04*
	24,555 *<0,0001*	16,452 *<0,0001*	0,999 *NS*	0,430 *NS*	1,291 *NS*	2,914 *0,04*	7,027 *0,0002*	23,808 *<0,0001*	17,275 *<0,0001*	12,034 *<0,0001*	

Table 2-2. For each digit, first line: RL; second line italic: percentage of errors. Bottom row: F and *p* testing the presence of a speed difference across the 4 (or 2) possible digits for each finger; rightward column: F and *p* testing the presence of speed difference across the 4 (or 2) possible fingers for each digit. Empty circles: compatible with the SNARC mapping; filled circles: compatible with the Italian finger-counting mapping; no circle: other mappings.

The first ten ANOVAs and related t-tests tested the best associations between fingers and digits (Table 2-2)[6]. Nine of the 10 specific associations from the prototypical Italian counting were among the fastest or second fastest associations (all digits but digit *2* which was not the fastest in the counting situation, and digit *4* which was associated with two fingers), and 3 of the 10 specific SNARC-congruent associations were among the fastest. The error analysis showed that the left ring finger produced fewer errors when associated with *9* compared with digits *2, 4* or *7*, although the t-test confirmed a difference only between *9* and *7* [t(10) =

[6] The ANOVAs for digits *3, 5* and *0* did not reach the corrected *p* level (observed *p* levels = 0.048, 0.046 and 0.043 respectively); significant differences were revealed in any event by the t-tests.

5.109, p <0.0001]. For the left little finger, digit *1* produced fewer errors than the other possible associations (*0, 5* or *6*), but this difference was not significant. No other difference was observed.

The next ten ANOVAs and related t-tests revealed the best associations between digits and fingers[7]. This confirmed that the RH fitted small digits best whereas the LH fitted both small and large digits. Again, 9 of the 10 specific associations from the prototypical Italian counting were among the fastest or second fastest associations (all associations but digit *4* on the right index finger). Four of the 10 specific SNARC-congruent associations were among the fastest (or second fastest) associations (little finger LH: 1; ring finger LH: 2; middle finger LH: 3; ring finger RH: 9). The analysis of errors showed no differences for the ten digit-finger associations.

Finally, the RL differences between the fastest finger-digit associations and the prototypical Italian counting did not significantly differ from zero [t(10) = 1.479, ns], whereas the differences with the SNARC-congruent association did [t(10) = 4.177, p <0.002], confirming that prototypical counting was the fastest association.

2.3. Discussion of Experiment 1

In this experiment,finger-digit response compatibility was tested by asking participants to identify Arabic digits with key presses using all ten fingers. The direction of the finger-digit mapping was varied by manipulating the global direction of the hand-digit mapping as well as the direction of the finger-digit mapping of each hand. The hypothesis of a left-to-right mental number line predicted that a complete SNARC-congruent mapping should have been the easiest situation and a complete SNARC-incongruent mapping the most difficult, whereas the

[7] The ANOVAs for the *left index, middle* and *thumb fingers* did not reach the corrected *p* level (observed *p* levels = 0.048, 0.763 and 0.281 respectively); significant differences were revealed in any event by the t-tests.

finger-counting representation account predicted that a counting-congruent mapping should have been easier.

The main results are as follows. Firstly, a global SNARC-incongruent effect was found showing that, contrary to the mental number-line prediction, answers were globally faster and less error-prone when small digits were associated with the RH and large digits with the LH rather than the reverse, and they were fastest in the former case when the orientation of the LH was SNARC-incongruent. Moreover, hands and magnitude interacted such that the response to large digits was slower than to small digits with the RH, whereas the response to small and large digits with the LH showed no difference. When the LH dealt with small digits, RLs were slightly shorter with a SNARC-congruent direction of this hand; when it dealt with large digits, RLs were shorter with a SNARC-incongruent direction of this hand. For the RH, the response to small digits was always faster, whatever the direction of the mapping, and the SNARC-congruent direction was globally faster, whatever the size of the digits. This result, however, is equally compatible with the number line and the finger-counting accounts as both predict a superiority of a left-to-right mapping for the RH (respectively, from *6* to *10* and from *1* to *5*). Secondly, the prototypical Italian finger-counting mapping (starting with the right thumb from *1* to *5*, then the left thumb from *6* to *10*) appeared to be globally the fastest. It tended to be significantly faster than the complete SNARC-congruent mapping, which was not in itself different from the complete SNARC-incongruent mapping. Finally, the prototypical Italian counting was not only globally faster, but it also accounted for more of the observed associations between digits and fingers, as nine of its particular finger-digit mappings turned out to be the best mappings when looking for the fastest digit-finger and finger-digit associations (Fig. 2-5). In comparison, only four associations of the SNARC-congruent mapping fitted the best mappings.

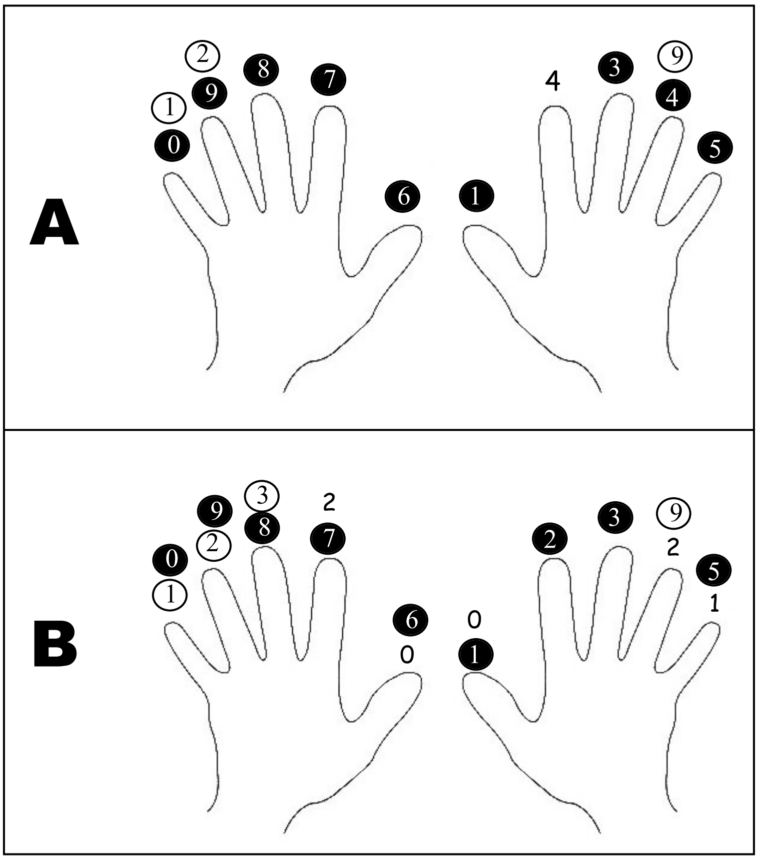


Figure 2-5. Optimal associations between (A) fingers and digits, and (B) digits and fingers (empty dots: compatible with the SNARC mapping; filled dots: compatible with the Italian finger counting mapping; no dot: other mappings). When two digits are displayed for the same finger (i.e., not significantly different; see Table 2), the lowest digit is the fastest one.

3. Experiment 2

Experiment 1 showed that the prototypical Italian finger-counting mapping was globally the best finger-digit mappings among those used. Experiment 2 tested whether this result truly reflects finger-digit associations or if it could be better accounted for by a visuo-spatial association. Indeed, in many situations, people count on their fingers looking at their palms up-oriented, and not with their palms down-oriented as imposed in experiment 1, which may have affected the way participants dealt with the task. We thus contrasted palm-up and palm-down postures and hypothesised that true finger-digit associations should not be affected by the palm-up/down posture of the hands whereas simple visuo-spatial associations should, as it would reverse the finger-digit associations. This was tested with the prototypical Italian finger-counting and the complete SNARC-congruent mappings only. Moreover, a few participants in experiment 1 did not in fact report using the prototypical Italian finger-counting, which may have introduced some variability in the data. This aspect was carefully controlled in this experiment.

3.1. Method

3.1.1 Participants

Forty Italian students from the Psychology Faculty of Trieste (all right-handed, 28 females) took part in experiment 2. The inclusion criterion was to spontaneously exhibit the prototypical Italian finger-counting when asked to count on one's fingers[8]. Ages ranged from 20 to 35 years (mean±sd age: 23.9±4.2 years). Half of the participants were randomly assigned to the palm-down group, the other half to the palm-up group; in each group, half of the participants started with the Italian-counting mapping and the other half with the SNARC-congruent mapping.

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[8] Once the experiment was finished, the participants were asked to place their hands palm down on their knees. After having adopted this position, they were asked to show "how they count from 1 to 10 on their fingers". All subjects spontaneously turned their palms up and used the prototypical Italian finger-counting.

3.1.2. Apparatus

The same experimental set-up as in experiment 1 was used in the palm-down group. For the palm-up group, the keyboard was turned upside down and fixed on a small wooden bench placed at about 15 cm over the table to allow hand movements.

3.1.3. Stimuli and procedure

The same stimuli and procedure as in experiment 1 were used except for the fact that only the two mappings of interest were tested: the SNARC-congruent mapping (starting with the left little finger from *1* to *5*, then the right thumb from *6* to *10*) and the Italian finger-counting mapping (starting with the right thumb from *1* to *5*, then the left thumb from *6* to *10*; see Fig. 2-6). The same motor baseline task was also used, with palm-up/down line drawings of the hands. Instructions made it clear for each participants that *0* was to be processed as *10*.

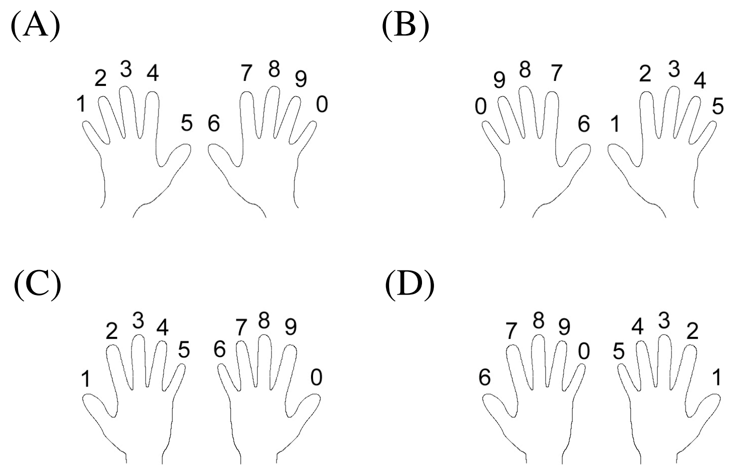

Figure 2-6. Finger-digit mappings of experiment 2. (A) SNARC-congruent mapping and (B) finger-counting mapping, with palms down; (C) SNARC-congruent mapping and (D) finger-counting mapping, with palms up.

3.1.4. Preliminary control analyses

As in experiment 1, preliminary analyses were carried out to check possible motor differences in the baseline task. In the palm-down group, error rate averaged over participants was 3.55%. There was no speed-accuracy trade-off as indicated by the absence of negative correlation between RLs and number of errors, computed over 20 couples [ten fingers separated for gender; r = + .402; n = 20; $p < 0.1$]. An ANOVA on RLs of correct responses with gender as a between and hands and fingers as within variables showed no significant gender difference on RLs [mean±sd RLs for females: 445±78 msec; for males: 428±79 msec; F (1,18) = 0,225; $p > 0.1$], but a significant difference between hands [mean±sd RL for LH: 460±94 msec; for RH: 412±63 msec; F (1,18) = 22.72; $p < 0.001$] and between fingers [F (4,72) = 10.43; $p < 0.001$]. There were also an interaction between hands and fingers [F (4,72) = 4.833; p = 0.002] as well as between hands, fingers and gender [F (4,72) = 2.909 p < 0.05]. In the palm-up group, error rate averaged over participants was 3.05%. There was no speed-accuracy trade-off as indicated by the absence of negative correlation between RLs and number of errors, computed over 20 couples [ten fingers separated for gender; r = + .635; n = 20; $p < 0.003$]. The same ANOVA as above showed no significant gender difference [mean±sd RLs for females: 446±93 msec; for males: 468±93 msec; F (1,18) = 0,314; $p > 0.1$], no difference between hands [mean±sd RL for LH: 461±91 msec; for RH: 453±94 msec; F (1,18) = 0.622; $p > 0.1$], but a difference was found between fingers [F (4,72) = 7.565; $p < 0.001$]. There was also an interaction between hands, fingers and gender [F (4,72) = 2.909 p < 0.05]. For these reasons, the RLs for digit identification were corrected prior to analyses by subtracting for each participant the median RL observed in her/his baseline task for each corresponding finger. As for experiment 1, blocks 1 and 2 did not differ [mean±sd RL for block 1: 372±96 msec; for block 2: 370±95 msec; F (1,36) = 0.047; *ns*], and there was a small training effect between the first five responses and the last five responses within a block [mean±sd RL for the first 5 trials: 397±135 msec; for the last 5 trials: 382±137 msec; F (1,36) = 3.385; $p < 0.1$]. Finally, RLs were converted to 1/RLs to avoid any problem of asymmetric distribution. Only latencies of correct responses were further analysed.

3.2. Results

Error rates and corrected RLs for each mapping are given in Table 2-3. There was no speed-accuracy trade-off as indicated by the absence of negative correlation between RLs and number of errors [computed on 80 couples, 40 subjects separated for first and second block; r = + .351; n = 80; p = 0.001].

An ANOVA with posture (Palm-down *vs*. Palm-up) and order of blocks (Counting-Snarc *vs*. Snarc-Counting) as between-subject and mapping (SNARC *vs*. Counting) and hand (LH *vs*. RH) as within-subject variables was carried out. A main effect of the mapping was found showing that the finger-counting mapping was globally responded to faster than the SNARC-congruent mapping [mean±sd RL for counting: 357±108 msec; for SNARC: 384±96 msec; F (1,36) = 6.156; $p < 0.05$]. There were no differences between postures [mean±sd RL for Palm-down: 375±95 msec; for Palm-up: 366±109 msec; F (1,36) = 0.115; *p* ns], between orders [mean±sd RL for C-S: 368±102 msec; for S-C: 373±103 msec; F (1,36) = 0.038; ns], or between hands [mean±sd RL for LH: 365±107 msec; for RH: 375±109 msec; F (1,36) = 1.741; ns]. Mapping and hand interacted (F (1,36) = 43.41 p < 0.0001): the LH was faster in the SNARC-congruent mapping and the RH was faster in the Counting mapping. T-tests, with *p* level set at 0.01 by using the Bonferroni correction for multiple comparisons, showed that even if there is no difference between the LH and the RH for the small digits [t(40) = 1.264, p > 0.1], the LH responded faster than the RH for large digits [t(40) = .177, p = 0.007]. The same analysis carried out on errors highlighted a significant difference between the mappings, where the finger-counting mapping yielded globally less errors than the SNARC-congruent mapping [F (1,36) = 4.483; $p < 0.05$]. No other main effects or interactions were found.

	Palms down		Palms up	
Mapping	Errors	RLs (sd)	Errors	RLs (sd)
Snarc	6.8	395 (83)	6.8	373 (98)
Counting	5.8	356 (92)	5.4	358 (109)

(LH = left hand, RH = right hand; RLs = response latencies)

Table 2-3. Mean error rates (%) and response latencies (msec) for each mapping as a function of palm posture in experiment 2.

3.3. Discussion of experiment 2

In this experiment, we tested whether the preferred finger-digit mapping observed in experiment 1 truly reflected finger-digit associations by contrasting palm-up and palm-down postures of the hands; the hypothesis being that true finger-digit associations should not be affected by the palm-up/down posture.

The results show no difference between the palm-up/down postures and the finger-counting mapping was faster than the SNARC-congruent mapping in both of them. It is worth noting that the hand-by-mapping interaction can be explained by a typical magnitude effect, with small digits simply responded to faster than large ones whatever the mapping. Interestingly, this magnitude effect indicates that an access to the semantic representation of magnitude took place and suggests that the finger-digit associations go beyond simple visuo-motor associations. As in experiment 1, large digits were responded to faster with the LH.

4. GENERAL DISCUSSION

Taken together, the results of the two experiments show that a left-to-right oriented mental number line is not the best account of these data, and demonstrate that finger counting strategies may influence the way numerical information is projected into physical space and perhaps mentally represented. In the first experiment, the RH was clearly superior when responding to small digits whereas no superiority was found for the LH; in the second experiment, the LH was faster than the RH when associated to large digits. This Small-Right superiority effect can be explained by the fact that, when both hands are available in daily-life activities, counting always starts with the RH whereas counting will start with the LH when the RH is occupied (e.g. when writing or holding something). This leads to the development of a strong association between small numbers and the RH, but between both large and small digits and the LH. It is worth noting here that neither the instructions nor the experimental set-up explicitly oriented the participants towards activating finger counting strategies, and that, prior to the analyses, RLs had been corrected for motor speed differences across hands (and fingers) that might have obscured the interpretations. Interestingly, the small-right superiority here observed echoes recent findings in parity judgment tasks using left-right pointing on a touch-screen as answer modality (Fischer, 2003). In these experiments, the "right-large" superiority effect congruent with the SNARC effect was not observed on response time: responses to the right side of the screen were more quickly initiated for small than for large digits.

One may argue that the results of the present study do not reflect long-term memory associations but simply stem from the experimental set-up: when finger-digit mappings are imposed, participants would learn and use better naturally easy mappings. This would explain why unidirectional mappings (complete right-to-left or left-to-right) are among the fastest mappings in experiment 1. Yet, with this line of reasoning, the SNARC-congruent mapping should have been even faster due to a double advantage (easy to learn and referring to a permanent mental representation). Moreover, a long-term memory association still remains necessary to account for the finger-counting mapping ease of learning and use, unless one argues that having a different mapping direction for each hand (i.e., L-S for the LH and S-L for the RH) would be a naturally easier situation, perhaps because the finger-digit association progresses the same way for the two hands (e.g., from thumb to little finger). In this case, mappings 2, 3, 6 and 7 should have been faster than the other mappings. Yet, mappings 1, 7 and 8 are the only ones that were statistically faster, and among the four thumb-to-little finger mappings, mapping 7 (i.e., Italian finger-counting mapping) was significantly faster than the others. In particular, it was 140 msec faster than mapping 3 that used the same thumb-to-little finger progression but starting with the LH. The only reason we see why mapping 7 could be faster than mapping 3 is because it is compatible with the Italian finger counting. Whether this long-term association is related to number semantics or simply reflects a strong asemantic motor association cannot be definitely disentangled from these experiments. Two arguments lead us to believe that the finger-digit association evidenced here may go beyond a simple visuo-motor association. First, it is worth stressing that finger counting is most probably more related to verbal numerals (mentally or overtly spoken) than to Arabic numerals as displayed in this experiment, which suggests at least some sort of Arabic-to-verbal transcoding. Second, the presence of a magnitude effect suggests that the stimuli were indeed processed up to the semantic level[9]. We thus argue that the finger-counting association is a valid and viable

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[9] The magnitude effect observed in this study (about 100 msec) is much larger than usually observed (about 30 msec classically). Although this difference may reflect some critical hand-switching cost related to finger counting that would support our view, it is likely due to our specific experimental set-up using ten possible answers whereas more classic experiment generally used only two different responses. Indeed, in choice decision situations RL increases with the number of possible responses - a phenomenon known as Hick's information-theory law - such that the mean choice response latency is equal to $K \log_2 N$, where K is a constant and N the number of possible responses (Hick, 1952). For example, if the absolute processing time is, say, 400 msec for small digits and 430 msec for large digits, the difference will be 30 msec with two responses ($\log_2 2 = 1$; mean

account of our data, which clearly fits the developmental, neuropsychological, cross-cultural and brain imaging functional data overviewed in the introduction. Using and practising a prototypical finger counting leads to long-term associations between fingers and digits that may explain the robust parieto-precentral activations observed in PET and fMRI experiments with numbers. What aspect of number semantics (cardinality or ordinality) is reflected in this long-term finger-digit association is still to be found.

