Subtle fingers – tangible numbers: The influence of finger counting experience on mental number representations

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Die ersten paar Zeilen möchte ich an die Menschen richten, die dazu beigetragen haben, dass diese Dissertation in der heutigen Form existiert.

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Chapter 1

Introduction

They are the object of affection and hate, the cause for anxiety and great wonder, a tool for deciding between two brands of toast in a supermarket and for flying to the moon. Numbers are a part of everybody's daily life, be it to indicate the time left to catch the train, the number of that train, or the number of stations one has to go. Numbers describe the size of the crowd inside the elevator of the office building, the storeys of that building, the pin for accessing online banking or the black or red balance of the bank account. That is, numbers do not only describe quantities: besides this *cardinal* meaning (for example, there were 6 other people in the elevator), they can have an *ordinal* meaning when they describe a position within a sequence (for example, the office is at the 4th of 6 floors), and a *nominal* meaning when they are used as labels to identify objects (for example, train number 42) (e.g., Nieder, 2005; Nieder & Dehaene, 2009). They can stand for so many different things that it seems amazing that our mind is able to grasp each of their meanings.

The present thesis approaches the question of how the human mind is able to process such an abstract thing as numbers. Specifically, I will address – and endorse – the idea that numbers gain meaning through their association with sensory and motor experience. And even more specifically, I will argue that such embodiment of number knowledge in particular takes place through the habit of finger counting starting early in life and that detectable traces of finger counting are still present in adult number representations. I will present four novel studies which were designed to detect those traces and I will draw conclusions regarding the influence of finger counting experience on mental number representations, leading to the formulation of a model which describes not only symbolic and non-symbolic number representations but also specifically the fingers' role therein.

If mental representations of numbers depend on experience, this entails that not everyone shares the same mental concepts. This realisation prompts many questions concerning the development and the malleability of mental concepts. First of all, is there an innate understanding of numbers? In addition, how strong is the influence of culture, that is, experience that is shared by a large group of people as a result of the characteristics of the culture that surrounds them? Furthermore, how strong is the influence of individual experiences that vary more strongly even within a culture? This first part of the present thesis is aimed to review the ever-growing body of research that addresses such questions and prompts even more questions.

Regarding the first question, an innate understanding of numbers (or rather, quantity) has been proposed – the number sense – which is shared by humans and many animal species (Dehaene, 2011). The basic number sense is regarded as a key concept of numerical cognition, upon which more complex numerical knowledge builds. The number sense will be a main topic in the next section "Mental number representations and a sense for numbers" and its presumed inner workings will be addressed in the following section "The accumulator model, the approximate number system, and subitizing".

Regarding the second question, one example of cultural influence is reading direction. Does it make a difference for mental number concepts whether someone reads and writes from left to right or from right to left? Evidence for this especially comes from the notion of a mental number line which involves increasing numbers either as directed from left to right or from right to left. This will be elaborated in the sections "The mental number line, the distance effect and the size effect" and "Spatial-numerical associations and the SNARC effect".

Regarding the third question, one example of inter-individual differences is the starting hand in finger counting. Is it that a person who starts to count on his or her left hand associates small numbers (i.e., from the beginning of the counting sequence) with the left side, whereas someone who starts to count on his or her right hand has the reverse association? (And do pure "left-starters" and "right-starters" exist or is the starting hand in finger counting more flexible?) Likewise, handedness and, more generally, any characteristics of individual bodies might influence mental concepts. The influence of individual experience and dependence on bodily representations for mental concepts in general, and the role of finger counting experience in mental number processing in particular will be specifically addressed in the section "The Embodied Cognition framework" and, constituting the main topic of the present thesis, in all subsequent sections.

The above considerations also introduce a key element of numerical cognition: there is a distinction between "true" quantities and mental representations thereof. Imagine a set of, say, 42 objects. The quantity is, by definition, 42. However, the person imagining it will at the very least have a hard time mentally visualizing the exact amount of objects. He or she will furthermore automatically co-activate a lot of related knowledge like that 42 is an even number, that it is close to decade 40, that it is a bit on the right from 40 on a left-to-right oriented number line, that it is read "forty-two", and so on. It is important to keep in mind that whenever we think about numbers, we are only mentally referring to external quantities, labels, positions, durations, or various kinds of measures. *Mental number representations*[1] can only be exactly this: more or less precise mental references to external referents (of quantity etc.) that furthermore activate related mental associations. Number concepts – the way they are to be understood within the present thesis – can refer not only to quantities (i.e., approximate amounts of countable or uncountable objects or events) and numerosity (i.e., exact quantities usually in the form of number of objects or events), but also to other magnitudes (i.e., everything that can be "more" or "less" like volume, luminance, size, quantity, duration, etc.) and number symbols like number words and Arabic numerals. The different notations, or representational formats, and the mental representation of magnitudes in general are specifically addressed by two prominent theories of numerical cognition and they will be elaborated within the two sections of the present thesis' Introduction that have been skipped in the above list ("A Theory Of Magnitude (ATOM)" and "The triple-code model").

All these considerations are relevant, because numerical knowledge plays a huge role within our daily lives. The present thesis addresses very basic components of

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[1] The terms *mental number representations* and *number concepts* are used synonymously within this thesis.

numerical knowledge – however, profound numerical knowledge and mathematical achievement have been found to be related to the most basic mental number representations (e.g., DeWind & Brannon, 2012; Gilmore, McCarthy, & Spelke, 2010; Halberda, Ly, Wilmer, Naiman, & Germine, 2012; Libertus, Odic, Feigenson, & Halberda, 2016; Lyons & Beilock, 2011; Mazzocco, Feigenson, & Halberda, 2011; Piazza et al., 2010; Starr, DeWind, & Brannon, 2017; Starr, Libertus, & Brannon, 2013) and these basic representations provide an opportunity for early mathematical trainings (e.g., Kucian et al., 2011; Wilson, Revkin, Cohen, Cohen, & Dehaene, 2006). The additional assumption that numerical knowledge is rooted in our bodily, sensorimotor experience with the physical world – and therefore also depends on our individual bodies and sensorimotor abilities – provides an additional leverage point for early mathematical trainings.

In the following sections I will present general information and findings concerning mental number representations and the embodied cognition framework to show why it makes so much sense for numbers to be embodied, and especially embodied "in the hands".

Mental number representations and a sense for numbers

Above I postulated the number sense as if it were self-evident. However, it was not always taken for granted that children had a stable concept of numbers.[2] Jean Piaget, an influential developmental psychologist who dedicated a lot of his work in the 1940s and -50s to children's concept of numbers and quantities in general, argued that a stable concept of numbers required an understanding for invariance of quantities, that is, the knowledge that a quantity cannot change when nothing has been added or removed (cf. Piaget & Szeminska, 1975). Children without this understanding would confuse different physical aspects with the total quantity, for example, the length of a row of beads with the number of beads. He accordingly denied young children under about 6 years of age the capability to understand the stable concept of numbers (e.g., Piaget & Szeminska, 1975). Other researchers finally proved that such young minds are capable of understanding a lot more about numerosities than assumed after all (cf. e.g., Barrouillet, 2015). For example 2 to 4-year-old children correctly distinguished numerosities independently from other dimensions such as space (Mehler & Bever, 1967). Five-month-old infants were found to understand that adding a doll to another doll behind a screen could not result in only one doll in the end (simple addition); and similarly, taking one of two dolls away behind a screen could not result in two remaining dolls (simple subtraction; Wynn, 1992). Already neonates are able to discriminate between small number sets of 2 to 3 visual items (Antell & Keating, 1983) and to connect sets of 4 to 18 auditory items with the same number of visual items (Izard, Sann, Spelke, & Streri, 2009). Wynn (1990) reported that starting from about three and a half years of age, children even begin to understand the cardinal word principle, that is, that the last number word from a counting sequence constitutes the total number of counted items. The cardinal word principle is one of the principles

[2] Note that the *number sense theory* is also still under discussion. It is sometimes pitted against the *sense of magnitude theory* which assumes that continuous magnitudes are processed more automatically than numerosities (for a rich debate see target article by Leibovich, Katzin, Harel, & Henik, 2017 with open peer commentary).

which, according to Gelman and Gallistel (1978; Gelman, 2015), are developed over time and guide children's counting without having to be taught explicitly. The counting principles are the 1) one-to-one principle (each counted object is assigned exactly one counting word), 2) stable-order principle (the counting words are always used in the same order), 3) cardinal principle, 4) abstraction principle (all objects, independent from their identity and tangibility, can be counted), and 5) order-irrelevance principle (the outcome of the count is independent from the order in which objects are counted as long as the above counting principles are followed).

Based on findings such as those reported above, Dehaene (2011) argues that there is a kind of sense for numbers. To be precise, Dehaene does not limit this to human cognition but also attributes a certain number sense to animals because they are able to process numerosities as well. It seems obvious that animals need to be able to discriminate between different amounts of food and predators, but it has furthermore been proven many times that they are also able to use their number sense for items different than that: for example rats are able to discriminate between numerosities as well as between durations (Meck & Church, 1983; see also Mechner, 1958; Platt & Johnson, 1971; also less common lab animals have proven similar numerical competencies: e.g., mosquitofish: Agrillo, Piffer, & Bisazza, 2010; salamanders: Uller, Jaeger, Guidry, & Martin, 2003; crows: Ditz & Nieder, 2016). Chimpanzees have to some extent even mastered the use of Arabic numerals as representatives for numerosities (for a summary see Matsuzawa, 2009). And even non-primates exhibit arithmetic capabilities: for example newborn chicks were able to perform easy non-symbolic additions and subtractions (Rugani, Fontanari, Simoni, Regolin, & Vallortigara, 2009). These findings speak in favour of the existence of an innate number sense. Humans' more pronounced ability to know and to handle number builds upon this basic ability (e.g., Halberda et al., 2012; Starr et al., 2013). The number sense is made up of two core systems with which we can represent numbers of objects without counting: the approximate number system and subitizing (Dehaene, 2011). These core systems and a proposed mechanism for a basic understanding of numerosities are described in the following section.

The accumulator model, the approximate number system, and subitizing

Findings that even animals are able to process numerosities to a certain extent, although they are lacking a verbal system to use for counting, indicate that they possess some other mechanism for keeping track of numerosities. The *accumulator model* has been proposed to offer such functionalities (Gibbon & Church, 1981; Meck & Church, 1983). The essential parts of this model are a pacemaker, a mode switch and the accumulator. The pacemaker sends out pulses which are or are not allowed to pass into the accumulator by the switch. Thereby, this system works both for numerosities and durations, because the switch either passes the flow of pulses for a certain amount of time or it opens and closes with each single event, thereby passing pulses according to the processed number of items or events. The final count can for example be stored in working memory and be compared to another, previously memorised numerosity or duration. However, this is not an exact system. The flow of pulses may vary and the amount of time that the switch opens or closes may also be inaccurate and therefore add noise to the mental representation of the numerosity or duration. Note that the inaccuracy of the system increases with increasing numerosity/duration because with the pulses also the noise accumulates. The inaccuracy can be visualised by Gaussian bell curves along the (mental) number line. Each curve represents a person's (or animal's) mental representation of a number, that is, there is one curve per number concept with the peak of the curve representing the highest possible certainty for that given number. The curves are very narrow for very small numbers and become wider and lower (i.e., variance of the number concept increases) with increasing numbers (cf. Figure 1, left panel). The wider distributions are due to the accumulated noise for increasing numerosity described above. There is overlap between curves and a wider distribution entails a larger overlap with neighboured distributions. For example, when a subject has to estimate the numerosity of a set of items, the accumulator would determine a position on the x axis (see Figure 1, left panel). The height(s) of the curve(s) at x then describe the probability of selecting the number corresponding to the given curve(s) as response. Even if the curve peaks at the given number, the overlap entails that more than one number are possible responses and larger overlap increases the probability of selecting an inaccurate response. Different people's mental representations of numbers vary from each other and may represent exact numerosities more or less accurately.