These results do not, of course, rule out the number line as a possible mental representation of numerical information, but they show that it may not be the only one leading to spatial congruency effects. Moreover, it would not be as strong a representation as usually expected, since finger-counting associations overcame it in our specific experimental situations where the ten fingers where to be used to perform the task. The differential effects observed between the hands (i.e. only magnitude matters for the RH, magnitude and orientation of the mapping matter for the LH) call for a more rigorous control of experimental protocols. Indeed, asking the participants to answer numerical stimuli using two fingers of one hand (usually, the middle and index fingers) may be different from answering with one finger of each hand (usually the index fingers). This point was not usually manipulated in previous experiments, nor were the latencies corrected for hand or finger motor speed differences. Because of such uncontrolled parameters (preferred personal finger-counting, hands and fingers motor differences), effects related to spatial preferences should be interpreted very cautiously in the present state of knowledge. This may also explain the apparent discrepancy between our results (Small-Right superiority) and previous results revealing a SNARC effect (Small-Left superiority) that were collected with participants whose finger-counting preferences were not known. A SNARC effect would emerge as a robust effect at the group level if, for example,

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small= 400 msec, mean large= 430 msec) but it will be about 100 msec with ten responses ($\log_2 10 = 3.32$; mean small= 1328 msec, mean large= 1428 msec; these mean RLs actually correspond to those observed before the motor correction). It is however worth noting that this does not weaken our current interpretations that are based on direct comparisons between mappings within our experiment.

the majority of the participants share the same finger-counting strategy (e.g., starting with the LH resulting in a Small-Left superiority). However, in typical experiments, the SNARC effect is not observed in all participants which, in our line of reasoning, could be explained if those who do not exhibit the SNARC effect have either no preferred left or right starting hand for finger-counting or no specific finger-counting strategy at all. This of course remains speculative and further work is clearly needed to see whether individuals or groups of individuals with different finger-counting strategies would differ in the present experimental set-up but also in more standard ones where the SNARC effect was previously observed. Further work will also have to tell the possible impact of teaching methods on finger-counting representations as the prototypical finger-counting strategies may be different from one country to the other (Butterworth, 1999b) and finger-counting may even be sometimes prohibited (as in some primary schools in southern France; Brissiaud, 2003).

Chapter 3 : Masked priming effect with canonical finger numeral configurations[10]

ABSTRACT

Discrete numerosities can be represented by various finger configurations. The impact of counting strategies on these configurations and their possible semantic status were investigated in young adults. Experiment 1 showed that young adults named numerical finger configurations faster when they conformed to their own canonical finger-counting habits than when they did not. Experiment 2 showed that numeral finger configurations used as unconsciously presented primes speeded up numerical comparative judgements of Arabic numeral targets. Participants responded faster and made fewer errors with numerical than with non-numerical primes, and when primes and targets were congruent (i.e., leading to the same response). Moreover, this priming effect generalised to novel never consciously seen numerosities for canonical configurations but not for non-canonical ones. These results support the idea that canonical finger configurations automatically activate number semantics whereas non-canonical ones do not.

[10] This section is a modified version of an article with identical title by Di Luca & Pesenti (2007). Masked priming effect with canonical finger numeral configurations. *Experimental Brain Research*.

1. INTRODUCTION

Links between fingers and numbers have long been acknowledged, but it is only with modern neuropsychological approaches that research scientists have tried to understand their functional interactions better. Gerstmann (1924; 1940) unified in a syndrome bearing his name four specific symptoms jointly presented by some patients: left–right disorientation, dysgraphia, acalculia and finger agnosia. He argued that the focal point of the syndrome was the loss of a "sense of fingers", because fingers were somehow involved in all the other disrupted skills, and he pointed to the left parietal lobe, specifically the angular gyrus, as the critical site for lesions that produce this syndrome. Although the existence of the syndrome has regularly been questioned (see, for example, Poeck & Orgass, 1966), and despite the fact that it has occasionally been described after various cortical and subcortical lesions (Santos, Cope & Keller, 1991; Jung et al., 2001), it is mostly found after left angular lesions. Even very focal angular lesions may lead to the co-occurrence of finger agnosia and numerical disorders (Mayer, Martory, Pegna, Landis, Delavelle & Annoni, 1999) without additional language or intellectual deficits. Brain-damaged patients studies have not been able to disentangle alternative interpretations of the syndrome, but a series of experiments using focal cortical stimulation have shown that stimulation of the left angular gyrus disrupts performance on finger recognition, writing, and calculation tasks (Roux, Boetto, Sacko, Chollet & Trémoulet, 2003). Similarly, repetitive transcranial magnetic stimulation applied over the angular and supramarginal gyri disrupts both calculation and finger selection (i.e., speeded key press with the same or opposite finger after tactile stimulation) tasks (Rusconi, Walsh & Butterworth, 2005). It is also worth noting that the angular gyrus is responsible for the initiation of bimanual finger movements (De Jong, Willemsen & Paans, 1999).

Other pieces of evidence supporting a functional link between fingers and numbers come from brain-imaging studies. It is well known that various visuo-motor functions, such as orientation of attention in space and time (Coull & Nobre, 1998), object manipulation (Binkofski et al., 1999), grasping (Culham et al., 2003) and visual pointing (Connolly, Andersen & Goodale, 2003), rely on parieto-premotor networks. In various numerical tasks, a focus in the left precentral gyrus was found to be co-activated with areas along the intraparietal sulcus (Dehaene, Spelke, Pinel, Stanescu & Tsivkin, 1999; Dehaene, Tzourio, Frak, Raynaud, Mehler & Mazoyer 1996; de Jong, van Zomeren, Willemsen & Paans, 1996; Ghatan, Hsieh, Petersson, Stone-Elander & Ingvar, 1998; Pesenti, Thioux, Seron & De Volder, 2000; Pinel et al., 1999; Rueckert et al., 1996). Since parietal activation is thought to reflect number semantic processing, and since no contribution of finger movements is expected during these numerical tasks, this joint activation of parietal and precentral areas suggests the involvement of a finger movement representation network in the concept of number (Pesenti et al., 2001). Such a network could underlie finger counting and numerosity quantification during childhood (Butterworth, 1999a; Simon, 1999) and, by extension, become the substrate of some numerical knowledge and processes in adults.

This developmental aspect was investigated by observing that children with finger agnosia were strongly impaired on all the tasks using numbers or relying on mathematical abilities in general (Gerstmann, 1940; Kinsbourne & Warrington, 1963). More recently, studies conducted with 5- and 6-year-old children demonstrated that finger abilities, evaluated by various neuropsychological tests including single finger recognition, finger discrimination, simultagnosia and graphestesia, were the best predictors of mathematical skills one (Fayol, Barrouillet & Marinthe, 1998) and even three (Marinthe, Fayol, & Barrouillet, 2001) years later. This predictive power of finger gnosia tests appeared to be specific to mathematical performance (and equally for numerical tasks that do or do not rely heavily on finger representation or on magnitude representation) as these tests were not found to be predictive of reading skills (Noël, 2005). Similar observations were made on children with neurodevelopmental spina bifida myelomeningocele: their performance in tests on fine motor skills implying fingers predicted their performance in tasks measuring conceptual competences in counting, whereas their results in visuo-spatial tests were not related to any of their specific number competence (Barnes, Smith-Chant & Landry, 2005). Finally, interactions between fingers and numbers have recently been demonstrated in adults. Interferences between number magnitude and grip aperture were observed in a stimulus–response compatibility paradigm where participants had to make parity judgements on Arabic digits using two responses, a grip closure or a grip opening (Andres, Davare, Pesenti, Olivier & Seron, 2004). Electromyographic recordings revealed that grip closure was initiated faster in response to small digit presentation, whereas grip opening was initiated faster in response to large digits, suggesting some form of congruency between the amplitude of grip aperture and the numerical magnitude of the digits. This interaction was interpreted as reflecting the computation of a magnitude estimate in the dorsal visual pathway where object size is processed to adjust grip aperture. It was further shown that number magnitude calibrated action judgements even if no actual action was required (Badets, Andres, Di Luca & Pesenti, 2007). When asked to judge whether they would be able to grasp a rod lengthways between their thumb and index finger, participants were influenced by the magnitude of irrelevant Arabic numerals priming the rod: they overestimated their grasp when a small number primed the rod and, conversely, underestimated their grasp when a large number primed the rod.

Besides their role in adjusting grip aperture to object size, fingers can be used to quantify or figure numerosities. Middle Age mathematicians, such as Fibonacci (Liber abaci, 1202) and Pacioli (Summa de aritmetica, 1494), mentioned the system of finger gestures developed by tradesmen during Antiquity and described by Beda (672–735) allowing numerosities up to a million to be represented (Butterworth, 1999b; Ifrah 1981). One peculiar aspect of such finger configurations, at least for units up to 10, is that they share non-arbitrary characteristics with the sets of objects they refer to. Indeed, some of these finger configurations directly represent the cardinality of sets of objects or events, and, like other symbolic systems[11] (e.g., Arabic digits), they also convey ordinality and nominality meaning. Children from every human culture spontaneously develop finger-counting strategies to enumerate sets of objects (Fuson, 1988; Ifrah, 1981). This ordinate way of raising fingers allows children to remember not only the cardinality of a set, but also the sequence of counted objects – in other words, ordinality – by establishing a one-to-one correspondence between the raised fingers and the enumerated objects.

Note that finger numeral representations do not disappear when symbolic representations develop and that, under some conditions, they may interact with symbolic representations. We recently showed that specific finger-counting habits actively interacted with Arabic digit processing during a digit-finger mapping task: when asked to identify Arabic digits by pressing the appropriate key with one of their ten fingers, participants produced faster responses when the mapping between the Arabic digits and the fingers matched their own prototypical finger-counting habits than other mappings (Di Luca, Granà, Semenza, Seron & Pesenti, 2006). This study demonstrated that finger-counting strategies might influence the way that numerical information is projected into physical space and induce compatibility effects at the level of motor outputs. Interestingly, the right hand was found to be strongly associated with the small numerosities, whereas the left hand was not preferentially associated with small or large numerosities. This finding was recently replicated in an experiment using transcranial magnetic stimulation to study changes in the corticospinal motor pathways to hands muscles of participants who were performing a parity judgement task (Sato, Cattaneo,

[11] Following the semiotic taxonomy introduced by Peirce (1931), we distinguish three kinds of signs: symbols, indices and icons. In symbolic reference, the link between the sign and the object it refers to is established by convention, as is the case for human languages. In indexical reference, the sign is related to the object by a physical or temporal relation (e.g., some alarm calls used by some animal species with specific reference to predators, magnitudes or directions). In iconic reference, the sign shares some features with its referent. An instance of such signing is cardinal icons (e.g., notches on a stick).

Rizzolatti & Gallese, in press). The results showed an increase in motor-evoked potentials for the right hand only for small numerosities.

However, if recent studies show a link between fingers and number semantics when motor responses are required by the tasks, there is so far no strong evidence of a possible influence of finger numeral representations on number processing in tasks that do not require a motor output. Thus, the idea that the interaction stems from peripheral non-semantic mechanisms cannot be totally excluded. This was tested here. In Experiment 1, participants were presented with photographs of hands showing numerosities in canonical and non-canonical configurations (see Appendix and Method) and they had to name the numerosities expressed. It was hypothesized that canonical finger numeral configurations would be named faster and more accurately than non-canonical ones. Moreover, if these canonical finger numeral configurations do actually convey some semantic meaning, they should induce some semantic effect. In Experiment 2, participants performed a comparison task in which target Arabic digits were primed by masked canonical or non-canonical finger numeral configurations. It was hypothesised that finger numeral configurations could give rise to a cross-notation priming effect (e.g., from finger numeral configurations to Arabic numerals), with a stronger effect for the canonical than the non-canonical primes.

2. EXPERIMENT 1: Assessing canonical finger numeral configurations

Children from every culture spontaneously use their fingers to count and to represent numerosities, and, on some occasions, adults still use their fingers to count for themselves or to communicate with other people about numerosities. However, even for numerosities smaller than ten, there is no unique way of raising or lowering fingers to count. For example, people from Northern Europe and its colonial outposts (United States, Australia, etc.) raise their index, middle and ring fingers to represent the quantity [3], whereas Mediterranean people usually raise their thumb, index and middle fingers (Butterworth, 1999b). Experiment 1 tests whether such typical and familiar use of fingers to express numerosities leads to finger configurations that are detected and named faster than other configurations expressing the same numerosities. We hypothesise that personal finger-counting habits (i.e., the way an individual usually counts from 1 to 10 on his or her fingers) and finger-"montring[12]" habits (i.e., the way an individual usually shows numerosities from 1 to 10 to other people using his or her fingers) would be the best candidates for such canonical configurations.

2.1. Method

2.1.1. Participants

Forty-six right-handed Belgian French-speaking students from the University of Louvain took part in this study for course credits. All the participants had normal or corrected-to-normal vision and were unaware of the objectives of the study. Two of them were excluded because they committed too many errors (more than the overall mean + 3 s.d.) and four because of technical problems. Among the 40 remaining participants, 32 were females, and ages ranged from 19 to 29 (mean ± s.d.: 22.3 ± 2.9 years old).

2.1.2. Apparatus

The experiment was run on a Pentium III PC Dell using the E-Prime software (Schneider, Eschmann & Zuccolotto, 2002) and equipped with a 17" CRT screen (1024 x 768 resolution). Response latencies were collected through a microphone and response accuracy was assessed by the experimenter.

[12] From the Latin *monstrare,* meaning *to show to others*. The way of raising fingers to show numerosities to other people (e.g., using the index and middle fingers for the quantity [2], which differs from counting to [2] using the thumb and index finger).

2.1.3. Stimuli

The stimuli were photographs taken with a digital Leica RD-1 camera (5.1 Mpixels), showing the palm or the back of the right hand of a person at a distance of 50 cm, with the hand at a distance of 20 cm from a black background. All photographs were of the same hand and were manually edited to equilibrate colour and luminance, and to replace the natural background by a black artificial background (32 cm large, 19.54 cm high) eliminating all residual shadows; they were then flipped horizontally to create the left-hand stimuli. The final size of the hand on the screen matched the real size of a hand.

The photographs of the hand represented numerosities from 0 to 10, with palm and back photographs. Numerosities from 1 to 5 were represented by one hand only (with 1 to 5 fingers raised) and the other hand closed[13]; numerosities from 6 to 10 were represented by the same finger configurations, with all five fingers on the other hand raised. Ninety-two different configurations were used: one finger configuration for numerosities 0 (both hands closed) and 10 (both hands open), two for numerosity 5 (left or right hand open, the other closed), ten for numerosities 1, 4, 6 and 9 (five possible configurations for each numerosity, starting with the left or the right hand), and twelve for numerosities 2, 3, 7 and 8. For these numerosities, the configurations were selected by counterbalancing the distances between the raised fingers (see Fig. 3-1). Configurations were the same for the back and the palm photographs.

[13] Configurations where both hands are used to express numerosities less than 5 were avoided. To the best of our knowledge, there are no reports of finger-counting systems using two "incomplete" hands: all systems use all the fingers of one hand and only then is the other hand brought into use (Butterworth, 1999b; Ifrah, 1981).

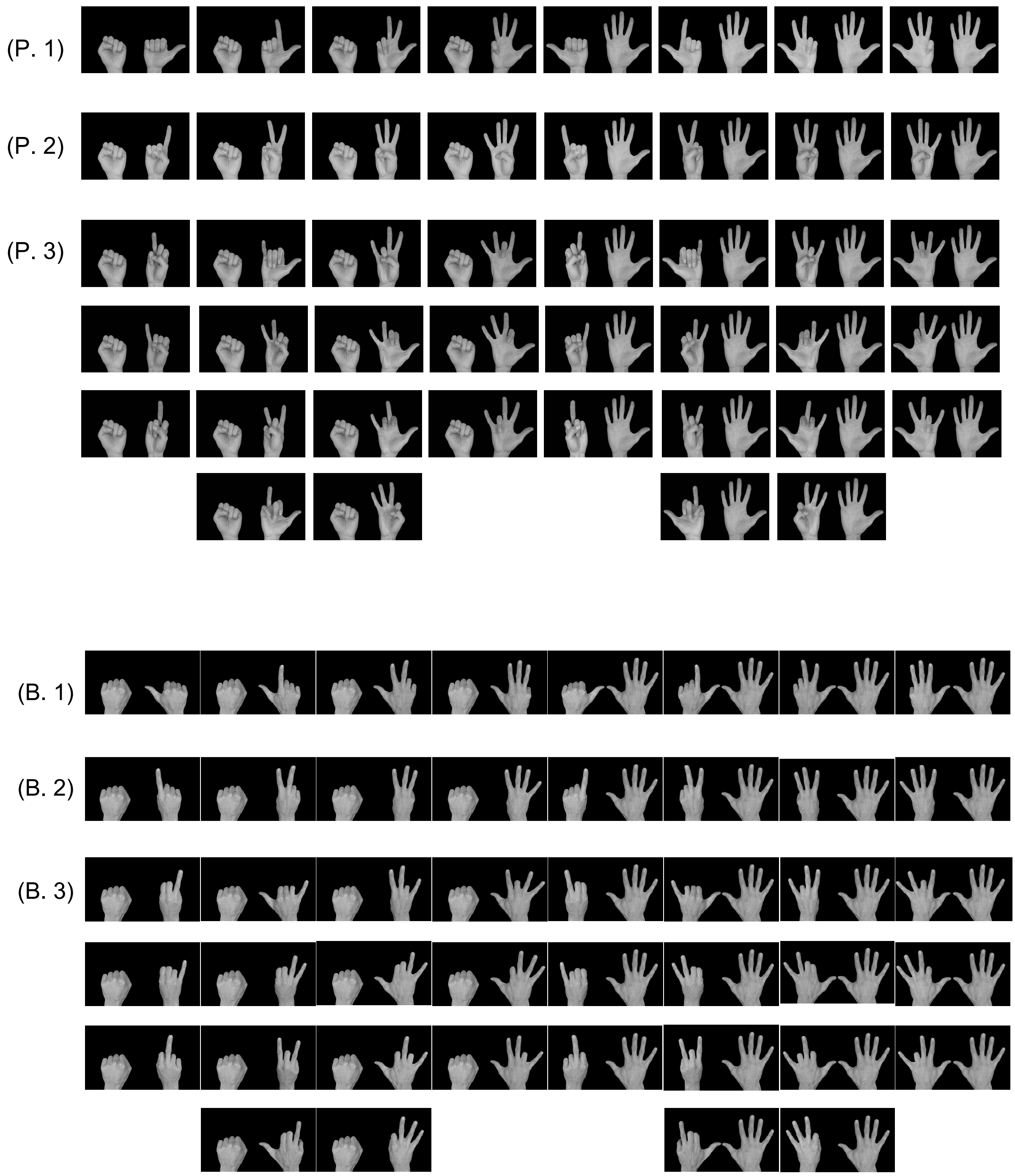

Figure 3-1. Photographs representing (1) Counting, (2) Montring, and (3) Other finger numeral configurations for palms (P) and backs (B) starting with the right hand. Experiment 1 also used the same configurations starting with the left hand. Experiment 2 used the first row of P3 as "Other" configurations.