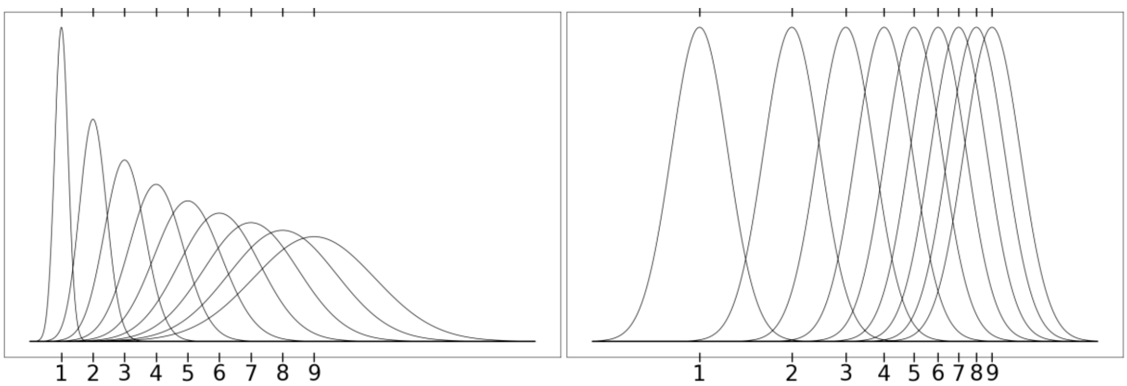

Figure 1. Illustration of two number lines ranging from 1 to 9 with different characteristics; left: linear number line with increasing variance; right: logarithmically compressed number line with equal variance. Each curve represents a mental number concept. Both representations predict an increasing overlap of number concepts with increasing magnitude.

One finding that runs through research on the development of numerical cognition is that first, individuals (be it children or animals) are able to solve mathematical problems only approximately – or exactly if the numerosities are small enough. These abilities constitute the two "core systems" of numerical cognition, namely the *approximate number system* and *subitizing*[3] (Feigenson, Dehaene, & Spelke, 2004). The approximate number system theory in general describes that large numerosities can be mentally represented – independent from low-level features like surface area of visual stimuli – in an approximate fashion, the degree of approximation increasing with numerosity (Burr, Anobile, & Arrighi, 2017; Feigenson et al., 2004;

[3] The term subitizing can be derived from the Latin word "subito", which means "suddenly".

Halberda, Mazzocco, & Feigenson, 2008)[4] (cf. Figure 1). The accumulator model described above illustrates a possible mechanism which is responsible for increasing inaccuracies of numerically increasing number concepts. Besides the approximate number system, a different mechanism exists for small numerosities: numerosities up to about four can be “subitized”, that is, they are processed very accurately and very fast (about 50 ms per item), which represents a different mechanism than counting and estimation (Kaufman, Lord, Reese, & Volkmann, 1949). Subitizing up to three or four is also reflected in all known cultures’ early number writing systems, which did not use more than four identical symbols in a uniform row (Dehaene, 2011; Ifrah, 1998). An example known to most is the Roman notation, in which only the first three number symbols consist of the matching number of bars. A continuous adding of bars for every further number would exceed the subitizing range starting from about 5 bars, which would render larger numbers very difficult to read and therefore rather useless as symbolic representations. Some cultures have deviated from this obvious pattern more (e.g., Arabic numerals) than others: for example modern Chinese number symbols for numbers one to three consist of a matching number of (non-identical) horizontal bars.

The number sense with its two core systems is an innate system that provides humans and animals with a basic understanding of quantities. The following paragraphs introduce one aspect of (mental) number representations that is culturally influenced, that is, the metaphor of mental number representations as being horizontally aligned on a number line.

The mental number line, the distance effect and the size effect

It is widely assumed that numbers are mentally ordered as ascending from left to right in Western cultures (Dehaene, Bossini, & Giraux, 1993) or from right to left in cultures with a right-to-left writing direction of words and number symbols (in Palestinians: Shaki, Fischer, & Petrusic, 2009), either in a linear way (Fischer & Campens, 2009), or in a logarithmically compressed way (Dehaene, Izard, Spelke, & Pica, 2008; Longo & Lourenco, 2007) (see Figure 1). A logarithmically compressed mental number line (MNL) is also consistent with an approximate number system that enables to only sharply discriminate between small numbers while larger numbers, being located closer to each other on the number line, become increasingly blurred and harder to distinguish. If the mental representation of each number were illustrated by identical Gaussian bell curves, the curves would overlap only a little bit for small number concepts, but increasingly more so for larger number concepts (see Figure 1, right panel). Note, however, that the above description of the accumulator model also predicts increasing overlap for increasing number concepts for a linear MNL: here, the Gaussian curves are assumed to have increasing widths (i.e., increasing variance) with increasing number concepts because of the accumulating noise with an increase of pulses, so that the overlap between number concepts increases after all (see Figure 1, left panel). There is an ongoing debate about the question whether numbers are mentally represented on a linear or logarithmically compressed number line.

[4] Although the existence of an approximate number system is widely accepted, it is challenged by some researchers who propose that large numerosities (e.g., above the subitizing range) can only be estimated from low-level sensory cues like surface area (e.g., Gebuis, Cohen Kadosh, & Gevers, 2016, 2017; Gevers, Kadosh, & Gebuis, 2016; Zimmermann, 2018).

Nieder and Merten (2007) provided evidence for Gaussian-shaped number representations in the form of Gaussian-shaped tuning curves of neurons in the prefrontal cortex of monkeys. In a single-cell study the authors showed that at least up to numerosity 30, there are numerosity-selective neurons whose tuning functions peak at the preferred numerosity. Firing rates of these neurons decrease and widths of the approximately Gaussian-shaped curves increase with increasing numerical distance from the neurons' preferred numerosity.

The above considerations concerning mental number representations as partly overlapping Gaussian curves (Figure 1) entail that the amount of overlap between the curves decreases with the numerical distance between numbers. Behavioural evidence for an overlap of mental number representations comes from the distance effect: whenever the numerical sizes of two numbers have to be compared with each other, responses are generally given faster and more accurately for larger than for smaller numerical distances between the two numbers (Moyer & Landauer, 1967; Restle, 1970). The increasing overlap of the curves with increasing numerical size is further endorsed by the size effect: for constant numerical distances, comparisons of numerical sizes of two numbers become more difficult with increasing numerical size (e.g., Cohen Kadosh, Lammertyn, & Izard, 2008). These two effects are considered typical markers of analogue number processing.

Spatial-numerical associations and the SNARC effect

Although the MNL is most commonly referred to as being horizontally aligned, the actual individual preference of mental number arrangements might be a different one. There is evidence for a variety of number arrangements when participants are asked to spontaneously allocate numbers to positions in space (cf. e.g., Galton, 1880). In a study by Fischer and Campens (2009), participants arranged their numbers horizontally from left to right, from right to left, radially away from the body or vertically from bottom to top when they had no further instruction as to the space or direction they were allowed to use.

Also other aspects of the format of the MNL are still under debate as for example the already mentioned question whether it is linear or logarithmically compressed. Besides evidence for the one and the other, some studies suggest that a logarithmic representation gradually develops into a linear one with mathematics education (Ashcraft & Moore, 2012; He et al., 2016; Siegler & Booth, 2004; White & Szűcs, 2012; but see Stapel, Hunnius, Bekkering, & Lindemann, 2015). Another unclear point is whether negative numbers are represented as an extension of the line beyond zero or whether they are represented as positive numbers with an attributed "minus" (for a short overview over the discussion about some aspects of the format of the MNL see Sixtus & Fischer, 2015). A default spatial mapping of numbers was not always taken for granted.[5] Even in numerical cognition research, those associations were not considered relevant for a long time, probably confounding some results and – as is nicely documented for spatial-numerical associations – leading to quite unexpected results at

[5] A prominent exception is constituted by Galton (1880; see also Seron, Pesenti, Noël, Deloche, & Cornet, 1992) who reported stable number-space relations for some individuals. Importantly, however, those spatial mappings were not inter-individually consistent, except for a postulated hereditary characteristic.

the time: Dehaene, Dupoux, and Mehler (1990) set out to investigate the processing of two-digit numbers and accidentally found that participants who responded to small numbers with a left hand button and to large numbers with a right hand button were considerably faster than participants whose response arrangement was reversed. With a few more experiments Dehaene et al. (1993) found that indeed, this pattern of results is very stable and dubbed it the spatial-numerical association of response codes (SNARC) effect.

A lot of SNARC research has been done since then (for a meta-analysis see Wood, Willmes, Nuerk, & Fischer, 2008; for a meta-analysis on mapping general magnitudes on space see Macnamara, Keage, & Loetscher, 2018) and it is widely accepted that numbers trigger spatial associations according to their magnitude (but see Proctor & Cho, 2006; van Dijck & Fias, 2011 for alternative explanations) and even orient visual attention (Fischer, Castel, Dodd, & Pratt, 2003). An explanation for the effect is based on the MNL: we represent small numbers on the left side of space and large numbers on the right side. Processing a number orients our attention towards its position on the horizontal MNL. This leads to response time advantages in congruent situations, that is, when we have to give a response on the side towards which our attention is currently directed.

These number-space associations can, however, also be triggered by the experimental setup. When the task involves vertically or radially arranged responses or primes instead of horizontally arranged ones, different but also often consistent number-space associations become visible. Small numbers are usually associated with lower as well as proximal space, whereas large numbers are associated with distal as well as upper space (Hartmann, Grabherr, & Mast, 2012; Sell & Kaschak, 2012; Winter & Matlock, 2013; Winter, Matlock, Shaki, & Fischer, 2015). As mentioned before, individuals might however differ in their preferred spatial number representation (Fischer & Campens, 2009). It is therefore not surprising that studies that presume a left-to-right MNL (like most SNARC studies) do not usually deliver homogeneous results. Albeit almost ubiquitous in studies using number targets, the SNARC effect almost never is present in each and every subject: usually some show a reverse SNARC effect or none at all (e.g., Fabbri, 2013; Fischer, 2008). And also, when assuming a general MNL underlying number representations, there are some well-known differences in its shape: the direction of the horizontal SNARC effect is at least partly culturally determined (Dehaene et al., 1993; Shaki et al., 2009), because the underlying MNL arises from overlearned number-space associations in timelines, on rulers, etc. and is thereby also at least partly determined by reading direction. Shaki et al. (2009) found the usual left-small/right-large SNARC effect in Canadians, a reverse SNARC effect in Palestinians who write words and numbers from right to left, and no reliable SNARC effect in Israelis who write words from right to left and numbers from left to right. However, the SNARC effect also relies on situational, i.e., highly flexible factors: Fischer, Mills, and Shaki (2010) reduced English speakers' SNARC effect and unmasked Hebrew speakers' reverse SNARC effect by having them read cooking instructions with large numbers (embedded within the recipes) presented on the left side and small numbers on the right side. Bächtold, Baumüller, and Brugger (1998) reversed the SNARC effect by having their (Swiss) participants judge times as earlier or later than 6 o'clock on an analog clock where small numbers are on the right and large numbers on the left side. The vertical SNARC effect (small numbers are down, large numbers are up) is often assumed to be a less flexible concept than the horizontal one as it is grounded in the physical properties of the world (e.g., more is up: high piles usually contain more elements than low piles; cf. Fischer, 2012; Lakoff, 1987).

Moreover, it is still under discussion whether number-space associations are not only culturally or situationally induced but whether there might actually be some natural predisposition to associate numerosities with space that is not limited to the human race: even newborn chicks showed spatial preferences after being presented with small or large numerosities (Rugani, Vallortigara, Priftis, & Regolin, 2015). Also in humans, recent evidence points towards an innate number-to-space mapping: 0- to 3-day-old neonates associated small quantities with left space and large quantities with right space (de Hevia, Veggiotti, Streri, & Bonn, 2017). The authors speculate that a predisposition to map number onto space facilitates learning – an argument strengthened by findings that show that for example in 7-month-old infants pattern acquisition is enhanced by a left-to-right directional presentation (Bulf, de Hevia, Gariboldi, & Macchi Cassia, 2017) and that spatial skills in children are positively correlated with the development of numerical knowledge (Gunderson, Ramirez, Beilock, & Levine, 2012).

Experiments that measure associations between concepts – like the above experiments investigating the association between space and number – are a powerful tool for exploring the mental representation of concepts and might therefore point towards the individual *meaning* of concepts in general, and specifically of number. An assumption that researchers have derived from such research is that numerical representations do not necessarily depend on space but on any dimension with which we have had sensorimotor experience (e.g., Krause, 2014). A prevailing assumption of interacting magnitude modalities has been formulated by Walsh (2003) and will be elaborated in the following.

A Theory Of Magnitude (ATOM)

Walsh (2003, 2015) promoted the idea that interactions between different types of magnitude take place because all magnitudes that can be "more" or "less" (i.e., prothetic dimensions, cf. Stevens, 1957) share a common (albeit not yet fully defined) metric. That is, a number that classifies a lot or a little is represented similarly as space that is more or less to the right or to the left, or that takes up a lot or little room, and so forth. In his seminal paper Walsh (2003) referred to the dimensions of time, space and quantity as examples for such interacting prothetic dimensions. He pointed out overlapping activation of brain regions for the processing of the three dimensions and proposed the inferior parietal cortex to be the locus of common magnitude processing. He argued that concepts interfere when tasks require the processing of more than one of the given dimensions. The reason for their common representation is proposedly the need to integrate all available magnitude information for successfully coordinated action. The idea of such a *generalized magnitude system* – away from purely modularised categorization – has over the years proven to be a promising one. Further studies have addressed further prothetic dimensions and whether their magnitudes also fit into a generalized magnitude system. Mostly, it was investigated whether their magnitudes interacted with other dimensions' magnitudes. This has for example been found for pitch (Hartmann, 2016; Ishihara et al., 2013; Lidji, Kolinsky, Lochy, & Morais, 2007; Rusconi, Kwan, Giordano, Umiltà, & Butterworth, 2006), luminance (Cohen Kadosh, Cohen Kadosh, & Henik, 2008; Pinel, Piazza, Le Bihan, & Dehaene, 2004), and motor functions such as manual force (e.g., Krause, Lindemann, Toni, & Bekkering, 2014) and action planning in grasping (Lindemann, Abolafia, Girardi, & Bekkering, 2007). Action and other magnitudes are seemingly linked, which endorses the hypothesis that magnitude representations interact to guide action. Binetti et al. (2015) furthermore showed that the interaction between different magnitudes can indeed be directly modulated by actions. They found that exerting manual force to control visually perceived spatial changes (as opposed to visually perceiving externally controlled spatial changes) enforced the interaction of spatial and temporal representations. That is, action seems to bind (mental representations of) space and time.

The relevance of a generalized magnitude system for the current thesis is therefore twofold: first, finger counting as an action might function as a catalyser for binding mentally represented magnitudes with one another (cf. Binetti et al., 2015), thereby allowing (mental representations of) external quantities to be processed by the generalized magnitude system (see also Andres, Di Luca, & Pesenti, 2008; Coolidge & Overmann, 2012). Second, fingers or finger postures themselves might constitute a new prothetic dimension within the generalized magnitude system, because they, too, can be "more" or "less" and they, too, interfere with the processing of other magnitude dimensions as this thesis will document.

The triple-code model

A most influential model of number processing was developed by Dehaene (1992; Dehaene & Cohen, 1995) and assumes three different, interacting formats in which numbers are represented in the brain (see Figure 2). The adequately named *triple-code model* (TCM) comprises a verbal code for number words, a visual code for Arabic numerals, and an analogue code that handles magnitude representations of different kinds. In the verbal code, number facts that are memorised verbally like counting, simple addition, and multiplication tables are stored. The input and output in this format take place in written or spoken form. In the visual code, other number-related knowledge like their parity is stored and harder operations that are mentally visualised like multi-digit operations are executed. The input and output take place in the form of written Arabic numerals. In the analogue code, numbers can be compared and approximate calculations can be performed. An input can take place through subitizing and estimation, but a direct output is not possible in this format. Numerosities would have to be translated into one of the other formats first. In contrast to the other two codes, the analogue code is independent from notation or modality (e.g., Cohen Kadosh & Walsh, 2009). Dehaene (1992, p. 35) refers to it as "the main, and perhaps the only, 'semantic' representation of numbers". He furthermore specified that "[i]n the *analogue magnitude code*, numerical quantities are represented as inherently variable distributions of activation over an oriented analogical number line obeying Weber-Fechner's law" (Dehaene, 1992, p. 30), giving again the MNL the key role in his model in that it constitutes the meaning of number. Importantly, the MNL – or positions on the MNL – as the underlying meaning of number suggests that also spatial representations are an indispensable part of number concepts. Furthermore, also numerosities of sets of auditory objects, which are defined by temporal aspects, are extracted and processed by the analogue code (e.g., Dehaene & Cohen, 1995). It is therefore conceivable that here a very direct link between the TCM and Walsh's (2003) ATOM model can be forged: analogue magnitudes (of the TCM) possibly directly correspond with the magnitudes of the generalized magnitude system. The most parsimonious hypothesis might be to consider them to be identical.

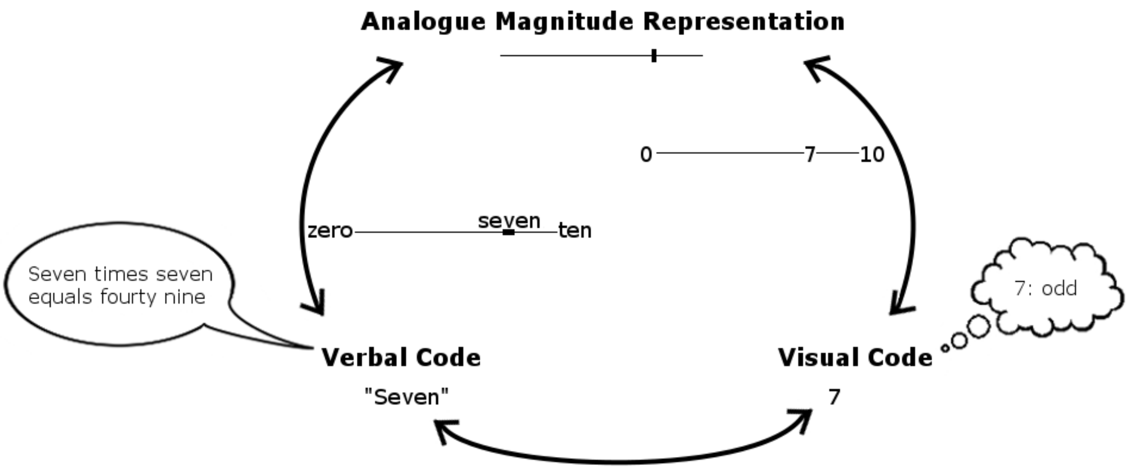

Figure 2. The triple-code model, adapted from Dehaene (1992) and Sixtus and Fischer (2015).

Due to the present thesis' main topic, it is of special interest how the TCM relates to finger counting. Numerical meanings of fingers can be fitted into the model in two different ways. They can adapt to the TCM, or the model can be adapted to them. That is, they can either be seen as a sub-dimension of one of the three codes – either as another symbolic form within the visual code or a magnitude of sensorimotor activation within the analogue code (or both) – , or they can constitute a fourth, new code (e.g., Di Luca & Pesenti, 2011; Moeller et al., 2012; Roesch & Moeller, 2014). Di Luca and Pesenti (2011, p. 2) explicitly argue that "finger numeral representations (…) qualify as another type of numerical representation worthy of being considered by current cognitive number-processing architectures – perhaps as a fourth type of representation if they were to be integrated into Dehaene's (1992) Triple Code framework". Moeller et al. (2012, p. 273) conclude that "finger-based representations of number (magnitude) are a distinct and automatically activated numerical representation", in addition to the traditional three codes of Dehaene's (1992) model. The question whether or not finger counting should be part of the TCM has not yet been conclusively answered. My research included in the present thesis therefore also aimed to investigate whether finger counting fits into the TCM as an extension of an existing code or requires its extension into a quadruple-code model.

The Embodied Cognition framework

Mental number representations, and knowledge representation in general, have once been believed to be of purely abstract nature and their processing to be completely detached from bodily properties and experience (e.g., Mandl & Spada, 1988). This is not the leading opinion anymore and today bodily experience, that is, sensory and motor information, is often attributed a leading role in cognition (e.g., Gallese & Lakoff, 2005), especially in understanding action (e.g., Andres, Finocchiaro, Buiatti, & Piazza, 2015), but also in intuitively more abstract domains as for example in processing number (e.g., Andres, Seron, & Olivier, 2007). The term *embodiment* in general describes that “[t]he content of semantic representation is sensory and motor information” (Meteyard, Cuadrado, Bahrami, & Vigliocco, 2012, p. 790). There is a vast range in interpretations of the extent to which cognition is embodied (for an overview over a broad range of embodiment theories see Meteyard et al., 2012), but in general, the so-called embodied cognition framework states that when we gain (abstract) knowledge, the sensorimotor experience that accompanied the learning process stays a fundamental part of the knowledge representation.

The paradigm shift has already started some decades ago. One of the first seeing the need for a departure from theories of amodal knowledge representation was John R. Searle. Searle (1980) reflected that any sensible symbols can be sensibly manipulated with the appropriate instructions, without the need of understanding any meaning behind those symbols. Addressing this *symbol grounding problem*, Harnad (1990) pointed out the need for a bottom-up grounding of symbolic representations in nonsymbolic representations so that a meaningful handling of symbols can take place. Known as pioneers in the field of grounded cognition, Barsalou (1999) and Glenberg (e.g., Glenberg & Kaschak, 2002; Glenberg & Robertson, 2000), among others, then followed up on the symbol grounding problem. As an approach to a solution, Barsalou (1999) suggested that “simulators” steadily simulate stored perceptual components of the concepts that currently have to be understood by the cognitive system and introduced the theory of perceptual symbol systems. Part of the idea is that sensorimotor states are simulated (through re-enactment) in modality-specific systems. These simulations are flexible to meet the situational requirements. They prepare for actions within the particular situation; however, they also carry information that is not necessarily present in the current situation. It is through such *pattern completion* that priming effects of related concepts may take place, which are often reported in studies referring to embodied cognition (Barsalou, 2008; Barsalou, Niedenthal, & Barbey, A., Ruppert, J., 2003; Barsalou, Simmons, Barbey, & Wilson, 2003). Glenberg and colleagues investigated the role of the body and bodily experience in language comprehension (Glenberg & Kaschak, 2002; Glenberg & Robertson, 1999, 2000). A prominent example of the body’s role in language comprehension is the action-sentence compatibility effect: Glenberg and Kaschak (2002) found that participants were faster to respond to sentences about an action implying a direction when manual responses were in the same direction (e.g., movements towards the body for the sentence “open the drawer” and movements away from the body for the sentence “close the drawer”). Casasanto (2009) furthermore proposed that all cognition depends on the thinker’s specific body, because cognition always involves experience of bodily interactions with the physical environment. This is known as the *body-specificity hypothesis* (Casasanto, 2009). Right-handers for example tend to associate positive ideas with rightward space and negative ideas with leftward space; this association, which is also reflected in idioms in many languages, is reversed for left-handers (Casasanto, 2009; Casasanto & Henetz, 2012). It can even be reversed in right-handers through long-term or short-term handicap of the right hand due to left-hemisphere stroke or 12 minutes-intervention hindering right-hand actions, respectively (Casasanto & Chrysikou, 2011; see Chrysikou, Casasanto, & Thompson-Schill, 2017 for conceptual replication of the body-specificity hypothesis for stroke patients).