2.1.4. Procedure

A trial constituted a fixation cross lasting randomly between 500 and 1100 ms, followed by a photograph of hands lasting for 250 ms, and ending with a completely purple screen. Each block contained 92 trials corresponding to the 92 configurations. The sequence of stimuli within the blocks was pseudo-randomly determined (the same numerosity was not presented more than twice, and no conventional sequence of numbers was allowed). Each participant was presented with 6 blocks of palm photographs or 6 blocks of back photographs of hands. The task was to name the numerosity expressed by the hands; instructions emphasised the necessity to respond as quickly as possible while keeping errors to a minimum.

Since initial letter and word length differences can affect latencies recorded through a microphone (Kessler, Treiman & Mullenix, 2002), a naming task was also administrated as a baseline control condition after the six blocks with hands. A number-word from *zéro [0]* to *dix [10]* was presented for 3000□ms at the centre of the screen; participants had to remember it and say it aloud each time a cross appeared. Each of the eleven number-words was named 8 times in a row at random intervals from 500 to 1100 ms, which resulted in a control block of 88 trials.

At the end of the experiment, the participants were questioned on their personal finger-counting and finger-montring habits. All the participants reported starting to count with the right hand, from thumb to little finger, from 1 to 5, and then using the left hand, from thumb to little finger, for the numbers from 6 to 10; moreover, they all started montring with the right hand, from the index to little finger, from 1 to 4, and then raising the thumb for 5. Numerosities from 6 to 10 were shown with the left hand, from index to little finger, 6 to 9, and finally the thumb, 10, with the right hand open.

2.1.5. Preliminary control analysis

A preliminary analysis was carried out to assess possible differences between verbal numerals in the control naming task. No naming errors were made (mean percentage of unreliable errors due to coughs, noise or microphone failures: 1.2%; no speed/accuracy trade-off calculated). A one-way within-subject analysis of variance (ANOVA) performed on the response latencies (RLs) showed naming differences between the eleven verbal numerals (mean ± s.d. RL: *zero*: 426±54ms; *one*: 412±55ms; *two*: 437±63ms; *three*: 397±64ms; *four*: 427±70ms; *five*: 434±54ms; *six*: 436±58ms; *seven*: 436±51ms; *eight*: 430±59ms; *nine*: 433±67ms; *ten*: 447±57ms; $F(1,38) = 3{,}697$; $p < .001$). For this reason, the RLs in the experimental task were corrected prior to analyses by subtracting the median RL for each participant (observed in his or her own control task) for each corresponding verbal numeral. In all subsequent analyses, corrected RLs were converted to 1/RLs to avoid any problem of asymmetric distribution. Only the latencies of correct responses were analysed.

2.2. Results

Unreliable responses due to coughs, noise or microphone failures (0.175%) were not included. Overall, the participants made 1371 errors out of 21120 trials (6.5%). There was no speed/accuracy trade off as indicated by the positive correlation between RLs and the number of errors ($r = .182$; $p<.05$), computed over 120 pairs, and demonstrating that faster RLs were linked to lower errors rates

2.2.1. Latencies

The whole set of trials was divided into three categories: counting (P.1 and B.1), montring (P.2 and B.2) and other configurations (P.3 and B.3; see Procedure and Fig. 3-1) involving 16, 16 and 56 configurations respectively. Numerosities 0, 5 and 10 were not included in this analysis because they were not balanced across categories (no non-canonical configurations used). To test possible differences in the way these categories convey numerical information, a two-way ANOVA was carried out, with the configuration (Counting, Montring, Others) as a within-subject variable, and the side of hand (Back, Palm) as a between-subject variable. This ANOVA showed a main effect of configuration (mean ± s.d. RL for Counting: 309±74 ms; Montring: 300±77 ms; Others: 356±84ms; $F(2,76) = 21.896$, $p<.001$). T-tests revealed no difference between Counting and Montring configurations ($t(40) = 1.605$, $p = .117$), but showed that both differed from the Others configuration ($t(40) = -9.043$, $p<.001$ for Counting and $t(40) = -12.519$, $p<.001$ for Montring). Despite a tendency for the palms to be responded to slightly faster, no statistical main effect of hand side was found (mean ± s.d. RL for Palms: 304±75ms; Backs: 339±82ms; $F(1,38) = 2.093$, $p<.15$). A two-way interaction between configuration and side of hand was found. For the back hand photographs, the RLs had the same profile as above, with no significant differences between Counting and Montring (mean ± s.d. RL for Counting, 316±77ms; Montring 326±83ms; $t(20) = 1.317$, $p = .203$), whereas both differed from Others (mean ± s.d. RL for Others: 376±86ms; $t(20) = -8.253$, $p<.001$ for Counting and $t(20) = -9.292$, $p<.001$ for Montring. For the palm hand photographs, on the contrary, Counting and Montring configurations differed (mean ± s.d. RL for Counting: 302±71ms; Montring 275±71ms; $t(20) = 4.729$, $p<.001$), and again both differed significantly from the Other configurations (mean ± s.d. RL for Others: 337±83ms; $t(20) = -5.253$, $p<.001$ for Counting and $t(20) = -8.821$, $p<.001$ for Montring).

2.2.2. Errors

The same ANOVA applied to errors showed a main effect of configuration (error rate for Counting: 192/3840 [5.00%]; Montring: 182/3840 [4.74%]; Others: 997/13440 [7.42%]; $F(2,76) = 21.896$, $p<.001$). As for RLs, the Counting and Montring configurations did not differ from each other ($t(40) = .539$, $p=.593$), but both differed from Others ($t(40) = -5.605$, p<.001 for Counting; t(40) = –6.558, p<.001 for Montring). A main effect of hand side was found: responses to palm photographs were less prone to errors than responses to back photographs (F(1,38) = 6.470, p<.01). No interaction was observed (F(2,76) = .204, p=.784).

2.3. Discussion of Experiment 1

Fingers can be used to directly express numerosities up to [10], and various finger configurations can express each numerosity, some of them being more frequently used in daily-life activities. In Experiment 1, participants had to name finger configurations conforming either to their own finger-counting or finger-montring or to other finger configurations. The results showed that there was no difference between finger-counting and finger-montring configurations but that both were identified more quickly and gave rise to fewer errors than other configurations. Both could thus be considered as *canonical* numerical finger configurations. However, this could be a mere perceptual effect: being more familiar to the participants, counting and montring configurations might be visually processed more quickly than other less familiar configurations, without there being any difference in terms of further activation of their possible semantic meaning. Such potential semantic differences between canonical and non-canonical configurations were tested in Experiment 2.

3. EXPERIMENT 2: Numerical priming with finger numeral configurations

Whereas cross-notation priming effects were found in word reading primed by pictures but not the reverse (Glaser, 1992; MacLeod, 1991), in the numerical domain, cross-notation priming effects have been observed with both Arabic primed by verbal numerals and verbal primed by Arabic numerals (Naccache & Dehaene, 2001; Reynvoet, Brysbaert & Fias, 2002). Such priming effects are usually interpreted as indicating semantic access even when the primes are not processed consciously. To test whether any numerical semantic meaning was conveyed or accessed by canonical finger numeral configurations, Experiment 2 used a standard comparison task with Arabic digits primed unconsciously by canonical and non-canonical finger numeral configurations. If the same priming effect were observed with canonical and non-canonical configurations, this would indicate that finger numeral configurations have or give access to a semantic meaning linked to numerosity but this would not be specific to canonical configurations as this semantic effect would take place with non-canonical configurations too; canonical configurations would simply be processed faster. On the contrary, if a priming effect is observed with canonical primes only, or with both types of primes but more strongly for canonical than non-canonical ones, this would indicate semantic differences going beyond mere encoding processes.

However, an alternative non-semantic account has been proposed for such unconscious semantic processing in word reading – the *direct motor specification hypothesis* (DMS; Neumann & Koltz, 1994; but see also Eimer & Schlaghecken, 1998; Damian, 2001). According to this hypothesis, pseudo-semantic priming could appear when the same set of stimuli is used as primes and targets. In such circumstances, participants would associate each target or fragments of it (e.g., sub-strings of letters in a word) with the correct response and generalise this association to any visually close stimulus, even one that is processed unconsciously, without resorting to semantic access. In the present experiment, the problem could appear when the same numerosities are used as primes and targets. Even if targets and primes do not share visual features (Arabic numerals *vs*. finger configurations), the possibility that repeatedly processing the targets could unconsciously direct the participants' attention to the corresponding numerosities, and hence to the corresponding finger numeral configurations, cannot be excluded. To disentangle the semantic and non-semantic interpretations, two sets of primes can be used (Naccache & Dehaene, 2001): one containing primes that can also appear consciously as targets (the *old primes set*), the other restricted to primes that never appear as targets (the *new primes set*). If the priming effect stems from a true unconscious semantic processing, then it will generalise to the new primes set.

3.1 Method

3.1.1. Participants

One hundred right-handed Belgian students from the University of Louvain took part in this study for course credits. All the participants had normal or corrected-to-normal vision and were unaware of the objectives of the study; none had participated in Experiment 1. From these participants, 30 took part in two pilot experiments investigating prime visibility (see Procedure, below) and 70 in the main experiment. Seven of these were excluded because they made too many errors (more than overall mean + 3 s.d.) and six because they were able to process the primes (less than 25% errors in the forced choice task – see Procedure). Among the 57 remaining participants, 32 were female, and ages ranged from 19 to 23 (mean ± s.d. age: 21.3±1.6 years old).

3.1.2. Apparatus

The same apparatus was used as in Experiment 1.

3.1.3. Stimuli

The targets were the Arabic digits 1, 4, 6 and 9. The primes could be either numerical or neutral. Numerical primes were the same hand photographs as used in Experiment 1, representing numerosities from [1] to [9], excluding [5] in a canonical (i.e., Montring; see P.2 in Fig.1) or non-canonical (i.e., Others; see P.3 in Fig.1) way. Numerosities [1], [4], [6] and [9] formed the old primes set as they were presented both as primes and targets; numerosities [2], [3], [7] and [8] formed the new primes set as they were never used as targets and were thus never consciously presented. Palm configurations were used as they appeared slightly faster and were less prone to errors than back photographs in Experiment 1; for the same reason, montring configurations were used as canonical primes. The neutral prime was constituted by a scrambled hand photograph created by dividing the photograph of two hands with the ten fingers raised by a grid of 20 x 15 lines, yielding 300 squares that were randomly redistributed inside the frame in such a way that the hands could no longer be identified (Fig. 2). Forward and backward masks were identical to the neutral prime. Excluding the neutral prime trials, half the trials were congruent (both prime and target yielded the same response) whereas the other half were incongruent (prime and target produced different responses).

3.1.4. Procedure

In each trial, the following sequence of events appeared at the centre of the screen: (1) a scrambled photograph lasting for 68 ms used as a forward mask; (2) the prime lasting for 68 ms; (3) a scrambled photograph lasting for 68 ms used as a backward mask; and (4) the target lasting for 200 ms (Fig. 3-2). The participants had to decide whether the target was larger or smaller than five by pressing (with one finger of each hand) one of two response keys positioned 17 cm from each other on a standard keyboard. The instructions emphasised the need to respond as quickly as possible while keeping errors to a minimum.

Every participant was presented with 8 blocks of 72 trials composed of each target preceded twice by each numerosity (1 canonical and 1 non-canonical configuration), and twice by a neutral prime. The sequence of stimuli within the blocks was pseudo-randomly determined (the same target was presented no more than twice, the same configuration was presented no more than twice, and the same response was never required more than four times in succession). In the first four blocks, the answer *smaller than five* was assigned to the left-hand and the answer *larger than five* to the right-hand key; the answer keys were then reversed for the last four blocks. This order was counterbalanced across participants. Two practice blocks of 16 trials were administrated before the first and fifth blocks, and were not included in the analyses. After the 8 blocks, the participants were fully informed of the nature of the primes and were tested with a block assessing prime visibility as in the second pilot experiment (see below).

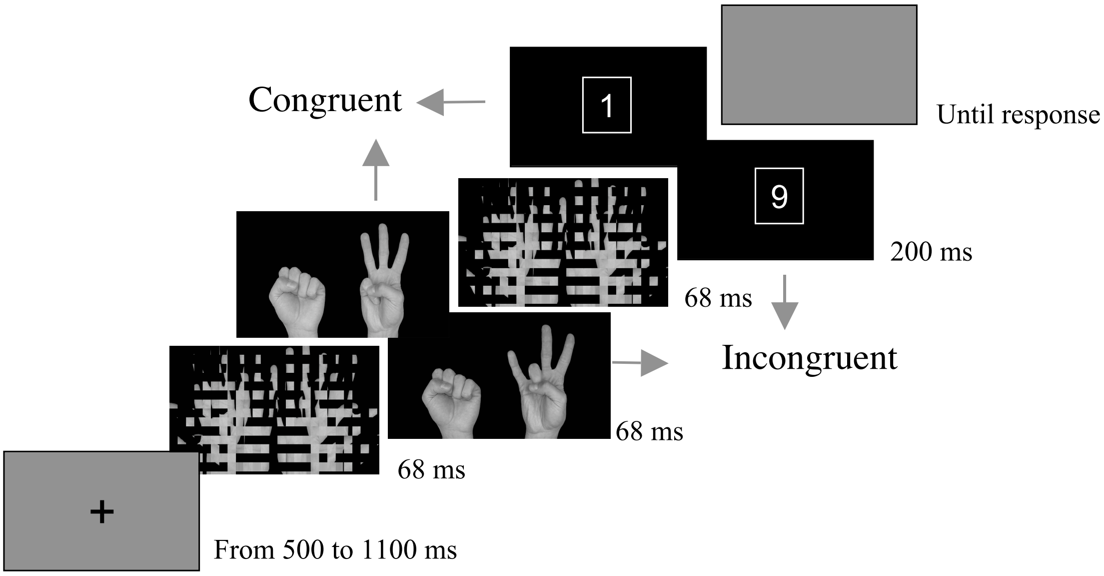

Figure 3-2. Sequence of events. Congruent vs incongruent and canonical vs non-canonical primes from the new set of primes are illustrated.

3.1.5. Assessment of prime visibility

In the main experiment, participants were not told about the nature of the primes but were informed that each trial would be introduced by a "neutral visual signal". To ensure that the timing used in the experiment (based on verbal and Arabic numerals processing times as in Koechlin, Naccache, Block & Dehaene, 1999) really made the finger configuration primes undetectable, two pilot experiments were run. In the first, a forced-choice detection task was run on the masked signals. Ten participants were informed of the nature of the masked signals (real or scrambled pictures of a hand presented between two masks) and instructed to decide by pressing one of two keys whether or not a photograph of hands was presented; masks and stimuli lasted for 68 ms. A single block of 64 trials was run with 16 canonical, 16 non-canonical, and 32 scrambled stimuli. The analyses showed that participants were able to distinguish between real and scrambled hand photographs in about 75% of the trials (162/640 errors; $\chi^2(2) = 316$, $p<.001$). However, participants reported that they were able to detect the presence of a hand only because the left and right top corners of the photographs were completely black, which was not the case for the scrambled photographs. When further questioned, they declared themselves unable to report the numerosities that had been displayed.

In the second pilot experiment, 20 participants were informed of the nature of the masked signal and had to decide if the masked numerosity was larger or smaller than five. Each participant was exposed to 1 block of 64 stimuli, with 32 canonical and 32 non-canonical photographs of hands displaying numerosities from [1] to [9], excluding [5], with both masks and stimuli lasting for 68 ms. Overall, participants made 633 errors on the 1280 stimuli (an error rate of 49.5%). A chi-square analysis confirmed that the distribution of responses was essentially random ($\chi^2(8) = 1.23$, $p=.654$). An ANOVA run on error rate with the variables size (Small, Large), configuration (Canonical, Non-canonical) and numerosity (Small: [1], [2], [3] and [4], Large: [6], [7], [8] and [9]) showed no significant differences between large and small numerosities ($F(1,19) = .120$, $p=.732$), between canonical and non-canonical primes ($F(1,19) = .072$, $p=.791$), or between numerosities ($F(3,57) = .034$, $p=.991$) (see Table 3-1a).

Prime visibility was tested on the 57 participants in the main experiment to be sure that the primes were still undetectable after the 8 experimental blocks. Overall, the participants made 1793 errors on the 3648 stimuli (an error rate of 49.2%). A chi-square analysis confirmed that they responded randomly ($\chi^2(8) = 3.281$, $p = .236$). A 3-way ANOVA with size, configuration and numerosity as within-subject variables showed that there were no significant differences between large and small numerosities (F(1,56) = .773, p=.383), between canonical and non-canonical primes (F(1,56) = .134, p=.716) or between numerosities (F(3,168) = .511, p=.675) (see Table 3-1b).

(A)

	canonical		non-canonical	
	err	%	err	%
1	37	*46,25*	39	*48,75*
2	42	*52,5*	38	*47,5*
3	41	*51,25*	41	*51,25*
4	40	*50*	42	*52,5*
6	42	*52,5*	39	*48,75*
7	39	*48,75*	41	*51,25*
8	36	*45*	39	*48,75*
9	38	*47,5*	39	*48,75*
	39,38	*49,22*	39,75	*49,69*

(B)

	canonical		non-canonical	
	err	%	err	%
1	108	*47,37*	117	*51,32*
2	106	*46,49*	116	*50,88*
3	116	*50,88*	115	*50,44*
4	117	*51,32*	118	*51,75*
6	107	*46,93*	118	*51,75*
7	114	*50,00*	106	*46,49*
8	105	*46,05*	110	*48,25*
9	113	*49,56*	107	*46,93*
	110,75	*48,57*	113,38	*49,73*

Table 3-1. Number of errors and error rates during (A) forced-choice detection task of the first pilot study and during (B) forced-choice comparison task of second pilot study.