These ideas of bottom-up grounding of representations, of simulators that simulate perceptual knowledge, of language comprehension depending on action experience, and of cognition depending on specific bodies lay the foundation to the embodied cognition idea. The previous paragraph was a short and straightforward overview over the in fact neither short nor straightforward pathway towards a relatively broad acceptance of the embodied cognition framework. As mentioned before, there is a wide range of interpretations of the extent of the role that bodily representations play in cognition, and also regarding the kinds of knowledge representation that depend on bodily representations (Meteyard et al., 2012). The more moderate embodied cognition approaches attribute the body and the external world functions that the mind can use for processing information more efficiently. Following this logic, especially action understanding should draw on bodily representations due to bodily experience (Mollo, Pulvermüller, & Hauk, 2016; Pulvermüller, Hauk, Nikulin, & Ilmoniemi, 2005). On the other hand, radical embodied cognitive scientists like Chemero (2011, 2013) doubt the existence of mental representations altogether. Standing in the tradition of William James, James Gibson and Rodney Brooks, among others, radical embodied cognitive science explains the human interaction with the world as interactive without the need of forming representations. This radical view is anything but universally accepted. Less radical views are, however, especially criticised for being too vague and non-explanatory (Goldinger, Papesh, Barnhart, Hansen, & Hout, 2016). Chemero (2013, Abstract) also criticises current, more moderate embodied cognition approaches for merely "supplementing standard cognitive psychology with occasional references to the body". Meteyard et al. (2012) reviewed theories which explicate semantic representations, placing them on a continuum from completely unembodied to strongly embodied. The authors conclude that both ends of the continuum are not supported by neurophysiological findings, because there is evidence both for essential sensorimotor involvement in semantic processing (refuting purely abstract, unembodied knowledge representation) and for abstracted knowledge representation which does not fully depend on sensorimotor representations (refuting fully embodied representations).

The present thesis should be contemplated in the light of a moderate embodied cognition approach. Finger counting offers numerical cognition research more than just an occasional reference to the body. The role of the body in finger counting as the embodiment of number concepts appears more or less self-explanatory in general, but the specifics and the extent of the body's role in number representations are yet to be explored. The fundamental idea of the embodied cognition approach which I like to refer to is nicely expressed in Glenberg, Witt, and Metcalfe's (2013, p. 573) words: "how we think depends on the sorts of bodies we have. Furthermore, the reason why cognition depends on the body is becoming clear: Cognition exists to guide action. We perceive in order to act (and what we perceive depends on how we intend to act)".

A hierarchy of groundedness, embodiedness, and situatedness

Over the years a big number of studies that explained their results as instances of embodied cognition have accumulated. The underlying mechanisms however vary, indicating a further subdivision. One widely accepted subdivision embeds embodied cognition in a hierarchical structure of grounded cognition, embodied cognition, and situated cognition (Fischer, 2012; Fischer & Brugger, 2011). Good examples of the grounded and situated levels have already appeared in the SNARC section: a vertical mapping of numbers to space which follows physical rules ("more is up") is grounded, because it is derived from general laws of physics of the world that we live in. It reflects so to say our default knowledge of the world and provides the default context in which we process information. This can be overridden whenever embodied or situational factors provide more immediate processing information. As described above, the horizontal SNARC effect was reversed when participants were asked to handle numbers as hours on an analogue clock face (Bächtold et al., 1998), which is a prime example of situated cognition. Quite a few studies more have shown that numerical processes are influenced by situated conditions, for example by allocating attention on the MNL or by co-activating the respective magnitude representations. Loetscher, Schwarz, Schubiger, and Brugger (2008) found that participants who generated random numbers while alternately turning the head to the left and right side generated more small numbers with the head turned left than right. Shaki and Fischer (2014) reported that in participants who were asked to walk and turn while generating random numbers, turn direction and number generation interacted. Eerland, Guadalupe, and Zwaan (2011) reported that also the estimation process was influenced by body posture: participants who estimated numerical values like heights of famous buildings gave smaller values when leaning to the left than when in an upright position or when leaning to the right. Unlike in Loetscher et al.'s (2008) experiment, participants were not aware of the body manipulation. That is, proprioceptive information in the absence of awareness interacted with mental number representations.

The main focus of the present thesis lies on the embodied level of numerical knowledge representation because it tests the assumption that mental number representations partly rely on our bodily experience with numbers (in the form of finger counting). To be precise, the novel studies addressed situated effects of embodied number representations, that is, the automatic interaction of the available sensorimotor information with mental number representations which rely on finger counting experience. The above examples already showed that bodily states and the performance of actions influence number processing and are in turn influenced by it. In the following I will present evidence that bodily states not only act on number processing but that bodily representations also constitute a part of number representations. The term *manumerical cognition* has been established to emphasise the role of the hands, and specifically of the fingers in mental number representations (Fischer, 2008; Fischer & Brugger, 2011).

Manumerical Cognition – evidence so far

We have seen that numerical representations and estimation are influenced by action and perception of one's own body. While the effects described above are assumedly a consequence of attention being spatially shifted on the MNL, there are also closer connections between bodily and numerical representations. The most obvious connection is established early in life: most children start to represent numbers with their fingers. For example, when asked about their age, many children proudly present the enquirer with a scrupulously rehearsed finger configuration, often before they are even able to grasp the meaning of the posed number. Fingers or finger configurations then become progressively linked with numbers through finger counting, which probably aids acquisition of counting principles such as proposed by Gelman and Gallistel (1978). Especially the first three principles, which they called "how-to-count principles", can be perfectly experienced by finger counting: the one-to-one correspondence, stable order, and cardinal principle become obvious when raising fingers one after the other in a fixed order, that is, sticking to consistent (Western) finger counting practices (cf. Andres, Di Luca et al., 2008; Di Luca & Pesenti, 2011). This can be viewed both as an opportunity for reinforcing the comprehension of numerosity – visible and easy to manipulate as fingers are – and as a risk for the internalization of the abstract concept of numbers (Beller & Bender, 2011; Moeller & Nuerk, 2012). There are plenty of different finger counting styles in different cultures (Bender & Beller, 2012). However, most research so far involves Western participants who mostly count in a more or less specific way. Also the current section – and the present thesis in general – will involve mainly the Western finger counting style. In Western cultures, most individuals use a one-to-one correspondence of numbers to fingers, that is, incrementing the involved fingers by one also augments the represented number by one. The increment however can comprise either folding fingers out or folding them in. Also the order of the involved fingers differs. For example Germans, French, Canadians, Scots, Italians, and Belgians, among others, have been reported mostly to start by folding out the thumb of one hand, proceeding with the index finger, middle finger, ring finger, and pinkie of the same hand and repeating the process with the other hand (Brozzoli et al., 2008; Di Luca & Pesenti, 2008, 2010; Domahs, Moeller, Huber, Willmes, & Nuerk, 2010; Fabbri, 2013; Fischer, 2008; Morrissey, Liu, Kang, Hallett, & Wang, 2016; Sato & Lalain, 2008; Zago & Badets, 2016). Many Spaniards and Russians, on the other hand, start to count on the pinkie (Liutsko, Veraksa, & Yakupova, 2017; Okan, Fischer, & Lindemann, in preparation). Furthermore, there is evidence that counting behaviour is stable across time: Sato and Lalain (2008) reported that in their French sample different age groups between four and 47 years of age exhibited stable counting behaviour.

Even individuals that share a finger counting sequence (e.g., from thumb to pinkie) often differ regarding the order in which they use their hands. The starting hand seems to be strongly influenced by situational factors like whether one hand is holding something or whether the instructions are given in written or verbal format by a questionnaire or the experimenter, respectively (Wasner, Moeller, Fischer, & Nuerk, 2014a). However, the starting hand is also to a certain extent culturally determined: in a more large-scale online survey, about two thirds of Western individuals reported to start counting on the left hand and about two thirds of Middle Eastern individuals reported to start counting on the right hand (Lindemann, Alipour, & Fischer, 2011). Moreover, even within Western countries the prevalence differs: while around 85 % of the U.S.-Americans reported to start counting on their left hand, Italians and Belgians started on their left hand about equally often as on the right hand.

Having established that there are predominant finger counting habits and that finger counting is a very common habit I will elaborate on the cognitive consequences and also to some extent on the roots of this habit. There are indications that fingers are an especially handy tool for representing and manipulating numbers and there is quite some evidence that finger counting establishes a very strong mental link between fingers and numbers. Fingers seem to be predestined for representing numbers also for other than the obvious reason that they are physically readily available: there is cortical overlap between finger and number representations. Following, I will first describe some of the neuroscientific foundations for finger-number interactions in the parietal and the motor lobe of the human brain, which possibly promote the prevalence of finger counting.[6] Subsequently, I will present behavioural evidence for existing finger-number interactions, i.e., the long-lasting effect of finger counting habits and the relevance of finger-number associations.[7]

Neuroscientific evidence – associations in the parietal lobe

Gerstmann (1940) reported a syndrome, which was named after him, which consisted in damaged parietal cortices, with affected left angular gyri. Among other things, the patients suffered both from acalculia and finger agnosia, a symptom that involves the inability to discriminate their own fingers as well as visually perceived fingers of other people. For some time, the Gerstmann syndrome was taken as evidence that fingers and numbers are mentally represented by the same cortical area. Finally, the pure Gerstmann syndrome was shown not to result from damage of a shared cortical substrate for finger and number representations. Instead it was found that damage to a small region of subcortical parietal white matter cascades to provoke all of the disorders of the syndrome (Rusconi et al., 2009; see also Dehaene, Piazza, Pinel, & Cohen, 2003). However, despite the misinterpretation of the Gerstmann syndrome, it had aroused interest in the connection between mental finger and number representations, which nevertheless turned out productive. Roux, Boetto, Sacko, Chollet, and Trémoulet (2003), at this time still referring to the Gerstmann syndrome, studied the cerebral functions represented in the angular gyrus and close regions by using electrostimulation. Both calculation and finger recognition skills could be located in the angular gyrus, the supramarginal gyrus, and close to the intraparietal sulcus (IPS). Moreover, Rusconi, Walsh, and Butterworth (2005) also found a neuronal connection between the ability to discriminate fingers ("finger gnosis"[8]) and to process numbers. The authors applied repetitive transcranial magnetic stimulation (rTMS) to their participants' left angular gyri and the same intervention induced a transient finger agnosia and disrupted number processing in the same participants. Andres, Michaux, and Pesenti (2012) also looked into the parietal cortex; to be more precise, the authors used functional magnetic resonance imaging (fMRI) to investigate the cortical areas involved in finger discrimination and mental arithmetic. They found that the horizontal part of the IPS and the posterior superior parietal lobule bilaterally subserve both competencies.

The associations and co-activations of mental number and finger representations, and specifically of neuronal circuits underlying both representations, first appear to be a

[6] Another locus of interactions between fingers and numerical processes, which is less often mentioned, is the cerebellum. Vandervert (2017, p. 10) described that "practiced improvements in number calculation (or in anything else practiced) would be learned as constantly error-corrected internal models in the cerebellum (…). And, it is proposed that, because it sets the occasion for structured practice, the use of fingers in calculation improves arithmetic ability via the cerebellum-driven collaboration between the cerebellum and cerebral cortex". Importantly, he stresses that the cerebellum's proposed significant role in the formation of a mental number concept and in finger-number interactions does not necessarily conflict with the intraparietal cortex' also proposedly significant role in mathematics or a number sense.

[7] Furthermore, there is even computational evidence for finger counting being an effective tool for basic numerical competencies: a computer simulation model of a humanoid robot developed initial number representations faster with the help of finger counting configurations than when number words were simply learned out of sequence (De La Cruz, Vivian M., Di Nuovo, Di Nuovo, & Cangelosi, 2014).

[8] *Gnosis* comes from the ancient greek word for "knowledge"; the term finger gnosis therefore denotes the opposite of the above described symptom of Gerstmann syndrome *finger agnosia* (the prefix *a-* indicates a negation). That is, finger gnosis describes the ability to discriminate fingers, for example when trying to locate tactile stimulations of the own finger tips.

chicken-and-egg problem. Are the two representations related because of the given anatomical reasons – i.e., neighbouring underlying brain areas? Or does our cortical architecture adapt through Hebbian learning to the experiences we made when learning numbers through fingers? Additionally to the former (a localizationist view; Dehaene et al., 2003) and the latter (a functionalist view; Butterworth, 1999b; Penner-Wilger & Anderson, 2013), another view has formed. Dehaene and Cohen (2007) and Penner-Wilger and Anderson (2013) propose that numerical abilities build on older, pre-existing neural circuits that subserve cognitive functions with the same requirements. Neural circuits that support certain aspects of finger representations would be “recycled” or “redeployed” for certain aspects of numerical abilities and the cortical overlaps reported above should then be expected. While Dehaene and Cohen (2007) attribute the “recycling” process to the course of development, Penner-Wilger and Anderson (2013) propose that “redeployment” is a persistent, evolutionary process. All of these explanations are plausible and probably several, if not all, of them contribute to associations of mental number and finger representations.

One further recent finding including parietal activations worth mentioning concerns a dissociation of cortical activations in different groups of participants when being confronted with various mathematical statements (Amalric & Dehaene, 2016). The authors did not specifically test finger representations but basic number recognition, which is another precursor ability of numerical competencies. In professional mathematicians, but not in non-mathematician controls, cortical regions activated during evaluation of complex mathematical statements overlapped with those activated during arithmetic calculation and basic number recognition (including parietal regions). This suggests that our most basic representations of any concepts permeate throughout all knowledge that builds upon this original construct, which implies a major importance of getting it right – right from the start. What is more, one of the regions with stronger activation for meaningful than for meaningless math statements in professional mathematicians only was the IPS (bilaterally) which has also been shown to subserve finger knowledge (e.g., Andres et al., 2012; Roux et al., 2003). As stated above, this has not been tested by the authors, but it is conceivable that finger representations also interact with proficiency in higher mathematics to some degree.

Neuroscientific evidence – associations in the motor cortex

Additionally to findings of co-activations for finger and number processing in the parietal lobule, the motor cortex has been found to be active in both finger and number processing. While that is not at all surprising for the finger part, the role in number processing is not as obvious. The functionalist view provides a plausible explanation: after using our fingers for representing and learning about numerical values, mental finger representations become a fundamental part of number knowledge and are therefore always co-activated. That is, number knowledge is embodied, or grounded (by this wording referring back to the “symbol grounding problem” addressed above, which is aimed to be hereby resolved) in the fingers. This should not be taken to mean that people without fingers were not able to understand numbers as well, but they would have to rely on other means. Neuroscientific evidence for the role of the motor cortex in numerical processing will be reviewed in the following short paragraphs. The line of argument in each of the three following studies is that mental number processing co-activates hand motor representations, which is measured by recording motor-evoked potentials (MEPs) or using fMRI.

Andres et al. (2007) induced transcranial magnetic stimulation (TMS) while participants counted items, using either numbers or letters of the alphabet. TMS was applied to the primary motor cortex and MEPs were recorded from the hand (right FDI), arm (right biceps brachialis), and foot muscles (right tibialis anterior). Results showed that corticospinal excitability was increased for hand muscles, but not for arm or foot muscles, during both counting tasks. The authors proposed that any ordered series used for counting should yield these results.

Sato, Cattaneo, Rizzolatti, and Gallese (2007) also applied TMS to participants' primary motor cortices of the hand. Participants performed a parity judgement task for numbers 1 to 9 except 5. MEPs were recorded from the hand contralateral to the stimulated cortex. Smaller numbers (1-4) evoked larger MEPs in the right hand muscles than did larger numbers (6-9). Importantly, all participants were right-starters in finger counting, that is, they used the right hand for counting numbers 1-5 and the left hand for numbers 6-10.

A similar finding comes from Tschentscher, Hauk, Fischer, and Pulvermüller (2012), who used fMRI to examine participants' motor and premotor cortices during visual number presentations. The numbers were presented to left- and right-starters as Arabic numerals and number words. Presentations of small numbers 1-5 in either notation evoked cortical activity selectively in the motor cortex contralateral to the individual starting hand in left-starters as well as in the premotor cortex contralateral to the individual starting hand in both left- and right-starters.

While the first of the three studies shows the general role of the hand motor cortex in number processing, the latter two furthermore show that this link of hands and numbers is even more specific in that it is shaped by individual experience: individual finger counting habits seem to modulate cortical activity during number processing.

Behavioural evidence

Unspecific and specific hand-number associations have also been found in behavioural studies. Interactions of manual actions with number and magnitude processing have for example often been found in grasping (Andres, Davare, Pesenti, Olivier, & Seron, 2004; Andres, Ostry, Nicol, & Paus, 2008; Badets, Bouquet, Ric, & Pesenti, 2012; Lindemann et al., 2007; Moretto & Di Pellegrino, 2008; Namdar, Tzelgov, Algom, & Ganel, 2014) and with active (Crollen & Noël, 2015; Michaux, Masson, Pesenti, & Andres, 2013) or passive hand movements (Imbo, Vandierendonck, & Fias, 2011). However, interactions of numerical stimuli with grasping have assumedly different underlying mechanisms than interferences between number processing and hand movements: while in grasping the generalized magnitude system presumably directly mediates between numerical magnitudes and the magnitudes inherent in grip size (e.g., precision vs. power grips, Lindemann et al., 2007; Moretto & Di Pellegrino, 2008), unspecific hand movements are presumed to interfere with number processing because of the hands' direct link to mental number representations as established through and reflected in finger counting (Imbo et al., 2011; Michaux et al., 2013). The associations are even more specific and exist between individual fingers and magnitudes (Riello & Rusconi, 2011), individual fingers and specific numbers (Di Luca, Granà, Semenza, Seron, & Pesenti, 2006) and between finger counting postures and numbers/magnitudes (Badets, Pesenti, & Olivier, 2010; Di Luca & Pesenti, 2008).

All the research on the body's role in mental number representations is in its own right of interest for the sake of basic research. Even more gratifying is it that some of it is already applicable in the "real world". Before going into more detail of some of the most relevant (basic research) studies, I will present some of the applications of the gained knowledge in education settings.

Applied manumerical cognition

Regardless of where finger-number interactions stem from – be it coincidental adjacency of cortical regions, Hebbian learning through recurring co-activation of the two concepts, or redeployment of evolutionarily older neural circuits – it is a good idea for mathematics education to build on it. There is growing evidence that motor skills in general (e.g., Reikerås, Moser, & Tønnessen, 2017) and especially manual fine motor skills are positively related to numerical and mathematical skills (Asakawa & Sugimura, 2014; Dinehart & Manfra, 2013; Fischer, Suggate, Schmirl, & Stoeger, 2017; Grissmer, Grimm, Aiyer, Murrah, & Steele, 2010; Luo, Jose, Huntsinger, & Pigott, 2007). Given the evidence reviewed in the previous sections concerning interactions between mental number processing and both finger counting habits and finger gnosis, the following two paragraphs will briefly present applicable findings concerning finger counting and finger gnosis.

Based on findings concerning the development of numerical knowledge, including the development of counting principles (Gelman & Gallistel, 1978) and the structure of an assumed mental number line (Ashcraft & Moore, 2012; Siegler & Booth, 2004), researchers have formulated models of how children acquire basic and progressively complex mathematical knowledge (Fritz, Ehlert, & Balzer, 2013; Fritz & Ricken, 2008; Fuson, 1988; Krajewski, 2008; Resnick, 1989). Part of the process involves that children first rely on concrete items before they are able to represent and manipulate numbers mentally. As such concrete items, obviously the fingers come into play, being always at hand and easily manipulable. However, reliance on finger counting practices in math education becomes a problem and at the beginning of second grade, finger counting is usually given up as it is seen as a dead end for further mathematical competencies (Moeller & Nuerk, 2012; Soylu, Lester, & Newman, 2018). There is evidence that early reliance on finger counting is helpful for developing mathematical competencies, while it becomes detrimental from second grade on (Dupont-Boime & Thevenot, 2018; Jordan, Kaplan, Ramineni, & Locuniak, 2008; for a detailed review see Soylu et al., 2018). More systematic research concerning this matter is however needed, for example regarding the specific way of how (finger) counting should be prompted. There are first indications that consistency in counting direction is connected to maturity of number representations: Rinaldi, Gallucci, and Girelli (2016) assessed children's consistency of spatial-numerical associations, that is, whether they counted their fingers as well as other objects in peripersonal space consistently from left to right versus from right to left. A consistent counting direction including a consistent starting hand in finger counting was found to be associated with a linear (as opposed to logarithmic) positioning of numbers onto a number line which was only labelled with 0 and 10 on the left and right side, respectively. That is, consistency of counting direction and a consistent starting hand correlated with the linearity of number representations, an established signature of the maturity of number representations.

Referring to evidence indicating the relationship between finger gnosis and mental number representations, finger gnosis was investigated as a precursor of mathematical abilities in young children. Finger gnosis is usually measured as the ability to discriminate the own fingers when the tip of one or two fingers of one of the participant's hands are lightly touched. The hand is usually hidden from his or her view. The participant then, for example, has to name the stimulated finger(s) or point to the stimulated finger(s) on his or her own hand using the other hand (e.g., Benton, 1955; Gracia-Bafalluy & Noël, 2008; Noël, 2005). Findings as to the relation between finger gnosis and arithmetic skills vary substantially (e.g., Fayol, Barrouillet, & Marinthe, 1998; Noël, 2005 reported positive correlations between the two skills; Long et al., 2016 reported no correlation; Newman, 2016 reported positive correlations only for older, but not younger children). One influential study was conducted by Gracia-Bafalluy and Noël (2008). In their intervention study the authors trained first-grade children's finger gnosis and tested numerical competencies before and after eight weeks of training. The trained children outperformed a control group of children (who received training in story comprehension) in quantification tasks that comprised subitizing and counting raised fingers in pictures of hands (but see Fischer, 2010 for methodological criticism). However, fully functional finger gnosis cannot be a necessary condition for numerical abilities, because in children with congenital hemiplegia (who show lower finger gnosis on their plegic hand than children without hemiplegia on their non-dominant hand) arithmetic skills are preserved (Thevenot et al., 2014). Thevenot et al. (2014) tested the theory that finger use is a necessary step for the transition from non-symbolic to symbolic numerical abilities. Although their results rather indicate that fingers are useful instead of necessary, it is worth mentioning that, apart from arithmetic skills, symbolic numerical tasks and subitizing were impeded in children with hemiplegia, while other non-symbolic tasks were not. Finger gnosis thus apparently left traces in some numerical competencies even if it wasn't a prerequisite for number processing per se. Furthermore, Poltz, Wyschkon, Höse, Aster, and Esser (2015) studied a group of over 1500 children of about 4-7 years of age. The authors reported that finger gnosis predicted counting and calculation abilities about nine months later to some extent, even when controlling for the influences of nonverbal intelligence, visuo-spatial working memory and selective attention. Wyschkon, Poltz, Höse, Aster, and Esser (2015) used data of the same sample and looked for low finger gnosis as a risk factor for later mathematical deficits, but this was not supported by the results. Kohn et al. (2015), who tested children between 7 and 11 years of age, found no correlation between finger gnosis and mathematical abilities. However, they did report a correlation of finger gnosis with basic numerical abilities like the detection of dot patterns with less than 10 dots and the visuo-spatial attention span. Furthermore, Wasner, Nuerk, Martignon, Roesch, and Moeller (2016) also investigated the role of finger gnosis in the prediction of initial arithmetic performance (simple single-digit addition and subtraction problems) in first-graders at the beginning of the school year. The authors report that although finger gnosis is not fit for diagnostic purposes due to its weak predictive value of 1-2%, it still provided a unique part in the prediction of the tested children's initial arithmetic competencies beyond the influence of various control variables like general cognitive ability, short-term memory, numerical precursor competencies, age, and gender. Hence, there is accumulating evidence of a role of finger gnosis in numerical competencies, although in most of the reported studies the results did not speak for a developmentally indispensable influence. Nevertheless, finger gnosis still seems to serve as a starting point for pre-numerical training even if it were not of diagnostic use.

Research on finger-number interactions in adults, that is, persons with consolidated number concepts, is a promising basis for the search of pre-numerical trainings. Knowing which parts of actual finger counting shape numerical concepts in the long term and lead to more or less efficient number handling might point out the components of finger counting we have to focus on during children's number acquisition.

Further behavioural evidence and thesis outline

The present thesis builds on behavioural evidence for finger-number interactions in that the main part is constituted of 4 novel studies reporting behavioural experiments. My studies aim to systematically investigate the ways in which active or passive finger involvement affects number processing. Finger knowledge and finger counting as a precursor of number processing skills is of particular interest because here we can exert influence on numerical skills in the earliest stages of number acquisition (e.g., Gracia-Bafalluy & Noël, 2008) and the earliest, most basic representations of numerical knowledge might determine how numbers are processed throughout life (Amalric & Dehaene, 2016).