3.2. Results

In all the analyses, RLs were converted to 1/RLs to avoid any problem due to asymmetric distributions. Only the latencies of correct responses were analysed.

3.2.1. Magnitude priming effect

Overall, there were 527/14592 (3.61%) errors for the canonical, 488/14592 (3.41%) errors for the non-canonical, and 130/3468 (3.56%) errors for the neutral trials. There was no speed/ accuracy trade-off (as indicated by the absence of a negative correlation between RLs and number of errors [r = +.019; ns], computed over 684 pairs).

An ANOVA with the type of prime (Canonical, Non-canonical, Neutral), the target distance (Close to 5: targets *4* and *6*, Far from 5: targets *1* and *9*), and the target response (Smaller than 5, Larger than 5), was carried out to test whether there was a global priming effect of numerical magnitude[14]. A main effect of the type of prime was found (mean ± s.d. RL for Canonical: 513±81ms; Non-canonical: 514±86ms; Neutral: 523±91ms; $F(2,110) = 8.678$; $p<.001$): targets introduced by neutral primes were responded to more slowly than those introduced by canonical ($t(57) = 3.149$, $p<.005$), and non-canonical ($t(57) = 3.118$, $p<.005$) primes which did not differ from each other ($t(57) = -0.637$, $p=.527$). A main effect of target distance was also found (mean ± s.d. RL for Close: 544±98ms; Far: 489±74ms; $F(1,55) = 137.647$, $p<.001$): participants responded faster to targets which were *far from 5* than to targets *close to 5*. No reliable main effect of response was observed (mean ± s.d. RL for Smaller: 520±88ms: Larger: 513±84ms; $F(1,55) = 3.04$, $p=.09$). These main effects were qualified by two interactions. Firstly, prime and target responses interacted ($F(2,110) = 9.406$, $p<.001$): the response *smaller than 5* was given more slowly when introduced by the neutral prime than when introduced by canonical ($t(57) = 4.294$, $p<.001$) and non-canonical ($t(57) = 3.76$, $p<.001$) primes, whereas there were no significant differences according to prime for the *larger than 5* response times ($t(57) = .788$, $p>.4$ for neutral and canonical primes; $t(57) = .963$, $p>.3$ for neutral and non-canonical primes; see Fig. 3-3). Secondly, a 3-way interaction

[14] Variables linked to the primes (e.g., distance from prime to target, distance from prime to 5) could not be entered into this analysis as they did not exist for the trials using neutral primes.

between prime, target response and target distance was found ($F(2,110) = 4.188$, $p<.05$): for the *close to 5* targets, the response *smaller than 5* occurred more slowly when it was preceded by a neutral prime than when it was preceded by a canonical ($t(57) = 3.953$, $p<.001$) or non-canonical ($t(57) = 3.534$, $p<.001$) prime, whereas there were no significant differences in the *larger than 5* response times according to the prime ($t(57) = -196$, $p>.8$ for neutral and canonical primes; $t(57) = -.327$, $p>.7$ for neutral and non-canonical primes); for the *far from 5* targets, neither the *smaller than 5* or the *larger than 5* RLs differed according to the prime (Fig. 3-3 and 3-4).

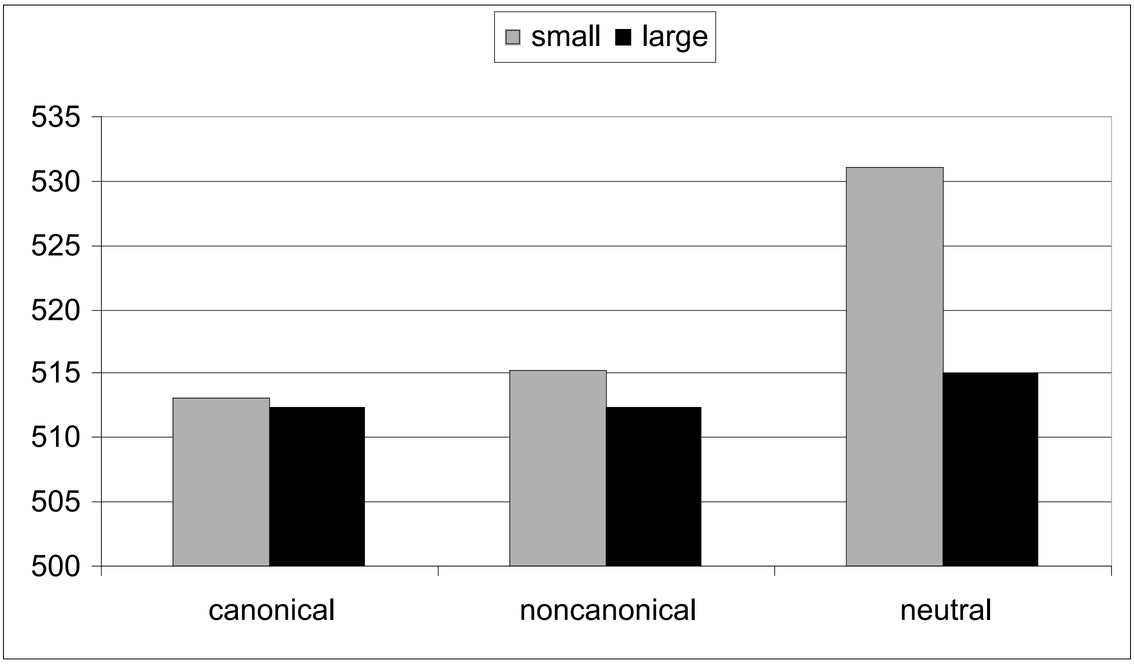

Figure 3-3. Mean respons latencies (RLs) as a function of Prime (canonical, noncanonical and neutral) and Target response (grey: response small; black: response large).

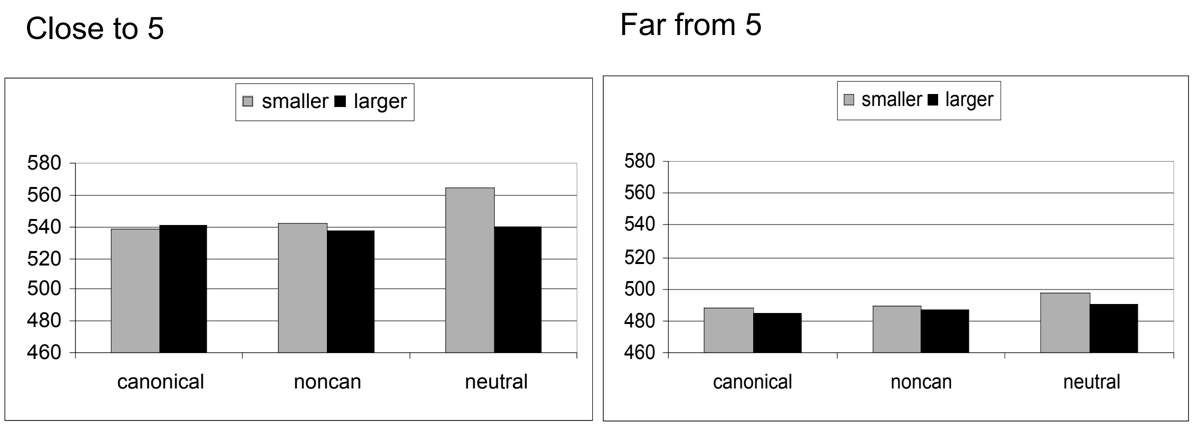

Figure 3-4. Mean respons latencies (RLs) as a function of Prime (canonical, noncanonical and neutral), Target response (grey: response small; black: response large), and Target distance (Close to 5: numerosities 4 and 6; Far from 5: numerosities 1 and 9).

The same ANOVA applied to the errors showed a main effect of target response: participants produced fewer errors for *larger than 5* than for *smaller than 5* targets (3.07±3.81% compared to 3.99±4%; F(1,56) = 8.855, p<.005). A main effect of target distance was also found: participants produced fewer errors for *far from 5* than for *close to 5* target distances (1.3±2.2% compared to 5.8±5.6%; F(1,56) = 115.63, p<.001). No main effect of the type of prime was found (F(2,112)<1), but a prime by target response interaction (F(2,112) = 3.467, p<.05) showed that, for the response *smaller than 5,* participants produced more errors when targets were introduced by the neutral prime than when they were introduced by non-canonical primes (4.5±5.5% compared to 3.3±3.5%; t(57) = 1.892, p<.06) but not than when introduced by canonical primes (3.9±3.6%; t(57) = 1.108, p>.2); for the response *larger than 5* there was no difference between primes. Prime and target distance were found to interact (F(2,112) = 4.908, p<.01): with *far from 5,* the participants produced fewer errors with neutral than with non-canonical primes (0.9±2.5% compared to 1.6±2.3%; t(57) = 2.838, p<.01), whereas there was no difference between canonical and non-canonical primes (t(57)= –1.249, p = .217), nor between canonical and neutral primes (t(57) = 1.676, p = .1); for *close to 5*, there was no difference between primes. Target distance and target response also interacted (F(1,56) = 12.945, p<.001): with *close to 5*, participants produced fewer errors for *larger than 5* than for *smaller than 5* targets (t(57) = 3.652, p<.001), whereas for the *far from 5* responses there was no difference between *larger than 5* and *smaller than 5* targets (t(57) = –.807, p>.4). Finally, a prime by target response by target distance interaction (F(2,112) = 6.069, p<.005) showed that for the *close to 5* targets, more errors were made on the *smaller than 5* responses introduced by neutral primes than those introduced by canonical (t(57) = 2.569, p = .01) or non-canonical (t(57) = –3.051, p<.005) primes. The error rates for responses *larger than 5* did not differ across primes for the *close to 5* targets, and for the *far from 5* targets, neither the *smaller than 5* nor the *larger than 5* responses differed across primes.

3.2.2. Congruency effects

To test whether the priming effect observed was truly semantic and to assess potential differences between the two types of numerical primes, an ANOVA was run with the type of prime (Canonical, Non-Canonical), the congruency (Congruent: prime and target yielding the same response; Incongruent: prime and target yielding different responses), and the primes set (Old: 1, 4, 6 and 9, New: 2, 3 ,7 and 8) as within-subject variables.

A main effect of congruency was found: congruent trials were responded to faster than incongruent ones (mean ± s.d. RLs for Congruent: 510±79ms; Incongruent: 518±84ms; F(1,56) = 28.562; p<.001). No main effect of the set (F(1,56) = 1.104, p = .318) or of the prime (F(1,56) = .318, p=.575) was found. However, the type of prime and congruency interacted (F(1,56) = 4.378, p<.05): the congruent trials were responded to faster than the incongruent ones, but this effect was stronger for the canonical (mean ± s.d. for Congruent: 508±73 ms; Incongruent: 519±85 ms; t(57) = –4.598, p<.001) than for the non-canonical primes (mean ± s.d. for Congruent: 512±85 ms; Incongruent: 517±83 ms; t(57) = –2.573, p = .001) (Fig. 3-5). Finally, prime, congruency and prime set interacted (F(1,57) = 3.865, p = .05): for the old primes set, RLs were shorter for congruent trials than for incongruent ones for both canonical (mean ± s.d. RLs for Congruent: 507±74ms; Incongruent: 516±81ms; t(57) = 3.136, p<.005) and non-canonical primes (mean ± s.d. RLs for Congruent: 510±84ms; Incongruent: 519±88ms; t(57) = 3.254, p<.005), whereas for the new primes set this was true for the canonical primes (mean ± s.d. RLs for Congruent: 509±73ms; Incongruent: 523±88ms; t(57) = 3.741, p<.001), but not for the non-canonical ones (t(57) = .312, p=.756) (Fig. 3-6).

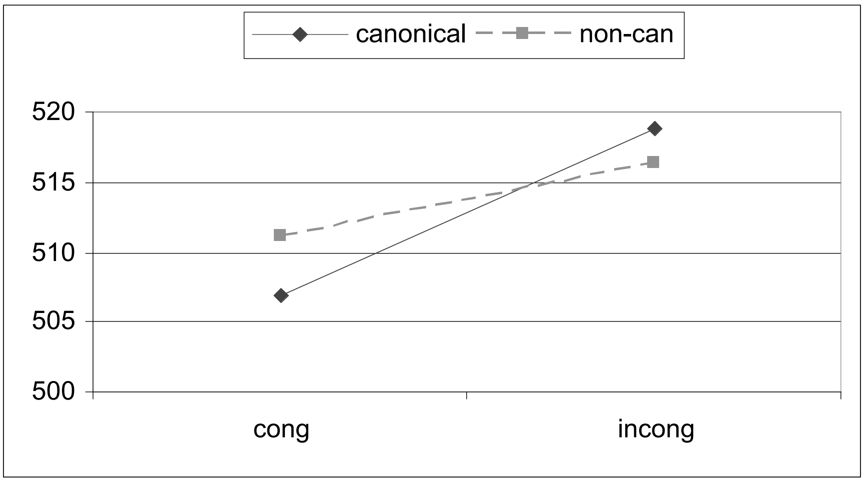

Figure 3-5. Mean response latencies (RLs) as a function of Prime and Congruency (diamonds: canonical primes; squares: noncanonical primes).

OLD set NEW set

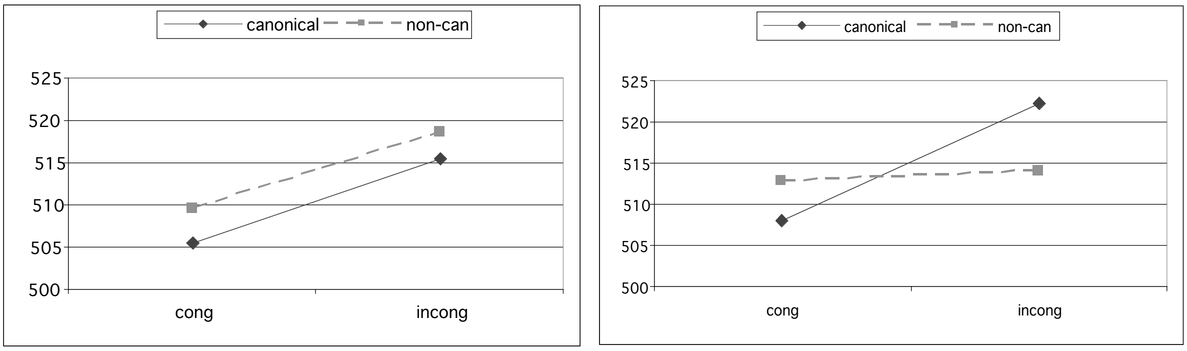

Figure 3-6. Mean response latencies (RLs) as a function of Prime, Congruency and Primes set (diamonds: canonical primes; squares: noncanonical primes; Old set; numerosities presented as targets; New set; numerosities never presented as targets).

The same ANOVA run on error rate only revealed a main effect of congruency: participants made fewer errors in the congruent than the incongruent trials (mean ± s.d. of % of errors: Congruent: 3.24±3.09%; Incongruent: 3.71±3.33%; $F(1,56) = 8.405$, $p<.005$). No other main effects or interactions were found.

3.3. Discussion of Experiment 2

Experiment 2 investigated the extent to which a comparison task using Arabic digits is semantically mediated when the semantic pathway is pre-activated by a subliminal prime consisting of photographs of hands expressing numerosities. This experiment replicated several classical effects in number comparison tasks. First, a semantic distance effect (Moyer & Landauer, 1967) was found: responses were faster and less error prone as the distance between the targets and the standard increased. Next, a lexical-marking effect[15] (Parkman, 1971) was detected: fewer errors were made with the response *larger than 5* than with the response *smaller than 5*. Finally, the target distance by target response interaction on errors corresponded to the asymmetry around the standard usually observed with latencies (Dehaene, Dupoux & Mehler, 1991; Hinrichs, Yurko & Hu, 1981): fewer errors were made with *larger than 5* than with *smaller than 5* targets close to the standard, whereas far from the standard there were no differences.

Experiment 2 also revealed a strong cross-notation effect of numerical primes: processing the Arabic targets was slowed down after non-numerical primes compared to canonical and non-canonical numerical primes. Interestingly, this effect was present for small magnitudes but not for large ones, and only for the magnitude closest to the standard (i.e., the Arabic target *4*), that is, the most difficult comparison to perform. This can be explained if the non-numerical primes have been unconsciously processed as non-specific but large numerosities. This pre-activation of "a lot of fingers" would make the response *smaller than five* for target 4 slower. Importantly, when canonical and non-canonical primes were directly compared, that is when this possible interfering effect of the neutral prime could not take place, the responses were faster and less error prone when primes and targets were congruent (i.e. both smaller or both larger than 5). This main effect of congruency was qualified by the type of prime, with large and small primes pre-activating large and small targets respectively, particularly in the canonical configurations[16]. This extends previous findings on cross-notation

[15] It is known that, in bipolar adjective couples, the two adjectives are not equivalent. One of them can be used for both sides of the continuum of judgement (the *unmarked* adjective) whereas the other cannot (the *marked* adjective). In linguistic models, the lexically unmarked sense is stored and retrieved more quickly than the marked one because of simpler memory coding (Clark & Stafford, 1969). For example, in the *long-short* couple, *long* is related to the name of the whole continuum *(length)* and is thus processed more efficiently, yielding the observed effect.

[16] The size of the prime (small: *1* to *4* *vs*. large: *6* to *9*) was introduced with the type of prime (canonical *vs*. non-canonical) and the target size (small: *1* and *4* *vs*. large: *6* and *9*) as within-subject variables in a separate ANOVA not fully reported here. Prime size had no main effect ($F(1,56) < 1$), but it interacted with target size ($F(1,56) =$

priming with Arabic, verbal, and dot numerals (Naccache & Dehaene, 2001; Reynvoet et al., 2002; Roggeman, Verguts & Fias, 2007).

The most critical finding, however, is that the congruency effect was present only in the old primes set for non-canonical primes, whereas it was present in both the old and the new primes sets for the canonical ones. In other words, the priming effect was only found to generalise to novel magnitudes that had never been presented as targets and thus never consciously processed for canonical primes. In addition to the fact that primes and targets were presented in two different notations, and therefore could not belong to the same input system, this interaction excludes the possibility that the present results could be explained by a mere associative relation within a non-semantic form-recognition system (i.e., the DMS hypothesis). This might be the case for non-canonical configurations in which the primed numerosities [1], [4], [6] and [9] might have been activated by the corresponding target magnitudes, and where large numerosities could have been perceived as “a lot” but not precisely quantified. On the contrary, our finding indicates a genuine semantic component of the priming effect (for a similar view, see Naccache & Dehaene, 2001). This conclusion holds even if canonical configurations are actually processed faster – which is probably the case. The fact that non-canonical configurations primed Arabic digits better than non-numerical primes shows that they were presented for long enough for them to be processed unconsciously, and excludes processing speed as the only source of the semantic difference between canonical and non-canonical configurations.

35.999, $p<.001$): responses to the small targets were faster when introduced by small than large primes ($t(56) = -3.771$, $p<.001$) and responses to the large targets were faster when introduced by large than small primes ($t(56) = 4.243$, $p<.001$). Moreover, there was a marginally significant interaction between the three variables ($F(1,56) = 2.977$; $p=.089$) showing that the above described pattern held for canonical primes only: for non-canonical primes, small targets were not better primed by small than large primes ($t(56)=-.79$, $p=.433$).

4. GENERAL DISCUSSION

Representing numerosity on fingers and finger-counting strategies have been extensively studied in children but little is known about the use of fingers to represent numerosities in adults. Experiment 1 showed that young adults named numerical finger configurations faster when they conformed to their own finger-counting and finger-montring habits than when they did not. We suggest that such configurations can thus be considered as canonical numerical finger configurations, stored in long-term memory. This extends our previous findings that, when asked to identify Arabic digits by pressing appropriate response keys with one of their ten fingers, young adults responded faster when the finger-digit mapping matched their own prototypical finger-counting habit (Di Luca et al., 2006). It is worth noting that, although the experimental requirement to use all ten fingers to answer might have induced or strengthened the observed finger-digit links in that study, this criticism does not hold here as only a verbal output was required. These two studies nicely highlight the dual function and nature of finger numeral configurations: the motor aspect revealed finger-counting configurations when an explicit manual response was required (Di Luca et al., 2006), while the visual aspect revealed finger-montring configurations when no manual response was required.

Experiment 2 shows that this facilitation of the naming of canonical configurations is not a mere perceptual effect (as might be the case if canonical configurations were named faster just because they were more familiar to the participants, and so visually processed more quickly than other, less familiar, configurations)[17]. Numeral finger configurations, used as unconsciously presented primes, speeded up numerical comparative judgements of Arabic

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[17] A complementary regression analysis shows that the number of raised finger explains about 70% of the variance of the RLs whereas the subjective and objective visual features of the stimuli explain only a small part of the variance (see Appendix of Chapter 3). Chapter 4 aims at assessing more formally the idea of a possible visuo-perceptual difference.

number targets. Participants responded faster and made fewer errors with numerical than non-numerical primes, and when primes and targets were congruent (i.e., leading to the same response). Importantly, this priming effect generalised to novel, never consciously seen, primes for canonical configurations but not for non-canonical ones. Whether this priming effect comes from a direct activation of finger numerical representation from Arabic numerals (e.g. the Arabic numeral *4* activating both finger configurations 4 and 3), is mediated by an indirect spreading of activation through the semantic magnitude representation (e.g. the Arabic numeral *4* activating the semantic magnitude [4] which in turn activates finger configurations 4 and 3), or arises from the finger configurations themselves (e.g. finger configuration 4 activating finger representation 3) cannot be determined here, but the critical point is that this direct or indirect semantic spreading does not take place with non-canonical configurations. This clearly supports the idea that, beyond possible processing speed differences, canonical configurations automatically convey or give access to number semantics whereas non-canonical ones do not, and require explicit elaboration to access semantics.

Taken together, these two experiments show that finger numeral configurations related to finger-counting or finger-montring have a specific status, and behave as prototypes in long-term memory. Such finger numeral configurations are not only used by children during numerical learning or by a few non-literate groups because they lack elaborated symbolic notations. On the contrary, finger numeral configurations contribute to number semantics and are still meaningful in educated adults. In addition to strictly anatomical considerations, this may be another reason why acalculia and finger agnosia are jointly observed in Gerstmann's syndrome. Interrestingly, numbers and fingers appear to be related through both continuous magnitude and discrete numerosities processing. Indeed, it has recently been shown that numbers and fingers are semantically linked through numerical magnitudes and goal-directed finger movement interactions (Andres et al., 2004; Badets et al., 2007), which basically means using fingers to represent continuous magnitudes through grip aperture adjustment. Here and in our previous work (Di Luca et al., 2006), we demonstrate a second type of semantic interaction, where fingers are used to represent discrete numerosities related to discrete entities. Even if limited in their extend, finger configurations guarantee the flexibility that a simple iconic system does not, since iconic systems are completely dedicated to one feature of the object to which they refers (e.g., a silhouette of a wheelchair as a visual icon, or tallies of drinks served for cardinal assignment; Wiese, 2003). The double iconic and symbolic nature of finger numeral representations suggests that they may be a fruitful tool for developing an appropriate representation of numerosity and, later, of numbers (Fuson, 1988; Butterworth, 1999a; Brissiaud, 2003; Fayol & Seron, 2005).

5. **Chapter 3 Appendix: Technical Supplement**

5.1 COMPLEMENTARY ANALYSIS: Subjective and objective visual control of the stimuli

In the experiments presented in Chapter 3, the difference in the speed of processing canonical and non-canonical configurations may somewhat stem from visuo-perceptual features that were not totally controlled. For example, it could be that the fingers that were lowered could present some protuberance that may affect processing, and that such protuberances could be more disturbing in the non-canonical configurations. Also, grouped fingers could be easier to detect, which would give an advantage to canonical configurations that are only composed of grouped fingers. To exclude such possibilities, we performed the following controls.

Firstly, two objectives measures were taken on the stimuli. The first one was the presence of the *physical protuberance*, calculated on the ratio of the sum of the length between raised and lowered fingers (see fig. 3-7). The second one was the *grouping characteristic*, separating the finger configurations in 4 groups, depending on the distance between the raised fingers: distance 0 when the raised fingers were consecutives (e.g., index, middle and annular), distance 1 (i.e. index, annular and little finger for distance 1), 2 and 3, when the raised fingers were not consecutive.

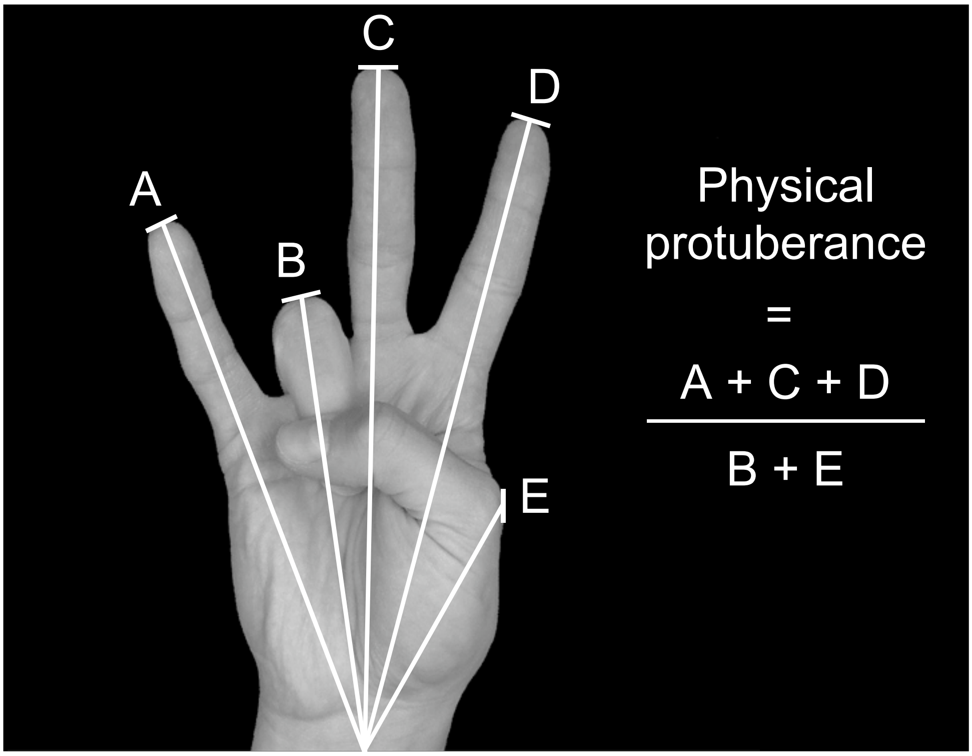

Figure 3-7. Physical objective protuberance ratio is calculated dividing the sum of the length of the raised fingers (in this case A, C and D) by the sum of the length of the lowered ones (in this case B and E).

Second, we have presented 36 participants (25 female; ages ranged from 19 to 28; mean ± s.d. age: 2.3±3.6 years old) who did not take part in the previous experiments with the same photos of the Experiment 1. They had to evaluate two visual characteristics by filling a questionnary using a 8-point scale. The first characteristic was the protuberance, i.e., how the lowered fingers could perturb the perception of the raised ones (from 0 = absolutely not disturbing to 7 = really disturbing), and the second one was the saliency of the raised fingers, i.e., whether the raised finger were well distinguishable (from 0 = barely distinguishable to 7 = perfectly distinguishable). Note that these measures refer to two distinct aspects. The first one refers to a subjective measure of focalized points of visual perception to evaluated the distance between the top of the raised and lowered fingers, whereas the second one catches in a glance the visual pertinence of the finger raised.

5.2. Results

For the back and palm photographs, two separated backward regressions were performed. Each of the regression accounted for the impact of the above mentioned variables (two subjectives and two objectives), to which the variable *numerosity* was added as the predictors of the RLs for each of the photographs. This allowed us to account for subjective and objective visual factors that could determine which configurations could be easier to process and faster to name. The backward regression analysis for the back photographs showed that the best predictor for the RL of the presented photographs was numerosity ($t = 18.731$, $p < .001$, $B = .839$) with 70.4% of the variance explained, followed by the subjective protuberance ($t = 5.566$, $p < .001$, $B = .291$) accounting for 8.46% of the variance, and the subjective saliency ($t = 2.954$, $p < .005$, $B = .157$) accounting for 2.46% of the variance. The backward regression analysis for the palm photographs showed that the best predictor for the RL of the presented photographs was numerosity ($t = 16.542$, $p < .001$, $B = .835$) with 69.7% of the variance explained, followed by the subjective protuberance ($t = 4.112$, $p < .001$, $B = .228$), accounting for the 5.19% of the variance.

Chapter 4 : Finger numeral configurations and the Pop-out effect

ABSTRACT

Finger numeral configurations conforming to typical finger-counting habits are named faster than others fingers configurations (Chapter 3, Experiment 1), and activate a semantic place coding representation as symbolic stimuli (see Chapter 5). This, however, does not exclude that some visuo-perceptual differences may exist between canonical and non-canonical finger configurations and partly explain the fact that canonical and non-canonical configurations are not processed equally faster. Here, we had participants decide whether or not a canonical finger configuration was present among distractors expressing the same numerosity but in a non-canonical way. The results showed that the time to detect the presence of the target grew linearly with the number of distractors thus demonstrating that there was no perceptual saliency of the canonical target among the non-canonical configurations. Visuo-perceptual differences between canonical and non-canonical finger numeral configurations can thus be excluded as the source of the better identification and semantic access of the former.

1. **INTRODUCTION**

Links between fingers and numbers have long been acknowledged and have been the subject of much research effort and theorisation attempts in the last years (e.g., Andres, Davare, Pesenti, Olivier & Seron, 2004; Badets, Andres, Di Luca & Pesenti, 2007; Brissiaud, 2003; Butterworth, 1999; Di Luca & Pesenti, 2007; Fayol, Barrouillet & Marinthe, 1998, 2001; Gerstmann, 1924-1940; Gracia-Bafalluy & Noël, 2008; Noël, 2005). Various contributions of fingers to number semantics have already been demonstrated in adults, among which, the role played by finger-counting. For example, in a recent study using an Arabic digit-to-finger mapping task, participants were asked to identify Arabic digits by pressing appropriate keys with one of their ten fingers. The data showed that the participants were faster and made fewer errors when the mapping was congruent with their own finger-counting habits than with other mappings (Di Luca, Granà, Semenza, Seron & Pesenti, 2006). We further showed that canonical finger numeral configurations, that is, configurations conforming to personal finger-counting habits, are named faster than non-canonical ones (Di Luca & Pesenti, 2007). Critically, this facilitation of naming canonical configurations was clearly not a mere perceptual effect. Indeed, numeral finger configurations used as unconsciously presented primes speeded up numerical comparative judgements of Arabic numeral targets. Participants responded faster and made fewer errors with numerical than with non-numerical primes, and when primes and targets were congruent (i.e., leading to the same response), but this priming effect only generalised to new, never-consciously-seen, numerosities for canonical configurations, and not for non-canonical ones.

Taken together, these results support the idea that canonical finger configurations automatically activate number semantics. However, they do not exclude that some visuo-perceptual features may contribute to the distinction between canonical and non-canonical configurations. Canonical configurations could indeed give a fast access to semantics and, at the same time, present visuo-perceptual features that make them easier/faster to identify. For example, fingers are always grouped in canonical configurations (i.e., numerosities being expressed by raising adjacent fingers) whereas some spacing may be present among the raised fingers in non-canonical configurations. Canonical configurations could thus be intrinsically easier to process visually. To assess this possibility, we capitalized on a well-known visual effect, the pop-out effect, which refers to the ability to detect an odd element in a display of distractors, independently of their number (Treisman & Gelade, 1980). In the last decades, the pop-out effect has often been studied using faces, a category of stimuli for which human beings are experts. Studies aimed at assessing whether this effect stemmed from high-level (Wolfe et al., 1992; Rousselet et al., 2002; Ahissar &Hochstein, 1997, 2004; Hershler & Hochstein, 2005; Pougeot & Bavelier, 2007), or low-level (Treisman, 1985, 1986; Treisman & Southern, 1985; Desimone &Ungerleider, 1989) visual mechanisms. Recent findings showed that both high-level and low-level processes can be used to detect a target (Van Rullen, 2006; see also Duncan & Humphreys, 1989). Participants used high-level visual searching strategies when targets differed categorically from the distractors (e.g., faces among cars, or faces among houses), but they used low-level strategies when targets and distractors shared some characteristics (e.g., faces among reversed faces, or among scrambled faces) with distractors (Van Rullen, 2006).

In the present experiment, we further investigated the visuo-perceptual properties of finger numeral configurations. Participants were presented with displays containing canonical and non-canonical configurations expressing the same numerosity. As targets and distractors shared several high-level characteristics (both were finger numeral configurations, both showed the same numerosity), the participants were likely to use a low-level search strategy. Therefore, if canonical and non-canonical configurations differ at a low visuo-perceptual level, then a pop-out effect should be observed. On the contrary, an absence of pop-out effect would clearly demonstrate that canonical and non-canonical configurations do not differ due to visuo-perceptual raisons.

2. Method

2.1. Participants

Twelve right-handed Belgian, French speaking, students from the University of Louvain took part in this study for course credits. All the participants had normal or corrected-to-normal vision and were unaware of the objectives of the study. Among the participants, 9 were females, and ages ranged from 19 to 21 (mean ± s.d.: 20.2 ±1.6 years old).

2.2. Apparatus

The experiment was run on a Pentium III PC Dell using the E-Prime software (Schneider, Eschmann & Zuccolotto, 2002) and equipped with a 17" CRT screen (1024 x 768 resolution). Response latencies (RLs) were collected through the keyboard.

2.3. Stimuli

The target and the distractors were photographs of the palm of the right hand of a person at a distance of 50 cm, with the hand at a distance of 20 cm from a black background. The photographs were taken with a digital Leica RD-1 camera (5.1 Mpixels), were manually edited to balance colour and luminance, and to replace the natural background by a black artificial one, so eliminating all residual shadows. Two types of finger configuration were used: the target was a canonical configuration (i.e., conforming to the participant’s own finger-counting strategy) representing numerosity "3", and the distractors were non-canonical (i.e., not conforming to the participant's own finger-counting strategy) presenting the same numerosity either with all fingers grouped or with some spacing between the raised fingers (Fig. 4-1A, B, C).

The entire surface of the screen was divided by an invisible 6x6-cell grid (36.1 cm large, 27.1 cm high), and filled with 5, 17 or 36 photographs. The arrangement of the photographs (individual size: 4 cm large and 4.5 cm high to fit the invisible cells of the grid) was pseudo-randomly determined, except for set of 36 stimuli where all positions were occupied. The target appeared only in a virtual 4x4 central grid to guaranty its foveal vision (Wolfe, O'Neil & Bennet, 1998). Distractors were equally distributed across the four up-left, up-right, down-left and down-right virtual sections of the grid (Fig. 4-1D).

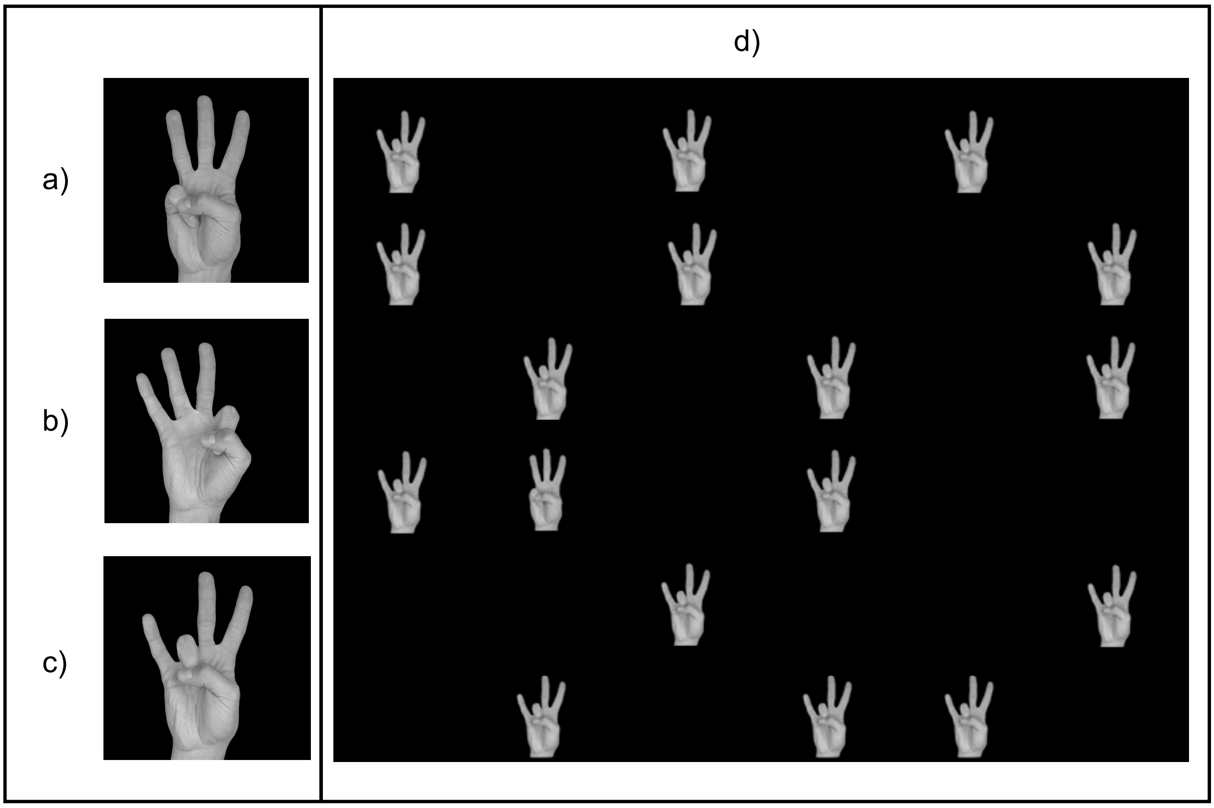

Figure 4-1. Photographs on the left represent (A) Canonical, (B) Non-canonical grouped, and (C) Non-canonical non-grouped configurations. Right side of the grid showed a stimulus to which participants were presented to. In this case thetarget, a canonical configuration showing numerosity "3", is presented surrounded by 16 non-canonical and non-grouped distractors showing the same numerosity.