In a cross-cultural study Domahs et al. (2010) provided evidence that adults' history of learning numbers by use of fingers still exerted influence on how numbers are mentally processed. German and Chinese participants were presented with two horizontally aligned numbers with the numerical distance of two and they pressed a button on the side of the smaller or bigger number (depending on task instructions). Germans were markedly slower to respond when at least one of the numbers exceeded five, that is, when manually performing the corresponding finger counting posture would have required two hands instead of one for at least one of the two numbers. Chinese participants, whose finger counting system requires only one hand for numbers up to ten, did not show such a *five-break effect*. In another study, (German) adult participants were slower in solving addition problems when the sum of the unit digits exceeded five, that is, it could not be represented with only one hand (Klein, Moeller, Willmes, Nuerk, & Domahs, 2011). Furthermore, especially (German) children at the end of second grade frequently make errors in simple addition problems that deviate from the correct result by five, that is, by a full hand (Domahs, Krinzinger, & Willmes, 2008). This is taken as evidence that the hands play a fundamental role in number processing even when they are not actively involved. The question now arises, whether these patterns also emerge when the hands are actually actively involved for responses. Furthermore, it has been shown that participants are intra-individually not fully consistent in their choice of finger configurations in counting versus montring[9] postures (Wasner, Moeller, Fischer, & Nuerk, 2014b). However, it is unclear whether participants are even consistent in their finger configurations when repeatedly performing the same task. **Study 1** addressed these points with a posture production task: participants repeatedly performed finger postures according to visually presented numbers. In the first of three tasks, the posture had to match the number and in the following two tasks, the number plus or minus one had to be produced. Specifically participants' consistency of the produced postures, the kind of produced errors, and the

[9] The term *montring* was established by Di Luca and Pesenti (2008) and describes the act of showing a numerosity with the fingers without counting up to this number first.

problem size effect usually inherent in arithmetic tasks (Zbrodoff, 1995) are discussed. Additionally, finger counting and montring postures for numbers up to 4 were compared in a larger sample.

Moreover, specific finger postures are automatically associated with numbers and magnitudes (Badets et al., 2010; Di Luca & Pesenti, 2008). Di Luca and Pesenti (2008) conducted a typical number classification task where numbers had to be classified as smaller or bigger than the reference number five. Before the visual presentation of the target number, pictures of finger counting postures were presented subliminally (for 68 ms and visually masked) and the postures did or did not match the required response (i.e., smaller or bigger than five). When posture and target number were congruently smaller or bigger than five, responses were faster than in incongruent situations, suggesting an automatic activation of the magnitude concepts that were subliminally delivered by the visual perception of the finger postures. Here, the question arises whether the proprioception of an actually performed finger posture exerts a similar priming effect. The first experiment of **Study 2** compared the priming effects of visually perceived and manually performed finger postures. While in the first experiment participants only produced finger counting postures, the second experiment tested whether the production of other finger postures with the same amount of extended fingers also co-activated number concepts.

As indicated before, not only links between finger postures and magnitudes, but also between single fingers and single numbers have been reported. Di Luca et al. (2006) tested participants' finger-to-number preferences: participants' fingers were positioned on a computer keyboard in such a way that one button of the keyboard was assigned to each finger. Depending on a visually presented number, a button had to be pressed with one of the 10 fingers. The authors tested different finger-to-number mappings and found that the mapping according to participants' finger counting preferences produced the fastest response times (see also Rinaldi, Di Luca, Henik, & Girelli, 2016). **Study 3** tested sequential finger movements in conjunction with a number reading task, that is, the sequence of button presses was predefined and the target numbers varied, which had to be read aloud. The study thereby investigated whether the motor experience of finger movements in counting is deeply linked to related number knowledge and still primes the reading of number words in adults.

Furthermore, not only active posture production or finger movements are linked to number processing, but also passive finger stimulation (Cohen, Aisenberg, & Henik, 2016; Cohen & Henik, 2016; Cohen, Naparstek, & Henik, 2014; Krause, Bekkering, & Lindemann, 2013; but see Brozzoli et al., 2008). Krause et al. (2013) reported that enumeration of tactually stimulated fingers and Arabic numerals were processed in a similar vein. Participants compared two numbers cross-modally and exhibited a distance effect – a typical marker of analogue number processing – which indicates that both number representations drew on the same underlying processes. **Study 4** investigated different finger configurations in more detail and specifically, whether finger counting habits have shaped specific finger configurations into number symbols which have a processing advantage compared to other configurations. The first experiment of this study compared efficiencies in naming the number of tactually stimulated fingers dependent on whether the set of stimulated fingers corresponded to finger counting habits. The second experiment furthermore addressed the association of mental representations of specific numbers and single fingers: does the tactile stimulation of single (passive) fingers prime specific number concepts? That is, using tactile finger stimulations, fingers remained passive in both experiments in order to investigate the direct link of mental finger and number representations which is shaped by individual counting experience.

Finally, I will contemplate the results of the novel studies in a comprehensive model of magnitude- and symbol representations which builds on the foundations laid by Walsh's (2003) ATOM and Dehaene's (1992) TCM.

Chapter 2

Study 1: Hands up: consistency and signatures of mental number processing in repeated finger posture production

Based on:

Sixtus, E., Lindemann, O., & Fischer, M. H. (submitted). Hands up: consistency and signatures of mental number processing in repeated finger posture production.

Abstract

Finger postures are one of several means to convey numerical information to others and they are the one where the numerical content becomes most tangible. In cultures with one-to-one mappings of numbers to fingers, represented numbers perfectly match the number of fingers involved. However, different finger configurations can be used to represent the same numbers and they might depend on the context of finger posturing, too. The present study addressed the consistency between finger counting and montring (i.e., spontaneously showing numbers) as well as intra-individual consistencies within montring configurations in repeated posture production. Participants produced finger postures according to visually presented numerals within three tasks: 1) produce the presented number, 2) produce one less, 3) produce one more. High intra-individual, but not inter-individual, consistencies in each task indicated individual predominant finger configurations, which are determined by their cultural background only to a limited degree. The simple mathematical operations of the latter two tasks affected the choice of the postures' starting hand and reaction time patterns. Reaction times were determined by a combination of each posture's motor complexity, a problem size effect, and a visual effect for the two-digit number 10. Additionally, errors most frequently involved the erroneous addition or omission of a single finger or a full hand, that is, responses deviating from the correct response by 1 and by 5, which matches previous findings from mental arithmetic. The present results thus provide further evidence that bodily representations and "abstract" mathematical tasks are tightly linked.

Introduction

The increasing body of studies documenting an impact of finger counting on numerical cognition motivated the present study. The views and conclusions in this field of study are, however, diverse. Some argue that finger counting limits young school children's development of arithmetic competencies, others that fingers are merely convenient tools – always at hand – to externally represent numbers (see Moeller, Martignon, Wessolowski, Engel, & Nuerk, 2011; Moeller & Nuerk, 2012). Yet others claim that finger counting constitutes a helpful step in reaching mature number concepts or that this step might even be a necessary one (Andres, Di Luca et al., 2008; Coolidge & Overmann, 2012; Costa et al., 2011; Di Luca & Pesenti, 2011; Dupont-Boime & Thevenot, 2018; Moeller & Nuerk, 2012). Consistent with this latter view, children with cerebral palsy (a motor disorder) display a higher prevalence of learning disorders, and specifically arithmetic learning difficulties (Frampton, Yude, & Goodman, 1998). Intriguingly, manual fine motor skills in those children were related to early numeracy (van Rooijen, Verhoeven, & Steenbergen, 2016). Also in healthy children manual fine motor skills predicted counting skills (Fischer et al., 2017) and math achievement (Dinehart & Manfra, 2013; Luo et al., 2007). On the other hand another study investigating children with cerebral palsy indicated that finger counting were not a necessary – albeit useful – step for the transition between non-symbolic and symbolic numerical skills (Thevenot et al., 2014).

Despite this controversy, there is fundamental agreement that finger representations are related with numerical representations in one or the other way. Not only do both representations have overlapping neuronal circuits, mainly in the parietal cortex (especially in the intraparietal sulcus and the left angular gyrus; e.g., Andres et al., 2012; Roux et al., 2003; Rusconi et al., 2005) – many neuroscientific and behavioural studies indicate that numerical cognition still draws on finger representations in adults (Domahs et al., 2010; Riello & Rusconi, 2011; Sato et al., 2007; Tschentscher et al., 2012). Some studies suggest a rather loose relationship, resulting in interferences between the two representations (e.g., Imbo et al., 2011; Michaux et al., 2013), others indicate an approximate relationship such that finger configurations facilitate related magnitude categories like "smaller/larger than 5" (e.g., Di Luca & Pesenti, 2008; Sixtus et al., 2017). Yet others claim that specific counting habits profoundly shape number representations so that they are deeply linked to their corresponding fingers or finger counting postures with each specific finger or posture standing for a specific number (Di Luca et al., 2006; Sixtus et al., 2017; Sixtus et al., 2018). Depending on the assumed relationship, finger-number interactions are explained either by redeployment of long-existing neural circuits that are reused by more recent cognitive faculties (Anderson, 2010; Penner-Wilger & Anderson, 2013), or by Hebbian association learning (Hebb, 1949) due to habitual finger counting during number concept acquisition in childhood. As a consequence of association learning, the bodily experience during concept acquisition should then become a fundamental and indispensable part of the entire cognitive representation of small numbers (Fischer & Brugger, 2011; Moeller et al., 2012; Sixtus et al., 2017; Sixtus et al., 2018; Tschentscher et al., 2012).

Previous studies reported that finger counting has shaped finger and posture representations into being a part of the actual number representation, so that each co-activates the other (Sixtus et al., 2017; Sixtus et al., 2018). It is therefore of particular interest how people perform finger counting. A few studies have already looked into specific patterns of individual finger counting habits in adults (Fabbri & Natale, 2016; Fischer, 2008; Lindemann et al., 2011; Pika, Nicoladis, & Marentette, 2009; Sato & Lalain, 2008; Wasner et al., 2014a, 2014b). The following section is therefore dedicated to giving an overview over previous research on various details of individual finger counting habits and other numerical finger postures.

Lindemann et al. (2011) employed an online questionnaire inquiring about finger counting habits of Middle Eastern and Western participants. Specifically, the questionnaire asked participants to "hold your empty hands in front of you and then count aloud from one to ten, using your fingers as you count" (Lindemann et al., 2011, p. 569) and then to fill numbers 1-10 into boxes above the ten fingers of two sketched hands referring to the order in which the fingers were used. Wasner et al. (2014a) criticised that the horizontal, left-to-right arrangement of the fingers in the questionnaire might have biased participants to unnaturally often indicate the left hand as the starting hand, because only for the left hand an assumed left-to-right mental number line direction matched the depicted finger counting sequence (from thumb to pinkie), especially after participants had to read the instructions prior to finger counting, which might have further activated a left-to-right scheme (Shaki & Fischer, 2008). In fact, Lindemann et al. (2011) reported a higher percentage of people starting to count on their left hand ("left-starters") than other studies from the same cultural background in which participants had to spontaneously count on their fingers with the experimenter noting the counting behaviour (e.g., Italian: Di Luca & Pesenti, 2008; Fabbri & Natale, 2016; Riello & Rusconi, 2011; Sato et al., 2007; Canadian: Morrissey et al., 2016; German: Sixtus et al., 2017; Wasner et al., 2014a). Wasner et al. (2014a) showed that visual perception of the horizontally aligned hands induces a leftward shift with regard to starting hand reports. That is, people more easily started to count on their left hand after holding their empty hands in front of them (i.e., the "visual perception group") than when they were asked to spontaneously demonstrate finger counting with both hands freely available. Furthermore, 19% of participants from the visual perception group transitioned to their second hand with the pinkie of the second hand while 100% of the spontaneous counting group transitioned to their second hand with the thumb. That is, a minimal task alteration of holding the hands in front of oneself – thereby giving participants a visual cue, as well as more time to reflect upon the own finger counting habits – significantly changed the outcome. This indicates at least two things: first, finger counting habits are not very stable across tasks. Second, to avoid contamination of measurements through task instructions, one ought to sample spontaneously produced finger counting (see also Lucidi & Thevenot, 2014).

The same should arguably be true for other numerical finger postures like finger montring. The term *montring* was established by Di Luca and Pesenti (2008) and describes the act of showing a numerosity with the fingers without counting up to this number first. Thus, even if finger counting and finger montring habits were each stable, finger postures still can differ between the two behaviours. A few studies have obtained both finger counting and montring information from the same participants (Crollen, Mahe, Collignon, & Seron, 2011; Di Luca & Pesenti, 2008, 2010; Pika et al., 2009; Rinaldi, Gallucci et al., 2016; Wasner et al., 2014b). The following section reviews the relationship between finger counting and montring.

Pika et al. (2009) asked German, English Canadian, and French Canadian adults to respond to various questions about how they would show or count up to different numerosities. The authors reported a high intra-individual consistency regarding the palm direction when counting and when montring. However, the consistency analysis refers to only two items (showing number 3 and counting up to 2); consistency in finger configurations between counting and montring gestures for the same numbers was not addressed. Importantly, the authors found intercultural differences not only in counting/montring habits, but also in inter-individual (intra-cultural) comparisons: Germans' number gestures mostly started with the thumb while English Canadians' number gestures mostly started with the index finger, whereas French Canadians' number gestures showed a high variety.

Di Luca and Pesenti (2008, 2010) reported that all of their Italian participants counted from thumb to pinkie on each hand – starting with their right thumb and ending with their left pinkie – while for finger montring they started with their right index finger, proceeding towards the pinkie and using the full right hand for number 5, continuing in the same vein on their left hand up to number 10. Thus, the Italian group demonstrated a very low consistency between counting and montring gestures and a very high inter-individual, intra-cultural consistency.

Wasner et al. (2014b) conducted a thorough investigation of gesture use and finger-number mappings across different tasks in a German sample. Finger counting habits were measured by letting participants count from 1 to 10 with the instruction: "Could you please count from one to ten by using your fingers" (Wasner et al., 2014b, p. 431). Finger montring habits were measured by letting participants show numbers 1 to 10 with finger postures after verbal instruction. The authors found that it depended on the specific number and magnitude whether the gestures more likely varied in the fingers used (especially numbers 2, 4, 9) or in the starting hand (especially numbers above 5, namely 6, 7, 8). Overall, consistency in counting and montring postures varied between 16% and 81% in their sample.

Specific finger counting habits are indicative of cognitive performance in other domains: Newman and Soylu (2014) reported that right-starters outperformed left-starters in addition tasks. Contrarily, Morrissey, Hallett, Wynes, Kang, and Han (2018) found that in their Canadian sample left-starters outperformed right-starters in various operation types. In both studies, however, counting habits were measured only once, so participants' consistency in counting habits is unknown. Consistency in counting habits is sparsely documented in the literature, but it might, however, (partly) account for the different results. One study that investigated the relation of consistency and numerical representations was conducted by Rinaldi, Gallucci et al. (2016) who assessed spatial aspects of pre-schoolers' finger counting and montring behaviour. The authors did not address the specific fingers used by the children, but mainly the consistency of spatial-numerical associations, that is, whether children represented numbers consistently as increasing from left to right versus from right to left. Interestingly, directionality of stable spatial-numerical association (if present) of finger counting did not significantly correlate with directionality of spatial-numerical associations in peripersonal space (i.e., on objects other than the own fingers). Results indicated that overall, spatial-numerical associations became more stable with increasing age and, intriguingly, that children with consistent spatial-numerical associations – regardless of their directionality –

showed more mature number representations as indicated, for example, by a linear (as opposed to logarithmic) representation of numbers in a number line task where children estimated the position of numbers on a number line which was only labelled with 0 and 10 on the left and right side, respectively. Thus, although Rinaldi, Gallucci et al. (2016) did not address the fine details of children's finger postures, their findings demonstrate that the consistency at least in the starting hand correlates with established signatures of the maturity of number representations.

The overarching objective of the current study was to investigate consistencies in counting- and montring behaviour. The first experiment addressed the consistency between counting- and montring behaviour for small numerosities and thus aimed to replicate previous findings regarding consistency between the two tasks (Wasner et al., 2014b). The second, more expansive experiment specifically addressed montring consistency and montring complexity effects. So far, counting and montring practices have been assessed by asking participants only once to demonstrate or indicate their counting or montring behaviour (per counting sequence / per number). It is therefore currently unclear whether these gestures are intra-individually consistent within the same task. After looking at the general predominant montring behaviour, we will therefore investigate various consistencies of this montring behaviour: how consistent are individuals within the same task? Are specific montring configurations an intra-individually consistent trait or is the choice of finger configurations affected by an additional task (add/subtract 1 before producing the posture)? Is there a culturally predominant strategy (e.g., Pika et al., 2009), which is reflected in the (inter-individual) consistency of the whole group of participants? Furthermore, we will address a potential quantity effect when gesturing numbers. A quantity effect – reflected in increasing reaction times with increasing numerosities – might result from increasingly complex finger postures or from decreasingly precise mental representations of increasing numbers. The latter is a typical explanation for the size effect which generally describes increasing reaction times for comparisons of number pairs of increasing numerical size (but equal distance; e.g. Dehaene & Changeux, 1993). We will try and dissociate the two explanations in our data. And finally, also erroneously produced finger postures might have their own story to tell. Domahs et al. (2008) reported an unexpectedly high percentage of split-five errors, that is, errors missing the correct result by 5, in pupils at the beginning of second grade for simple calculations. The percentage normalised for the same pupils at the end of second grade, but other studies have found base-five effects also in adults, usually in the form of slower reactions for calculations or comparisons crossing a five-border, assumedly as a consequence of the hands' base-five structure (Domahs et al., 2010; Klein et al., 2011). Domahs et al.'s (2008) split-five errors were interpreted to result from mentally adding or missing "a full hand" to/from the correct result, reflecting the sub-base-five structure of the hands, that is, each fully closed vs. opened hand represents 0 vs. 5, respectively. With our data, we are able to check whether adults are prone to miss the required result literally by a full hand. Domahs et al.'s (2008) results furthermore showed that most errors were split-one errors, that is, errors missing the correct result by 1. With our data, we are also able to check whether even these "numerically plausible errors" (Domahs et al., 2008, p. 362) are reflected in manual production of finger postures.

Experiment(s) 1: consistency in counting and montring behaviour

In the course of ten experiments, participants were asked about their counting and montring behaviour. We used these data to compare intra-individual details of showing and counting up to numbers 1 to 4.

Method

Participants

The data stem from participants who have been tested from 2012 to 2017[10] for either partial course credit or monetary compensation. Of the 301 participants tested, 13 were not native German speakers and their data were not analysed. Of the remaining 288 participants (mean age: 23.81 years, *SD* = 5.16 years; 240 female, 48 male), 281 were monolingual German speakers and seven were bilinguals with English, Turkish, Serbo-Croatian, or Polish as second native language.

Procedure

After each experiment participants were instructed to face the experimenter, shake out their hands, and show the experimenter how they would count from 1 to 10 with their fingers.[11] Afterwards, they were asked to imagine that they were in a loud bar where they could only communicate with their hands due to the noise: how would they indicate towards the bartender that they wanted to order one (two, three, four) drinks? Four of the ten experiments obtained montring postures for numbers 2-4 (N=112), the others (N=176) for numbers 1-4.

Analyses

Following Wasner et al. (2014b), the variations of counting vs. montring postures were classified as “identical” (same hand, same fingers), “hand-based” (different hand, same fingers), “finger-based” (same hand, different fingers), and “both” (different hand, different fingers). In addition, we recorded the starting hand in finger counting and the concordance between handedness and starting hand as well as the concordance between handedness and the montring hand.

All reported confidence intervals for the concordance rates are 95%-confidence intervals that were determined by nonparametric bootstrapping using 1000 nonparametric bootstrap samples following Pika et al. (2009) (for details on nonparametric bootstrapping see Johnson, 2001).

Five participants were excluded here because of missing data or missing certainty on the part of participants.

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[10] It is possible that a negligible (single digit) number of participants might contribute repeatedly to the data set if they participated in more than one experiment (in the last four and a half experiments we used subject codes which enabled us to avoid duplicates at least within these participants). However, due to the large size of the data set this would not bias the results.

[11] In one of the ten experiments, half of the participants received these instructions already before the experiment and a syllable counting task after the experiment (Sixtus, Lindemann, & Fischer, submitted).

Results

Regarding the general starting hand in finger counting, 95 of the participants (ca. 33.57%) were left-starters and 188 (ca. 66.43%) were right-starters.

Table 1.1 shows the number of participants that postured each of the four numerosities (rows) in a counting and in a montring context in the different fashions (columns). Missing cases arose from uncertainties on the part of participants, unclear records or – regarding the montring of numerosity 1 – not recording this numerosity in a montring context at all in four of the experiments.

Table 1.1. Number of participants with numerical finger postures starting from the different fingers.

	Counting			Montring		
Number	**From thumb**	**From index**	**Without ring**	**From thumb**	**From index**	**From middle**
1	280	2	-	110	62	0
2	280	2	-	110	169	0
3	281	1	-	253	29	2
4	274	6	2	43	241	0

Note. "Without ring" means that these participants started to count on their thumb but omitted the ring finger for number four, i.e., extending the pinkie before the ring finger.

Consistency rates ranged from 15 to 71%. All percentages as well as Wasner et al.'s (2014b) results for comparison are listed in Table 1.2. 73.48% of the participants, CI=[68.46%, 79.21%] started counting on their dominant hand. 85.25% of the participants, CI=[81.29%, 89.57%] used their dominant hand for montring. 77.78% of the participants, CI=[73.12%, 83.15%] started counting on their montring hand.

Table 1.2. Percentages of consistent ("identical") counting and montring postures as well as hand- and finger-based variations. Left: data from the current experiment; right: data from Wasner et al. (2014b) for comparison.

	Current data				From Wasner et al. (2014b)			
Num-ber	**Iden-tical**	**Hand-based**	**Finger-based**	**Both**	**Iden-tical**	**Hand-based**	**Finger-based**	**Both**
1	52%	12%	25%	12%	81%	13%	5%	1%
2	32%	7%	45%	16%	53%	12%	30%	6%
3	71%	17%	7%	5%	76%	15%	6%	3%
4	15%	2%	62%	21%	16%	3%	63%	18%

Note. Row sums above 100% result from rounding.

Discussion

We recorded participants' finger counting and montring habits for numerosities up to 4 and found that consistencies between the two behaviours differed essentially between the different numerosities. Participants were the most consistent for number 3 and the least consistent for number 4. Almost all participants started counting on the thumb and only a few switched to a posture sparing the thumb for number 4. Interestingly, however, finger montring varied more strongly between participants. Numbers 1 and 3 most often included the thumb while numbers 2 and 4 more often excluded the thumb. Thus, consistencies between counting and montring postures ranged from only 15% up to 71%, or more leniently (accepting switched hands as long as the fingers remained the same) from 17% to 88%.

Our results are on the one hand intriguingly similar to Wasner et al.'s (2014b) results for numbers 3 and 4 and on the other hand perplexingly dissimilar for numbers 1 and 2. Our participants seem to have preferred to use different fingers for number 1 and especially for number 2, for the latter even more often than using the identical posture. In Wasner et al.'s (2014b) study, participants more clearly preferred the identical posture for both numbers. All of our and Wasner et al.'s (2014b) participants were native German speakers but living in different federal states of Germany, so the different results might arise from regional differences. Alternatively or additionally, the different task demands might have caused the diverging outcomes: Wasner et al. (2014b) simply asked participants to show the different numbers with finger postures after verbal instruction while we asked participants to imagine ordering a specific number of drinks in a loud bar. These differences, however, left numbers 3 and 4 untouched.