2.4. Procedure

Every participant was presented with 2 blocks of 96 trials, each involving 32 presentations of each number of stimuli (5, 17 or 36 target and distractor). The target was present only in half of the trials. The sequence of trials within the blocks was pseudo-randomly determined such that the same number of distractors was not presented more than 3 times in a row, the same response no more than 4 times, and the target no more than2 times consecutively in the same cell. Trials were constituted by a centred fixation cross lasting between 500 and 1000 ms (at random), followed by the stimuli lasting either until participant responses or for a 3000-ms deadline. Every trial ended with a completely black screen of 1000 ms. The task was to detect the presence of the target by pressing one of two buttons (Q or M) on the keyboard. The order of the key assignment (target present or not) as well as the order of blocks was randomized across the participants. Eight practice trials were administered before each block started, but they were not included in the analyses; blocks were separated by a short pause. The instructions emphasised the necessity to respond as quickly as possible while keeping errors to a minimum.

3. Results

Analyses have been conducted only on the stimuli containing the targets as they are assumed to better reveal the parallel/serial nature of the search task (Treisman & Souther, 1985); trials with RLs exceeding three standard deviations from the participant's grand mean (2.21%) were excluded from the analyses. Overall, the participants made 267 errors out of 1152 trials (23.18%). There was no speed-accuracy trade-off as indicated by the absence of a negative correlation between RLs and the number of errors (r=.1; p=.4), computed over 72 pairs, and demonstrating that faster RLs were linked to lower errors rates.

A two-way analysis of variance (ANOVA) was carried out with the number of distractors (4, 16 *vs*. 35) and the type of distractor (Grouped *vs*. Non-grouped), as within-subjects variables. The ANOVA showed a main effect of the number of distractors (mean ± s.d. RL for [4]: 1118±225 ms; [16]: 1632±430 ms; [35]: 2798±1243ms; $F(1,11) = 13.25$, $p<.001$). T-tests revealed a difference between [4] and [16] distractors ($t(12) = 7.429$, $p < .001$), between [4] and [35] distractors ($t(12) = 3.893$, $p<.005$), and finally between [16] and [35] distractors ($t(12) = 2.649$, $p<.05$). The main effect of type of distractor ($F(1,11) = .08$, $p=.781$) and the two-way interaction between the type and number of distractors ($F(2,22) = .153$, $p=.858$) were not significant.

The same ANOVA applied to errors showed a main effect of the number of distractors (error rate for [4]: 10/384 (2.6%); [16]: 72/384 (18.75%); [35]: 185/384 (48.18%); $F(1,11) = 52.2$, $p<.001$). T-tests revealed a difference between [4] and [16] distractors ($t(12) = 4.999$, $p < .001$), between [4] and [35] distractors ($t(12) = 7.299$, $p<.001$), and between [16] and [35] distractors ($t(12) = 8.529$, $p<.001$). A main effect of the type of distractor was also found ($F(1,11) = 6.577$, $p<.05$): responses to non-canonical grouped distractors (111/576 (19.27%)) were less prone to errors than responses to non-canonical non-grouped distractors (156/576 (27.08%)). No significant interaction was observed ($F(2,22) = 3.00$, $p=.07$).

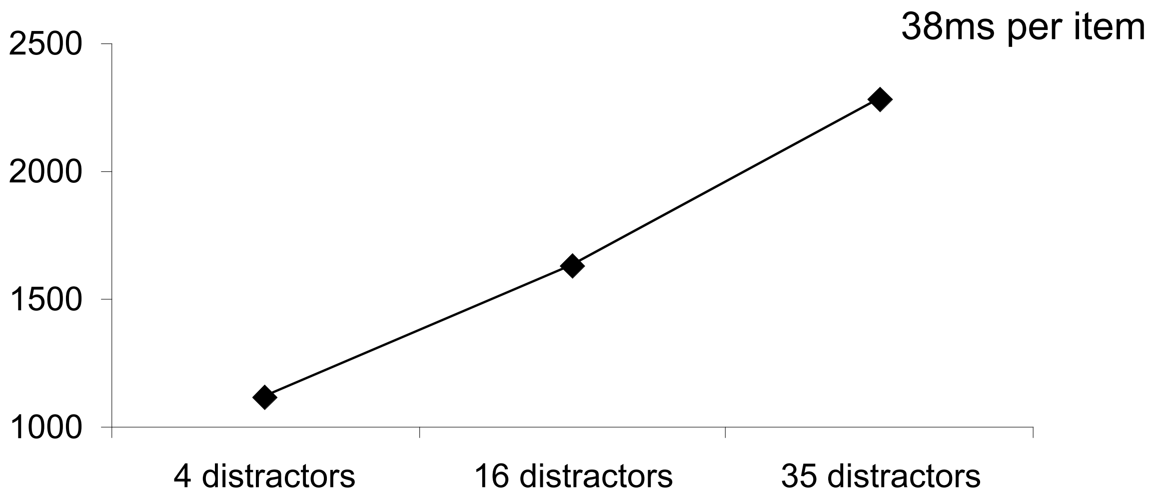

Figure 4-2. Target present slope as a function of number of distractors. Globally the slope obtained does not reflect a pop-out effect, as shown by an increase of 38 ms per item.

Regression analyses examining the slope of the regression as the number of distractors increased were performed on the correct RLs for each participant separately, and the beta values were subsequently compared to 0 (Lorch & Myers, 1990). Figure 4-2 shows that, globally, the RLs grew up linearly with the number of distractors (regression slope = 587, $t(12) = 4.01$, $p < .001$, 38ms per item), and that the low-level visual differences were insufficient to produce a pop-out effect as indicated by the relative comparison to 0 ($t(12) = 3.8$, $p < .005$). Regressions and relative comparisons to 0 separating the grouped and non-grouped non-canonical distractors showed that this was true for both types of distractors (non-canonical grouped regression slope = 574, $t(12) = 3.075$, $p < .005$, 37ms per item; non-canonical non-grouped regression slope = 601, $t(12) = 4.559$, $p < .001$, 39ms per item; Fig. 4-3), and that the low-level visual differences were insufficient to produce a pop-out effect for none of the type of distractors, as indicated by the relative comparisons to 0 (non-canonical grouped = $t(12) = 3.105$, $p = .01$; non-canonical non-grouped regression = $t(12) = 4.054$, $p < .005$).

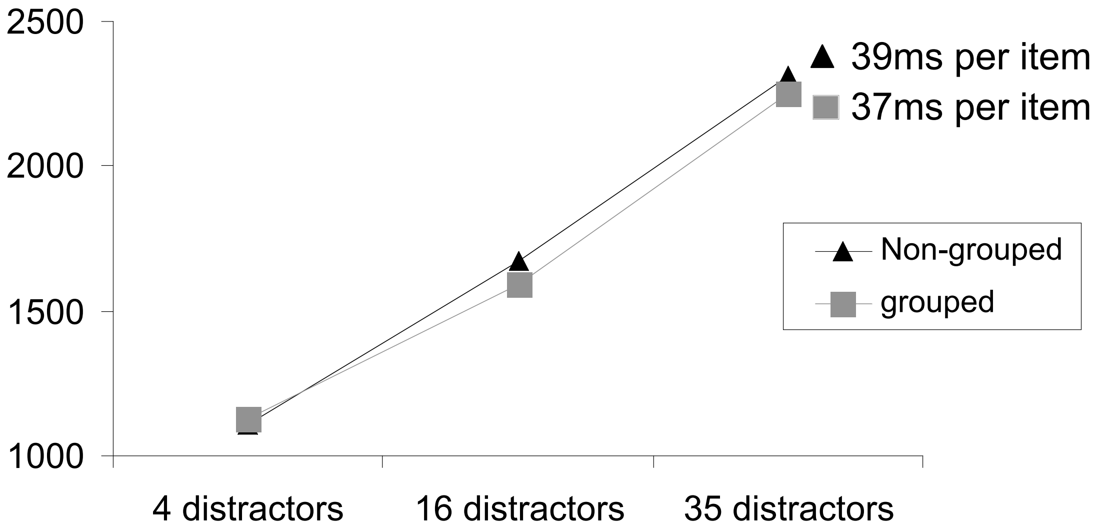

Figure 4-3. Target present slope as a function of number of distractors, separating the grouped and non-grouped distractors. None of the slopes obtained reflects a pop-out effect, as shown by an increase of 37 ms and 39 ms per item, respectively for grouped and non-grouped distractors.

4. Discussion and conclusion

Recent findings have shown that canonical fingers numeral configurations are identified more quickly and give rise to fewer errors than other configurations, and that they automatically give access to number semantics (Chapter 3). So far, however, one cannot exclude the possibility that the speed of processing canonical configurations may partly stem from visuo-perceptual features that would make them easier and faster to recognize without this being due to semantic access. In this experiment, we tested this possibility using a pop-out paradigm. Participants were asked to decide whether or not a canonical finger configuration was present among distractors expressing the same numerosity but in a non-canonical way. The results showed no pop-out effect: the time to detect the canonical configuration grew linearly as the number of distractors increased. This was true when the distractors displayed grouped fingers (as in the target), but also when the raised fingers were not grouped. A global regression run on the RLs as function of number of distractors showed an increasing of 38ms per item, and regressions separating the type of distractors confirmed the increase of 37 ms and 39 ms per item respectively for grouped and for non grouped non-canonical distractors. Usually, an increase over 10 ms per item is not viewed as a pop-out effect since the additional processing time taken for each stimulus in the display cannot be considered as in parallel (Wolfe, 1998). Thus, even when the distractors differed from the target not only by the position of the group of raised fingers, but also by the very nature of the grouping, this was not enough to make the canonical target perceptually salient. In visual search tasks, a pop-out effect is usually found for targets and distractors sharing high-level characteristics when they differ in low-level visual features (Duncan & Humphreys, 1989; Van Rullen, 2006). We can thus exclude low-level visual differences between canonical and non-canonical finger numeral configurations as the source of their better identification and semantic access. We have no specific interpretation for the fact that grouped distractors yielded fewer errors than non-grouped ones. Yet, it does not seem to stem from a real change in strategy. Indeed, the absence of a positive speed-accuracy trade-off both for grouped (r=.025; p=.886) and non-grouped (r=.182; p=.289) distractors suggest a unique searching strategy used by participants.

In Chapter 3, we showed that canonical configurations give automatic acces to number semantics. The present results show that such a symbolic status does not emerge from the external properties of the symbols used, but truly from the semantics behind them. It is because they convey a specific semantic meaning that canonical configurations, and symbolic notations in general, are processed differently, not because of some intrinsically easier visuo-perceptual properties.

Chapter 5 : Place coding for canonical finger numeral representations[18]

ABSTRACT

Fingers can be used to express numerical magnitudes, and cultural habits about the fixed order in which fingers are raised determine which configurations become canonical and which non-canonical. Although both types of configuration carry magnitude information, it has been shown that the canonical ones are recognised faster and directly linked to number semantics. Here we tested whether this difference is a consequence of differences in the qualitative way of processing the two types of configurations. When participants named Arabic digits primed by canonical and non-canonical finger configurations, qualitatively different priming patterns were observed for the two formats. Canonical configurations activated a place coding representation, with priming spreading to close smaller and larger magnitudes as a function of the prime–target distance. Conversely, non-canonical configurations activated a summation coding representation priming smaller or equal magnitudes independently of the prime–target distance, and larger targets depending on this distance.

[18] This section is a modified version of an article with identical title by Di Luca & Pesenti (submitted). Place coding for canonical finger numeral representations. *Cognition*.

1. Introduction

Children from every human culture spontaneously develop finger-counting strategies to enumerate sets of objects (Fuson, 1988; Ifrah, 1981). Discrete numerosities can be represented by various finger configurations, but raising fingers in a fixed order allows children to remember the cardinality of a set, as well as the sequence of counted objects by establishing a one-to-one correspondence between the raised fingers and the objects. We recently studied the impact of counting strategies on finger numeral configurations. We showed that even educated adults use their fingers as a visual and motor support to process and represent numerosities, and that finger numeral configurations contribute to number semantics. In a first study, specific finger-counting habits were found to actively interact with Arabic digit processing during a digit-to-finger mapping task: when asked to identify Arabic digits by pressing the appropriate key with one of their ten fingers, participants produced faster responses when the mapping between the Arabic digits and the fingers matched their own prototypical finger-counting habits than with other mappings (Chapter 2). In a second study, we demonstrated the semantic status of some finger configurations (Di Luca & Pesenti, in press). We showed that young adults named numerical finger configurations faster when they conformed to their own canonical finger-counting habits than when they did not. We proposed that such configurations could thus be considered as canonical numerical finger configurations, stored in long-term memory. Most importantly, we showed that this facilitation of naming canonical configurations was not a mere perceptual effect. Indeed, numeral finger configurations used as unconsciously presented primes speeded up numerical comparative judgements of Arabic numeral targets. Participants responded faster and made fewer errors with numerical than with non-numerical primes, and when primes and targets were congruent (i.e., leading to the same response), but this priming effect only generalised to new, never-consciously-seen, numerosities for canonical configurations, and not for non-canonical ones.

These results support the idea that canonical finger configurations automatically activate number semantics whereas non-canonical ones do not. However, they do not establish what type of numerical semantic meaning and representation is activated by canonical finger configurations. Mentally representing and processing numerical magnitudes is associated with two robust behavioural effects (Moyer & Landauer, 1967): the distance effect (i.e., two magnitudes are easier to distinguish if they are far from each other) and the size effect (i.e., holding size difference constant, the time to compare two magnitudes increases monotonically as the absolute size of the magnitudes increases, with pairs of small magnitudes having shorter response latencies than pairs of large ones). Various models have been proposed to account for these effects. These can all be grouped into two categories using the mental number line metaphor (i.e., an oriented inner line on which numerical magnitudes are represented from small to large; Dehaene, 1992): place coding and summation coding models. Place coding models describe numerical magnitudes as specific activated positions on the number line, with a spreading of activation to the neighbouring smaller and larger magnitudes (Dehaene, 1992; Gallistel & Gelman, 1992; Verguts, Fias & Stevens, 2005; see Fig. 5-1 left box). The overlap of activation with other magnitudes explains the distance effect, whereas the size effect stems from other assumed characteristics of the number line: compression (Dehaene, 1992), scalar variability in mapping the number line to tags (Gallistel & Gelman, 1992), and non-linearity in the mapping from the number line to output mechanisms (Verguts et al., 2005). Summation coding models propose that the activation accumulates on the line until the target magnitude is reached, hence including not only neighbouring magnitudes but also all smaller ones (Zorzi & Butterworth, 1999; Zorzi, Stoianov & Umiltà, 2005; see Fig. 5-1 right box). The distance effect is then explained by the fact that the closer the two magnitudes to be compared are, the more similar are their internal representations. The size effect is explained by the fact that, for a given distance, larger magnitudes share more units than smaller ones.

Interestingly, it has recently been demonstrated that both types of representation exist in adults, depending on the type of stimuli processed. In a priming naming task, qualitatively different priming patterns were observed for symbolic (i.e., Arabic numerals) and non-symbolic (i.e., dot patterns) primes and targets (Roggeman, Verguts & Fias, 2007): the priming effect induced by Arabic digits decreased with the distance around the prime, leading to a typical *V*-shaped pattern of priming (Reynvoet, Brysbaert & Fias, 2002), whereas the priming effect induced by dots generalised equally to all the smaller magnitudes, leading to a kind of step-like function with a decreasing priming effect only for magnitudes larger than the primes. Thus, Arabic digits appear to activate a place coding representation, and dots activate a summation coding representation.

In this study, we capitalised on these findings to assess the type of semantic meaning and representation associated with finger numeral configurations. We employed an experimental design similar to that used by Roggeman et al. (2007) and asked participants to name Arabic digits primed by canonical and non-canonical finger numeral configurations. We hypothesised that canonical configurations would be processed as symbolic stimuli due to their peculiar long-term memory status, whereas non-canonical ones would be processed as non-symbolic stimuli. Canonical configurations should thus activate a place coding representation, and non-canonical configurations a summation coding one.

2. Method

2.1. Participants

Twenty right-handed French-speaking Belgian students from the University of Louvain took part in this study for course credits. All the participants had normal or corrected-to-normal vision and were unaware of the objectives of the study. Among the participants, 14 were female, and their ages ranged from 16 to 24 (mean ± s.d.: 21.8 ± 1.7).

2.2. Apparatus

The experiment was run on a Pentium III PC Dell using the E-Prime software (Schneider, Eschmann & Zuccolotto, 2002) and equipped with a 17" CRT screen (1024 x 768 resolution). Response latencies were collected through a microphone and response accuracy was assessed by the experimenter.

2.3. Stimuli

The targets were Arabic digits from 1 to 5 presented in black against a grey background. The primes were photographs of the palm of the right hand of a person at a distance of 50 cm, with the hand at a distance of 20 cm from a black background. All the photographs were taken with a digital Leica RD-1 camera (5.1 Mpixels), and were manually edited to balance colour and luminance, and to replace the natural background by a black artificial one (17.5 cm large and 18 cm high), so eliminating all residual shadows. The photographs represented numerosities by 1 to 5 raised fingers on one hand. Two types of finger configuration were tested: canonical primes representing the numerosities 1 to 5 by finger numeral configurations conforming to the participant’s own finger-counting strategy, and non-canonical primes representing the numerosities from 1 to 4 by other configurations not conforming to the participant's own finger-counting strategy. A scrambled hand photograph was created by dividing the photograph of the hand with the five fingers raised by a grid of 20 x 15 lines, yielding 300 squares that were randomly redistributed inside the frame in such a way that the numerosity expressed by the hands could no longer be identified (see Fig. 5-1, and Di Luca & Pesenti, in press), and this was used as the forward and backward masks.

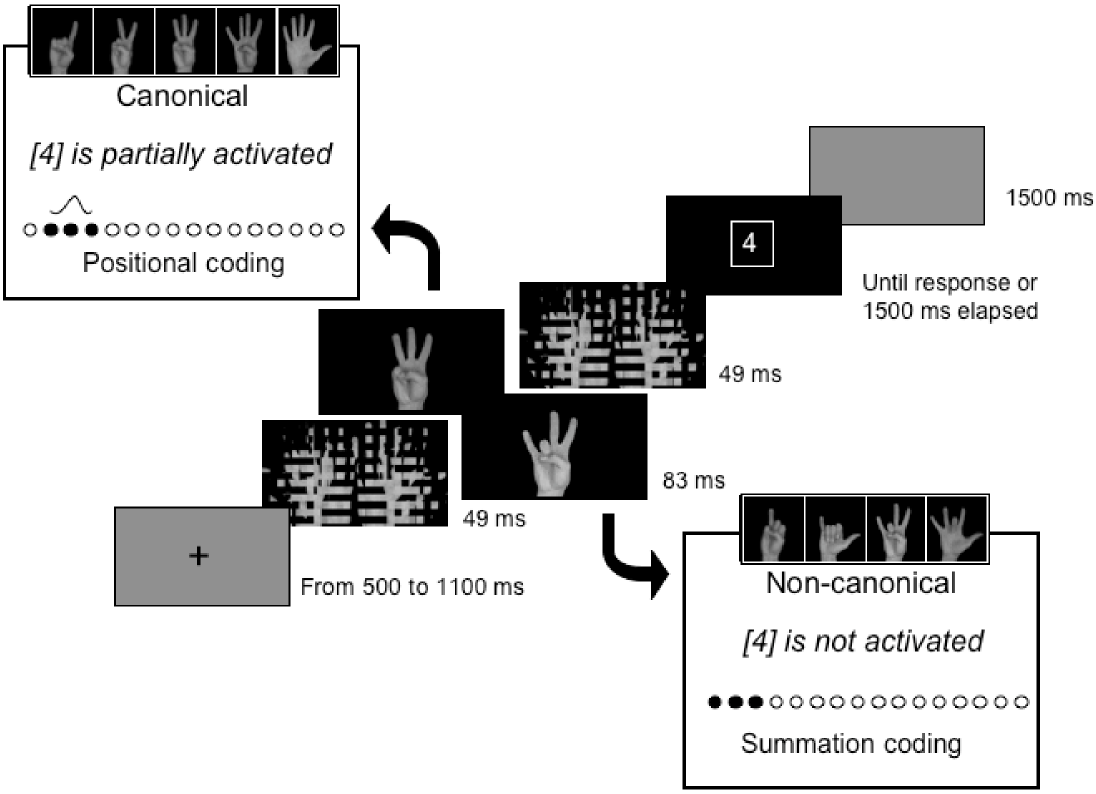

Figure 5-1. Sequence of events for one trial. Canonical and non-canonical primes [3] are illustrated for target [4]. The left box shows the canonical configurations and illustrates the place coding hypothesis (activation spreads decreasingly around the prime magnitude [3]). The right box shows the non-canonical configurations and illustrates the summation coding hypothesis (all the magnitudes smaller than the prime magnitude [3] are equally activated).

2.4. Procedure

The procedure was adapted from Roggeman et al. (2007). Each trial consisted of a fixation cross lasting between 500 and 1100 ms (at random), followed by a forward mask lasting 49 ms. Then the prime was presented for 83 ms, so that it was clearly visible but impossible to react to, and followed by a backward mask lasting 49 ms. Finally, the target was presented, lasting either until participant named it aloud or for a 1500-ms deadline (Fig. 5-1).

Every participant was presented with 5 blocks of 90 stimuli, each involving each prime–target combination (i.e., 5 canonical and 4 non-canonical primes by 5 targets) twice. The sequence of stimuli within the blocks was pseudo-randomly determined such that the same target was never presented more than twice in a row, and the same prime format (canonical or non-canonical) never more than four times in a row. Eighteen practice trials were administered before the experiment started, but these were not included in the analyses; blocks were separated by a short pause. The instructions emphasised the need to respond as quickly as possible while keeping errors to a minimum.

3. Results

Unreliable responses due to coughs, noises or microphone failures (0.35%), and trials with response latencies (RLs) exceeding three standard deviations from the participant's grand mean (0.58%) were excluded from the analyses. On average, participants made 1.28% errors (116/9000 trials), and these were not further analysed.

Regression analyses were performed on the correct RLs to identify which type of representation was activated. This was done by examining the slope of the regression as a function of the prime–target distance. For each prime format (canonical and non-canonical), one regression was carried out with negative prime–target distances (i.e. when the primes were larger than the targets) as the predictor, and another with the positive prime–target distances (primes smaller than targets) as the predictor. Negative beta values for the negative prime–target distances indicate that the RLs increase with distance; conversely, for positive prime–target distances, positive beta values indicate that the RLs increase with distance. Regressions were run for each participant separately, and the beta values were subsequently compared to 0 (Lorch & Myers, 1990). Both negative and positive beta values differing from 0 indicates a place coding representation. On the other hand, only positive beta values indicates a summation coding representation, because targets smaller than or equal to the primes would not be distinctly primed, thus generating a flat regression slope.

Figure 5-2 shows that the priming effect differed considerably depending on the type of prime. For the canonical primes, regressions on negative and positive prime–target distances revealed a *V*-shaped function, with significant negative and positive slopes (negative distances: regression slope = -7.172, $t(20) = -4.419$, $p < .001$; positive distances: regression slope = 9.047, $t(20) = 3.285$, $p < .005$). For the non-canonical primes, the positive prime–target distances generated a significant positive slope (regression slope = 8.61; $t(20) = 3.01$, $p < .01$), whereas the slope for the negative distances was not significantly different from 0 (regression slope = -3.041, $t(20) = -1.459$, ns). The same analyses restricted to the distances 1 to 3 to ensure that the *V*-shaped function was not simply due to an identity effect (i.e., when primes and targets are equal) and to eliminate distortions due to the low number of prime–target combinations for larger distances (Roggeman et al., 2007) showed the same patterns of priming effects. For the canonical primes both slopes differed significantly from 0 (negative distances: regression slope = -10.511, $t(20) = -3.439$, $p < .005$; positive distances: regression slope = 6.367, $t(20) = -2.125$, $p < .05$); for non-canonical primes, only positive prime–target distances showed significant slopes (positive distances: regression slope = 9.426, $t(20) = 3.422$ $p < .005$; negative distances: regression slope = -1.883, $t(20) = -.632$, ns).

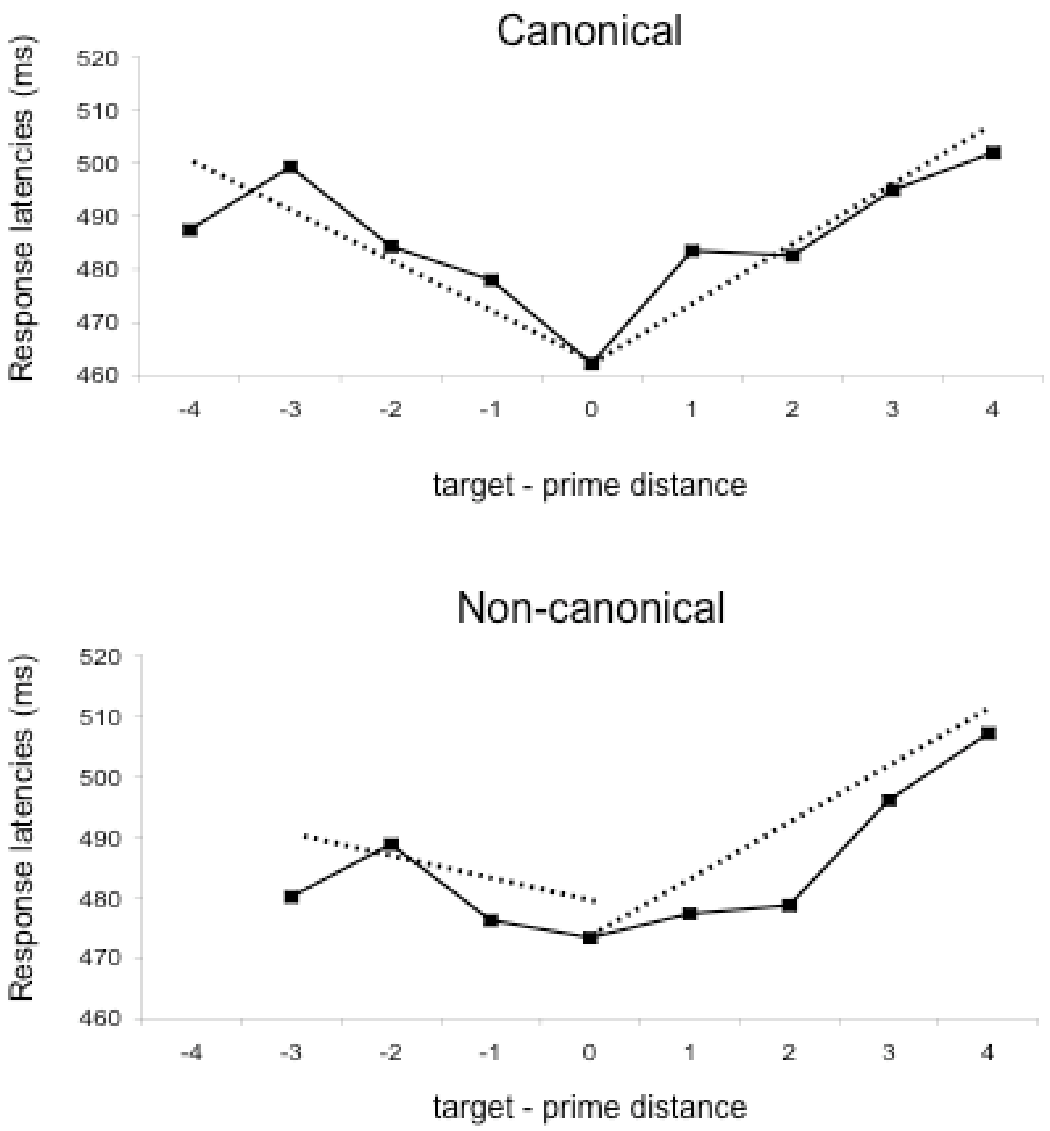

Figure 5-2. Mean response latencies as a function of prime–target distance (negative values denote primes larger than targets). The dashed lines represent the regression slopes for the canonical (upper panel) and non-canonical (lower panel) configurations.

4. Discussion and conclusion

Fingers can be used to express numerical magnitudes through canonical and non-canonical configurations. Canonical configurations automatically convey or give access to number semantics, whereas non-canonical ones require explicit elaboration to access semantics (Di Luca & Pesenti, in press). Here, we assessed the type of semantic meaning and representations associated with finger numeral configurations that were used to prime Arabic digits in a naming task. The results show that canonical configurations prime target numbers to which they are close, whether they are smaller or larger than the target, with the extent of activation decreasing as the prime–target distance increases. This results in a pattern of priming effect best described as a *V*-shaped function and supports the idea that canonical configurations activate a place coding representation (Roggeman et al., 2007). On the contrary, non-canonical configurations show a spreading of the prime–target distance effect only for targets which are larger than the primes; whereas targets smaller than or equal to the primes are all equally activated, regardless of the prime–target distance. This results in a pattern of priming effect best described as a step-like function, and supports the idea that non-canonical configurations activate a summation-coding representation (Roggeman et al., 2007). Analyses restricted to distances 1 to 3 show the same pattern of results.

These results support the idea that canonical finger configurations have acquired a specific semantic status, leading them to be processed as symbolic stimuli activating a place-coding representation. In this sense, canonical configurations seem to be processed by human adults in the same way as Arabic digits are processed, at least as far as small numerical magnitudes are concerned. This fully supports our proposal that canonical configurations stemming from personal finger-counting habits (and so capitalising on peculiar iconic visual and motor-programming familiarity) play an important role in building, accessing and using number semantics (Di Luca et al., 2006; Di Luca & Pesenti, in press). Non-canonical configurations that have not acquired such a semantic status are processed as non-symbolic stimuli activating a summation coding representation. Just as for any collection of objects that can be found in the environment, extrapolating their exact numerical meaning requires counting or estimation processes.

More generally, our findings provide further evidence of the co-existence of place and summation coding representations for small numerical magnitudes, and thus support models which involve both types of coding (Dehaene & Changeux, 1993; Verguts & Fias, 2004). Whether both types of coding co-exist for larger numerical magnitude remains an open question. The findings also extend Roggeman et al.'s (2007) finding of a qualitative difference between Arabic digits and dot patterns in coding numerical magnitudes to a more general difference between symbolic and non-symbolic notations, and demonstrate that this qualitative difference does not actually boil down to a difference between symbolic and analog representations. By analog, we mean a notation representing reality through structural and functional isomorphism (i.e., representing numerosity by the number of signs used). Indeed, any analog notation figuring numerosity would not necessary lead to summation coding: those that have acquired a specific status would be processed as symbolic stimuli through a place coding representation. Thus, we predict that a similar difference to the one we found would be observed between randomly arranged dot patterns and canonical dot patterns (such as those on dice).

In conclusion, developing finger counting strategies to represent and deal with numerosities leads to a modification of a natural and inner summation coding representation, that human adults possibly share with young children and some animal species, into a place coding representation, used to handle numerosities and numerical magnitudes symbolically. Canonical finger numeral representations seem to be a natural fruitfully toy for a progressive shift from one type of representation to the other.

Chapter 6. General discussion and conclusions

1. Finger counting habits mediate mental numeral representation

In Chapter 2, we have shown that a left-to-right oriented mental number line is not the best account for the data during a finger-digit association mapping task, and demonstrate that finger counting strategies may influence the way numerical information is projected into physical space and, perhaps, mentally represented. In the first experiment, the Right Hand was clearly superior when responding to small digits whereas no superiority was found for the Left Hand. This small-right superiority effect can be explained by the fact that, when both hands are available in daily-life activities, counting always starts with the RH whereas counting will start with the LH when the RH is occupied (e.g., when writing or holding something). It is worth noting also that neither the instructions nor the experimental set-up explicitly oriented the participants towards activating finger counting strategies, and that, prior to the analyses, RLs had been corrected for motor speed differences across hands (and fingers) that might have obscured the interpretations. Interestingly, the small-right superiority here observed echoes recent findings in an experiment using TMS to detect changes in the corticospinal motor pathways to hand muscles of individuals performing a parity judgment task, a task not requiring counting strategies. An increase in amplitude of motor evoked potentials was found for the right hand specifically for small numerosities (1 to 4), compared to large ones (6 to 9). The left hand did not show any preference (Sato, Cattaneo, Rizzolatti, & Gallese, 2007). In line with other findings, our data indeed support the idea that using and practising a prototypical finger counting leads to long-term associations between fingers and digits and explain as well the robust parieto-precentral activations observed in PET and fMRI experiments with numbers (see Chapter 1). These results do not, of course, rule out the mental number line as a possible representation of numerical information, but they show that other inner numeral representations could lead to spatial congruency effects. Moreover, results presented in Chapter 2 underlie the fact that response modality could lead the participants to using different kinds of numeral representations. In our case, with the use of all ten fingers as response modality, the motor representation of numerosity has overcome the visuo-spatial representation normally activated in tasks using only two fingers. The experiment also stresses the importance of a major control about the motor component concerning the response modality, because the apparent discrepancy between our results (small-right superiority) and previous results revealing a SNARC effect (small-left superiority) could stem from an uncontrolled motor component during the task (the familiarisation measured in RL for the left and right hands, as well as for each finger), or from the uncontrolled finger counting habits of the participants. A left- or right-starting hand for counting could indeed be critical for the presence or absence of a SNARC effect as currently assessed, and the fact that in typical experiments, the SNARC effect is not observed in all participants could be explained if those who do not exhibit the SNARC effect have either a right-starting hand for finger-counting, or no preferred left- or right-starting hand, or else no specific finger-counting strategy at all. This proposal is supported by the results of a very recent study using a parity judgement task in which only the participants starting their counting with the left hand showed a SNARC effect, whereas the participants starting with the right hand did not (Fischer, 2008).

2. Masked priming effect with canonical finger numeral configuration

Representing numerosity on fingers and finger-counting strategies have been extensively studied in children but little is known about the use of fingers to represent numerosities in adults. Chapter 3 showed that young adults named numerical finger configurations faster when they conformed to their own finger-counting and finger-montring habits than when they did not. We suggest that such configurations can thus be considered as canonicals and be stored in long-term memory so extending our previous findings presented in Chapter 2. It is worth noting that, although the experimental requirement to use all ten fingers as response modality might have induced or strengthened the observed finger-digit links in that study, this remark does not hold here as only a verbal output was required. These two studies highlight the dual function and nature of finger numeral configurations: the motor aspect revealed finger-counting configurations when an explicit manual response was required (Chapter 2), while the visual aspect revealed finger-montring configurations when no manual response was required (Chapter 3). However, we will see that these two aspects of the finger numeral configuration cannot be easily discriminated, and functional and behavioural evidence supports the idea that motor and visual information can mediate visual and motor processing both in bottom-up and top-down processes (Shulman et al., 1997). Moreover it remains to be shown whether individuals with different finger-counting or finger-montring habits actually have different canonical configurations. Further studies should also show in which contexts, if any, the finger numeral configurations are spontaneously used. They are probably used in arithmetical contexts, but their role may extend to other numerical contexts which are not strictly arithmetical.

Subsequently, we have used canonical and non-canonical configurations in a masked priming task. It turned out that finger numeral configurations speeded numerical comparative judgements of Arabic digit targets. Participants responded faster and made fewer errors with numerical than non-numerical primes, and when primes and targets were congruent (i.e., leading to the same response), but what it most important here, this priming effect generalised to novel, never consciously seen, primes for canonical configurations only. However, even if it still remains to determine if priming effect comes from a share activation of finger numerical representation and Arabic numerals or arises from the finger configurations themselves (e.g. finger configuration 4 activating directly Arabic digit 4), the critical point is that this direct or indirect semantic spreading does not take place with non-canonical configurations. This clearly supports the idea that, beyond possible processing speed differences, canonical configurations automatically convey or give access to number semantics whereas non-canonical ones do not, and requiring explicit elaboration.

In conclusion, these two experiments show that finger numeral configurations related to finger-counting or finger-montring have a specific status, and behave as canonicals in long-term memory and contributing actively to number semantics even in educated adults.

3. Visual differences between canonical and non-canonical configurations?

Chapter 3 shows that canonical fingers numeral configurations are identified more quickly and give rise to fewer errors than other configurations, and that they automatically give access to number semantics. However, one cannot exclude the possibility that the speed of processing canonical configurations may somewhat stem from visuo-perceptual features that would make them easier and faster to recognize without necessary involving semantic access. Although specific analyses conducted to disentangle this issue (see Chapter 3 Appendix) do not support the idea that visual characteristics fully explain the difference between canonical and non-canonical configurations, Chapter 4 provides further empirical evidence by using the pure visual characteristics of the pop-out paradigm. In visual searching tasks, a pop-out effect is usually found for targets and distractors sharing high-level characteristics when they differ in low-level visual features (Duncan & Humphreys, 1989; Van Rullen, 2006). Therefore, participants were presented with displays containing or not a canonical finger numeral configuration, surrounded by stimuli belonging to the same category, i.e. non-canonical configurations expressing the same numerosity. The results showed no pop-out effect: the time to detect the odd canonical configuration grew linearly as the number of distractors increased. We can thus exclude low-level visual differences between canonical and non-canonical finger numeral configurations as the origin~~e~~ of the effects found in Chapters 2 and 3. The results indirectly support the idea of a semantic difference between the two configurations, as we have shown in Chapter 5.

4. ***Semantic differences between canonical and non-canonical finger representations***

As shown, fingers can be used to express numerical magnitudes through canonical and non-canonical configurations. Canonical configurations automatically convey or give access to number semantics, whereas non-canonical ones require explicit elaboration (Chapter 3). Moreover, in Chapter 5, we assessed the type of semantic meaning associated with finger numeral configurations used to prime Arabic digits in a naming task. The results showed that canonical configurations prime smaller and larger target numbers to which they are close, with the activation decreasing with the prime–target distance. This results in a pattern of priming effect best described as a *V*-shaped function and supports the idea that canonical configurations activate a place coding representation (Roggeman et al., 2007). On the contrary, non-canonical configurations show a spreading of the prime–target distance effect only for targets larger than the primes; whereas targets smaller than or equal to the primes are all equally activated, regardless of the prime–target distance. This results in a pattern of priming effect best described as a step-like function, and supports the idea that non-canonical configurations activate a summation-coding representation (Roggeman et al., 2007). These results support the idea that canonical finger configurations have acquired a specific semantic status, leading them to be processed as symbolic stimuli activating a place-coding representation. In this sense, canonical configurations seem to be processed by human adults in the same way as Arabic digits are processed, at least for numerosities up to five maybe ten.

This fully supports our proposal that canonical configurations stemming from personal finger-counting and finger-montring habits (and so capitalising on peculiar visual iconic and motor-programming familiarity) play an important role in building, accessing and using number semantics (Chapters 2 and 3). Non-canonical configurations that have not acquired such a semantic status are processed as non-symbolic stimuli activating a summation coding representation. Just as for any collection of objects that can be found in the environment, extrapolating their exact numerical meaning requires counting or estimation processes.

More generally, our findings provide further evidence of the co-existence of place and summation coding representations, at least for small numerical magnitudes, and thus support models which involve both types of coding (Dehaene & Changeux, 1993; Verguts & Fias, 2004). The findings also extend Roggeman et al.'s (2007) findings of a qualitative difference between Arabic digits and dot patterns in coding numerical magnitudes to a more general difference between symbolic and non-symbolic notations.

5. General conclusions

Taken together, the experiments presented in this doctoral manuscript support the existence of a finger-numeral representation of numerosity. This representation originates from finger-counting and finger-montring habits in childhood (Fuson, 1982,1988; Gelmann & Gallistel, 1978; Wiese, 2003a/b; Butterworth, 1999a) and may possibly help the children to acquire a correct and complete concept of numbers in all their peculiar features: cardinality, ordinality and nominality. Moreover, we have shown that the finger numeral representation does not disappear in adulthood with the acquisition of a better and more abstract semantic system representing magnitudes, but that it persists in long-term memory and actively interacts with the processing of numerical information. The automatic access to the semantic representation of the canonical finger numeral configurations has been demonstrated in

Chapter 3 in which participants have been submitted to a masked priming task. Subsequently, we have shown that canonical and non-canonical finger-numeral configurations differ as concerns the way they carry the semantic information (Chapter 5): canonical configurations are processed as a symbolic system, and yield an access to a place coding semantic representation of magnitude, just as Arabic digits do. Non-canonical configurations on the contrary yield a summation coding semantic representation, just as arrays of dots do. This distinction between symbolic and non-symbolic representation for canonical and non-canonical finger-numeral representations corroborate the idea that the familiarisation with repetitive finger-counting habits gives to some finger configuration the status of iconicity (Wiese, 2003). This is exactly what we found in our experiments, and we want here to extent the concept of iconicity to any analog representation that has acquired a sufficient degree of familiarity to be processed as symbolic stimuli through a place coding representation (i.e., dots on a dice). Finally, in Chapter 4, we showed that in a visual searching task, the detection of a canonical finger configuration among non-canonical ones expressing the same numerosity did not give rise to a pop-out effect. Because searching a target among a certain number of distractors sharing high-level characteristics induces the participants to adopt a low-level visual searching strategy, we can exclude the hypothesis of a visual difference between canonical and non-canonical configurations as the origin of the above priming effects. Complementary analyses (Chapter 3 Appendix) support this interpretation by showing that only a small part of the variance is explained by the visual features of the finger numeral stimuli. To account for their faster processing, we suggested that canonical configurations might activate a familiar motor program in the repertoire of the observer through the "mirror neurons" system. Neurophysiological data have indeed shown that neurons of the ventral premotor cortex of monkeys discharge not only when a monkey performs a motor action but also when it observes another monkey (or human being) performing the same action (Di

Pellegrino, Fadiga, Fogassi, Gallese & Rizzolatti, 1992). A similar motor resonance system exists in the human premotor ventral cortex too, directly linked to the anterior part of the intraparietal sulcus, and constitutes the neural substrate of a corresponding mechanism recording the observed actions in the observer's motor repertoire (Gallese, Fadiga, Fogassi, & Rizzolatti, 1996; Rizzolatti, Fadiga, Gallese & Fogassi, 1996; Rizzolatti & Craighero, 2004). Canonical configurations would then be faster recognized and would give a better semantic access due to this evoked motor program. Because they are highly familiar and have been used in many occasions since childhood, canonical configurations automatically evoke the underlying motor program, which activates the corresponding numerical semantic meaning. On the contrary, non-canonical configurations do not activate a predefined motor program. It has been demonstrated that a hierarchical set of associative areas (the so-called *convergence zones*) progressively integrates modality-specific information across modalities (Damasio, 1989). For example, visual and motor properties of the premotor ventral areas are integrated in the parietal cortex and build visual-motor pathways for hand movements (AIP-F5 circuits; Murata et al., 2000) and gestures (PMv-AG; Tommasini et al., 2007). Top-down coactivation of information is also possible, and central information could retro-activate visual, motor and somato-sensory areas (Shulman et al., 1997). The top-down and bottom-up cross-modality coactivation could explain why the finger canonical numeral configurations, to which motor schemas are dedicated, could help the processing of visual information called by the common numeral information. This converging zones theory and top-down/bottom-up cross-modality retro-activation processes could account for the fact that children trained in finger differentiation tasks also improve their visual subitizing span (Gracia-Bafalluy & Noël, 2008).

Finally, we want to urge the current models to pay attention to various aspects of the experiments that could influence the access to and the process of the semantic information of numbers. The first one is response modality, as we have seen that it could play a role on the choice of the type of semantic numerical representation to be processed. The models need also to pay attention to the kind of stimuli used, as we have seen this to be responsible of the type of representation activated - either a place coding or a summation coding representation, for example. Last, we want to stress the importance of the cultural impact that determines the finger-counting and finger-montring configurations as this could indeed influence the orientation of the number line (Fisher, 2008).

6. *Perspectives*

6.1. Semantic representations of numerical magnitude: Towards a "Quadruple Code model"?

There are various anatomo-functional models trying to explain how human beings represent magnitudes, and how, in turn, this inner representation could determine some visuo-spatial compatibility effects during tasks in which, directly or indirectly, the access to the semantic magnitude information is required. However, the results reported in this thesis show that these anatomo-functional models lack the inclusion of the contribution of fingers during the acquisition and during the processing of the semantic information of magnitude. There are various contributions of the fingers during numerical tasks; we mentioned pointing, grip aperture adjustment, and, most importantly for this work, finger-counting and finger-montring strategies. Chapter 1 showed how each of these contributions is functionally represented and mapped in the human brain. However, in this thesis, we have only focused onto the canonical aspect of the finger numeral configurations in young adults. We found that canonical configurations give directly access to the semantic representation of magnitude, just as Arabic or verbal numerals do, because they have acquired the status of symbolic system. It is important, at this point, to underline the fact that non-canonical finger configurations give access to the semantic representation of magnitude too, yet in a different way, specifically through a summation coding representation. Our results thus support those models that admit the coexistence of a double representation of the magnitude information - with both place and summation codings - but they leave open two possible lines of research. The first one hypothesises that before developing a place coding representation, activated by symbolic systems, human beings need to pass through a summation coding representation, activated by any numerosities presented in the environment that have not yet acquired the status of iconicity of symbols. This would result in the two well-known place and summation coding representations. The second one hypothesises only one semantic representation that is differently activated by the strategy used by human adults during the estimation of the numerosity. In the case of symbolic systems, symbols give access and refer to a specific numerosity, whereas counting is needed when this piece of information is not directly accessed, indeed passing by all the numerosities until the target one. In other words, there would be only one representation expressing itself through summation or place coding effects depending on the process and/or the numerical stimuli at stake. This last interpretation seems to us more economical, as it allows human beings to develop, from a broadly analog and inner representation, a more and more accurate analog/discrete representation (see next paragraph).

In his Triple Code model, Dehaene tried to implement the model of multiple magnitude information processing of Campbell & Clarck (1994) more rigorously. He proposed that three types of numerical representations coexist, directly and bidirectionally interconnected to each others: the visual code (i.e., Arabic digits), the verbal code (i.e., number words), and the analog code, conceived as an inner line oriented from left to right representing the numerosities from small to large; this analog code is the semantic representation of magnitude. Were this functional organization proved to be right, we would like to introduce a fourth numerical code, the finger numeral representation, with a double visuo-motor nature. The visual aspect of finger numerals involves the canonical aspect of finger configurations, activating a specific numerosity on the analog magnitude representation, as Arabic digits do. The motor aspect involves the motor pathways used by humans in the gestures and movements to rise or lower fingers. Moreover, the motor aspect may involve all fingers and hands movements of pointing and grip aperture, when a continuous information is indeed modulated during the task. This continuous information could be represented as well on the same above-mentioned analog representation, onto which, with practice, humans are able to determine discrete numerosities. Several studies support this idea, since numerical information can mediate grip aperture movements (Andres et al., 2004), as well as calibrate finger grasping even in imagined movements (Badets et al., 2007).

The possibility to represent place coding, summation coding and analog magnitude information in a single representation system fits with the hypothesis that time, space and numbers derive from visuo-motor functions involved in the quantitative processing of sensory information (Walsh, 2003). Each of the pointing, grip aperture, counting and montring motor contribution on the semantic representation of magnitude has been developped in Chapter 1, in which we showed the specific brain areas activations for each of the above strategies. Even if it is too soon to speak of a functional finger numeral representation model, indirect pieces of evidence lead us to draw which future experiments should test the limits and strengths of a possible model including the contribution of the fingers during numeral tasks and acquisition of numeral concepts. Functional PMd areas, linked with MIP regions, would be activated during all the tasks in which a left and right motor response will be necessary. In this case a spatial and visuo-motor control of finger contribution would be supported by the MIP-F2 circuit, as for all the tasks in which visuo-motor coordination is needed (Göbel et al., 2004; Harrington et al., 2000). The AIP-F5 circuit would also be activated during numerical tasks, in which magnitude information is shared between numbers and motor circuit (Walsh, 2003; but see also Hubbard et al., 2005). This hypothesis is supported by two recent studies in which grip aperture (Andres et al., 2006) and potential grasping (Badets et al., 2007) were influenced by number magnitude. Finally, finger counting strategies should take into account for first numeral representations in children (Fuson, 1988) but also functional premotor activation (Coull & Nobre, 1998; Binkofski et al., 1999; Grefkes et al., 2002; Cohen & Andersen, 2002; Culham et al., 2003; Raos et al., 2004; Connolly, Andersen & Goodale, 2003; Frey et al., 2005; LeFevre, Sadesky, & Bisanz, 1996) and behavioural data profiles in adults (Gerstmann, 1924-1940; Hatkinsons & Warrington, 1963; Butterworth, 1999a; Andres et al., 2006; Badets et al., 2007), during various numerical task. The fact that numerical and magnitude representation take place in the areas in which visual, motor and somatosensory information are integrated in an inner and abstract information is a starting, but also last, evidence of the hand and finger visual-motor contribution to the concept of numbers.

Let us focus again on the montring and counting visuo-motor finger numeral representations to make some other predictions on the basis of the “Quadruple Code model” just proposed. By using functional imaging techniques, it should be possible to assess which areas are activated during specific tasks. First of all, these techniques could allows us to disentangle the question raised at the end of Chapter 2 in which we hypothesized that different response modalities could activate different aspects of the semantic representation of numbers. For example, during a given numerical task, one could assess whether the participants activate finger pointing areas (MIP-F2) or finger-counting ones (AG-F5), thus denoting either a visual searching strategy in which the participants may be virtually scanning the number line looking for a specific number, or a visuo-motor finger numeral representation, in which participants refer to the finger counting and montring representations stored in long-term memory. We suppose that the more fingers participants use as possible responses (from two to all ten fingers), the more there will be a shift from a visuo-spatial representation to a visuo-motor one, because that they can apply a fine motor control on the presented numerosities. It still remains to test what are the possible links between the finger numeral, visual, verbal and analogical codes. They may be directly and bidirectionally connected, as the visual, verbal and analog ones, or there may be preferred connections between codes, as we guess to be the case between finger-counting and verbal representations, since finger counting is almost always associated to the verbal sequence of numbers. It could be interesting to test if other numerical representations, as for example canonical dots configurations on dices, could acquire the status of iconicity and be integrated in the symbolic system. We expect such canonical configurations to acquire at least some of the properties of symbolic systems, giving rise to some of the behavioural effects usually observed with the latters, but we do not expect them to get the same status as finger numerals, for they lack the same developmental trajectory and motor component (note that this may not be true for people who developed personal visual or visuo-spatial systems of representation for numbers; Seron, Pesenti, Noel, Deloche & Cornet, 1992).

6.2. A developmental tool for the number concept?

What we want to argue here is the importance of the use of fingers during the development of the number concept. Children naturally use their fingers during arithmetical and numerical tasks and finger motor schemas, determined by motor constraints and cultural habits, could be at the origin of the transition from an innate predisposition of a numerical concept to an abstract and adult representation of magnitude (Butterworth, 199a; Fayol & Seron, 2005; Pesenti et al., 2000). Since childhood, in fact, children use their fingers and their hands to modify and interact with the extra-corporal space, and in some occasions to visualize and communicate concepts that are not yet well represented in their long-term memory (e.g., they imitate the gesture of eating instead of pronouncing the word “hungry”); among others, they use their fingers to visualize more abstract concepts such as the numerical information. As we reported in Chapter 1 and in the above paragraph, the imitation of gestures is supposed to be the basis of human communication when verbal competences are not yet acquired (Rizzolatti & Arbib, 1998; Rizzolatti & Craighero, 2004).

The impact of the verbal representation of numbers in childhood still remains controversial, because it lacks to capture that passage between an innate semantic representation into an adult abstract one. Verbal competences, and specifically the verbal contribution to the acquisition of numerical competences in adults, are not sufficient to explain some data. For example, they cannot explain why, after some verbal deficits such as aphasia, the numerical competences still remain intact, when they should have fallen down if they were build on a verbal basis (Fayol & Seron, 2005). Moreover, it has recently been shown that verbal numerals could be processed asemantically, whereas Arabic numerals could not (Fias, 2001). Finally, the models that attribute a verbal or a symbolic nature to the semantic representation of magnitude cannot explain spatial effects as the SNARC, size and distance ones.

Newborns and young children are able to discriminate small numerosities provided that they are small (1, 2 and 3 items; Antell & Keating, 1983; Starkey & Cooper, 1980; Strauss & Curtis, 1981) or provided that a ratio of 1/2 is present (e.g., 1 and 2; 2 and 4; 8 and 16, and even 16 and 32; Xu & Spelke, 2000; Xu, 2000). Moreover recent experiments conducted on monkeys have shown specific neurons activation in the parietal cortex for numerosities up to *3* (for a review, see Nieder, 2005). But what happened with numerosities larger than *3*? As describe above, is it possible that there exists only one analog semantic representation of magnitude, and the use that human beings do of it determines the pattern of data observed: effects suggesting a place coding representation for specific discrete numerosities, a summation coding representation for counting numerosities, and a continuous representation for movements, space or time judgements. It is possible that humans, and animals were born with a rough semantic representation of magnitude that allows them to distinguish small numerosities from each others, or larger ones differing at least by a ratio of 1/2. Differently from animals, human beings can improve their analog representation of magnitude with their daily-life experience, and above all with the use of symbolic systems. We suggest that the first steps over the numerosity *3*, is done through the use fingers, more precisely by a one-to-one correspondence strategy between the objects to be counted and the fingers. In this way, the children, even if they did not use the verbal numeral sequence to count, can represent small numerical concepts by the use of a body instrument: one raised finger for each of the objects to be counted. The use of fingers leads to gradually master numerosities increasingly larger passing by numerosity *five*, that is an important base for the pre-schoolers, until numerosity *ten*, with the application of the same rules to the other hand. In line with this, it is not a case that 10 is the basis of our positional numeric system.

Three characteristics give to fingers their critical role among the pedagogical tools to learn and develop the concept of numbers. The first one is the fact that they are at the same time an analog and a symbolic system. This is important for the children to extrapolate the numerical information from the sets of objects to be counted, and to relate this numerical information from an inner analog representation to a symbolic one (Arabic or verbal). Moreover, fingers keep the cardinal characteristics of the objects counted, by presenting the same number of fingers raised (or lowered) than the objects counted. At any time, indeed, the children can visualize how much objects they have already counted. Finally, motor constraints and cultural practice lead the children to raise their fingers almost always in the same order, carrying in this way the ordinal propriety of numbers, in which *1* is always before *2*, *2* always before *3*, and so on. Similarly, with fingers, the thumb comes always before the index, the index always before the middle finger, and so on. With finger-counting strategies, children thus develop a sense of order that they can apply to the ordered number series. As we have shown in this thesis, finger-counting and finger-montring strategies determine which configurations become more familiar than others, and with practice, these canonical configurations will directly recall the semantic representation of magnitude, without needing to count again, just like symbolic systems do.

Pre-school and school activities should thus integrate the use of finger-counting pedagogical methods during the acquisition of number abilities. In this way, visuo-motor finger-numeral representations, could prepare the children to turn an analogical and innate but poor magnitude representation into a more appropriate and pertinent one, to which, verbal, visual and of course visuo-motor codes can be referred.

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