Furthermore, the proportion of left-starters in finger counting in our sample was about 34% and thus comparable to the 28% left-starters in Wasner et al.'s (2014a) sub-sample with comparable conditions (i.e., spontaneous counting).

This first part of the present study mainly addressed counting and montring behaviour that was each measured only once per participant, that is, intra-individual consistency across tasks. In the second part we were now particularly interested in intra-individual montring consistency within the same tasks to answer the question whether participants in fact have predominant finger postures and whether previous measurements of asking only once reflect the individual predominant montring habit. Our setup enabled us to investigate further details of finger montring, as will be explained in the following.

Experiment 2: consistency within montring behaviour and further montring details

Experiment 2 addressed two main questions: first, are people consistent in their montring behaviour, that is, within the same task? Second, does manual production of montring postures reflect signatures of mental number processing? In this experiment, participants produced montring postures for the same numerosities multiple times in three contexts: 1) produce a given numerosity, 2) produce one less than the given numerosity, 3) produce one more than the given numerosity. This allowed us to address the question whether specific montring configurations were an intra-individually consistent trait. In this case variability of montring configurations should be low and furthermore, the produced configurations should not be strongly affected by the specific task within which they were assessed. Moreover, influences from montring complexity as well as from mental number processing like a quantity effect should be reflected in the reaction time (RT) patterns. With the second and third tasks we specifically addressed participants' consistency across different contexts as well as RT costs resulting from additional processing steps (i.e., simple calculations). In addition, we investigated whether previous findings from mental arithmetic, i.e., high incidence of split-one and split-five errors (Domahs et al., 2008), were reflected in incidence rates for errors in the manual production of finger postures.

Method

Participants

Thirty-seven participants took part in the experiment. Four reported to be left-handed, 33 to be right-handed. More detailed hand preference was assessed with an additional handedness questionnaire (see Procedure). All gave informed consent before data acquisition. The experiment was conducted in accordance with the ethical standards expressed in the Declaration of Helsinki.

Apparatus

Two buttons were placed in front of the participant with a distance of ca. 15 cm from the edge of the table and ca. 35 cm from each other. In the middle of the two buttons, a leap motion device (maximal frame rate of 200 Hz, measurement range of ca. 80 cm above the device, running with Orion Beta 3.1.2, Leap Motion Inc., San Francisco, CA, US) was positioned to capture finger postures via infra-red light recording. Visual stimuli were presented on a PC screen that was positioned about 40 cm behind the leap motion device. Artificial lighting in the room was switched off and natural lighting was dimmed by lowering the shutters to maximise measuring performance of the leap motion device.

Stimuli

The stimulus set consisted of numbers on a grey background in a sans serif font (FreeSans, Free Software Foundation, Boston, USA) with a text size of 46 pixels. The first part of the experiment included all integer numbers from 0 to 10. The second part excluded number 0 and the third part excluded number 10 – or the other way round, depending on the order of tasks.

Procedure

Participants placed each hand on its designated button with all fingertips touching the button. After pressing and holding both buttons down, a fixation dot appeared on the screen for a random period of time between 700 and 1200 ms, followed by the visual target number. Participants were instructed to show this number with a finger posture as fast and accurately as possible in a manner that seemed normal to them. Always both hands had to be lifted, often with one hand closed for numerosities up to 5 (see Figure 1.1). The lift-off times from the buttons as well as the posture classification time of the leap motion device were registered. The target number disappeared from the screen after the release of the first button.

For online feedback during the experiment, the built-in leap motion algorithm determined the number of fingers as soon as both hands' velocities fell below a fixed value[12] and the leap motion device continuously detected the same number of outstretched fingers for 200 ms, which in previous test sessions showed to be a sensible cut-off value, so that postures were not evaluated during the movement of the hands towards the final posturing position. If the detected number of outstretched fingers matched the required number, a green centred fixation dot appeared. This was the signal that the next trial could be initiated by the participant, that is, that both buttons should be pressed down again. If no correct number of fingers was registered within 3500 ms after the lift-off from the first button, an error feedback was given. After another 1200 ms a green fixation dot informed about the initiation of the next trial.

After the initial task ("exact" task), two slightly modified tasks followed. One task required participants to always show the presented target number minus one ("smaller" task), while the other task required participants to show the target number plus one ("bigger" task). The order of these two tasks was counterbalanced across participants.

Each task started with a short training block of at least 18 trials (or 20 trials in the "exact" task), which was repeated until the participant was able to carry out the procedure without problems.

At the end of the experiment, participants' finger counting (count from one to ten) and montring ("how would you order [1-4] drinks in a loud bar?") habits were enquired (see Method section of Experiment 1 for details) and a shortened German version of the Edinburgh Inventory (Oldfield, 1971) with ten questions was administered.

Design

Each of the three tasks comprised 5 blocks. Within each of the blocks, each number appeared twice in a random order. The whole experiment thus comprised 310 trials: 11 numbers (0-10) x 5 blocks x 2 repetitions = 110 trials in the "exact" task and 10 numbers (0-9 or 1-10, respectively) x 5 blocks x 2 repetitions = 100 trials both in the "bigger"- and "smaller"-task. In the training blocks each target number appeared twice, resulting in 20 trials for the "exact" task and 18 trials for the "smaller" and "bigger" tasks.

[12] To be precise, velocity was measured as the rate of change of the palm position in millimetres per second with a value each for x-, y-, and z-coordinates. The fixed value (fixed at 120) refers to the sum of the three values.

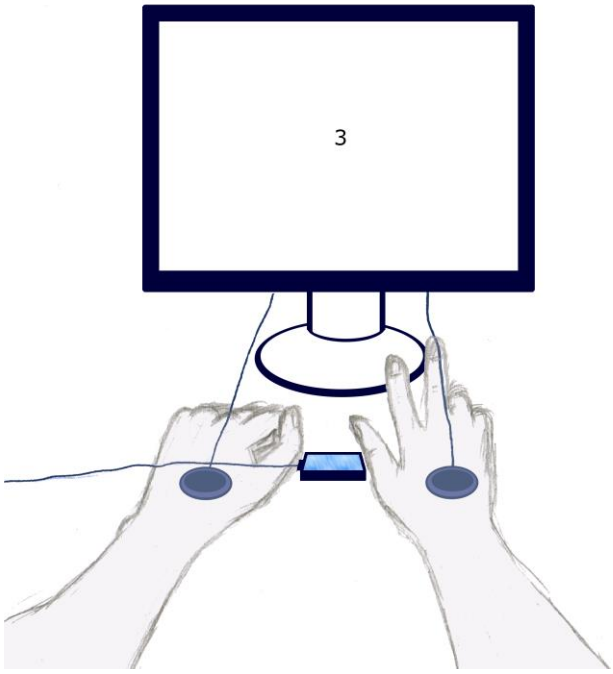

Figure 1.1. Illustration of the experimental setup. Two buttons and one leap motion device are placed on the table in front of the monitor. The buttons which were pressed until finger posture production was initiated show through the hands. Between the buttons, the leap motion device is visible. The target number is only visible for purpose of illustration: during the actual experiment, it disappeared when the hands lifted off the buttons.

Analyses

Due to a lack of reliability of the device's positional accuracy (Tung et al., 2015), we did not rely on finger recognition and response times (time until a posture was produced) delivered by the device. The experimental program therefore saved up to four pictures of the finger postures from the leap motion device for offline analyses. That is, multiple pictures were saved when the device detected postures that were not identified as the correct number of fingers, either because an actual error was made by the participant, because the hands moved slowly so that the picture was taken prematurely, or because the device didn't detect a (correct) posture correctly. Therefore, early postures that were registered as false before the correct one were also analysed offline. In the offline analyses of the pictures, a rater noted down the number and the identity of outstretched fingers for each hand in each picture. Always the first valid picture for each posture[13] was used for further analyses and all of the other pictures were discarded. Note that this posture did not necessarily constitute the correct response.

[13] Some pictures of finger postures were rated as invalid because one or both hands were not in the picture or because fingers were neither recognisable as fully stretched out nor as folded in. In most cases, the next picture from the leap motion device would then reveal the fingers' end state and therefore a valid posture.

The shortcomings of the device's positional accuracy were reflected in its insufficient posture recognition: in about 19% of the recorded cases, the leap motion device registered different fingers from those classified in the offline evaluation.

If not stated otherwise, *postures* were defined as the total number of outstretched fingers, regardless of their identity. For stressing finger identity, we henceforth use the term *finger configuration* which refers to the number of fingers as well as their identity.

The starting hand of each finger configuration was defined as the one that would have started counting to result in the current configuration. For example, posture 6 with a full left hand and the thumb of the right hand as well as posture 3 with all three fingers of the left hand both had a left starting hand. Postures 0 and 10 had no starting hand. "Mixed" starting hands are those of postures utilizing fingers of both hands without a full hand.

RTs were defined as the time from visual number presentation until the first release of the buttons that participants were required to press before posturing. Due to the leap motion's lack of reliability in detecting postures correctly, response times according to the time of response detection as measured by the leap motion device were not used.[14] Only trials with correctly produced postures (as evaluated in the offline analysis described above) were used for RT and consistency analyses. Trials with incorrect responses (7.14% in the "exact" task; 7.04% in "bigger" task: 7.20% in the "smaller" task) were only used for the confusion matrix analyses. Trials with RTs beyond the mean plus/minus three standard deviations per subject and per task were removed from analyses (1.54% of the data).

We considered *p*-values below .05 as statistically significant and for linear mixed-effects models, *t*-values equal or larger than 2 were considered as statistically significant (Baayen, 2008). In ANOVAs, degrees of freedom and *p*-values were Greenhouse-Geisser corrected where appropriate. All contrasts for pairwise comparisons following up on interactions used the Tukey method for adjusting *p*-values for multiple comparisons. All analyses were conducted in R (R Core Team, 2017), ANOVAs were calculated with the package *afex* (Singmann, Bolker, Westfall, & Aust, 2017), linear mixed-effects models with the package *lme4* (Bates, Mächler, Bolker, & Walker, 2015), contrasts with the package *lsmeans* (Lenth, 2016) including the default usage of the Satterthwaite method for degrees of freedom, and all plots were built with the package *ggplot2 (Wickham, 2016)*.

All reported confidence intervals are 95%-confidence intervals that were determined by nonparametric bootstrapping using 1000 nonparametric bootstrap samples (see Johnson, 2001).

The first main question of the experiment – regarding participants' consistency in their montring behaviour – was addressed by first identifying the predominant montring configurations (section "General montring details") and then analysing how consistently these predominant configurations were used (sections "Consistency of

[14] Preliminary analyses indicated a strong correlation between the two values: a linear regression of lift-off times on response detection times as measured by the leap motion revealed a slope of 1.01 and an adjusted R-squared of .81, $F(1,10568) = 46359$, $p < .001$.

montring postures within each task" and "Consistency of montring postures and starting hand across tasks").

The section "Consistency of montring postures with the dominant hand, with the starting hand in finger counting, and with the enquired montring configurations" especially addresses the question whether our measure of individual predominant configurations matches the traditional measure of asking participants only once to demonstrate montring behaviour.

The second main question of the experiment – regarding signatures of mental number processing in manual production of montring postures – was addressed by analysing RTs (section "Reaction time analyses") and by analysing the specific errors (section "Confusion matrix"). One signature of mental number processing is the quantity effect, which should be reflected in the RTs' regression slopes, while mean RTs of each task should merely reflect unspecific task difficulty. Another signature of mental number processing refers to "numerically plausible errors" (cf. Domahs et al., 2008) which should be reflected in split-one errors.

Results

General montring details

Only data from the "exact" task were used to establish quantitative aspects of montring. Table 1.3 lists all finger configurations that were used to represent target numerosities along with their total frequencies. Furthermore, the predominant finger configurations per person are listed. That is, the configuration per subject that was used most often for the respective numerosity. In five cases, two different configurations were used equally often by the same person – in these cases both configurations are included, resulting in five row sums of 38 (with only 37 participants).

Generalised across all participants, the predominant montring strategy was to successively extend one finger of the right hand in the order thumb-index-middle-ring-pinkie, but using the four fingers without the thumb for number 4. Numbers above 5 were predominantly produced with a full left hand and employing the same strategy with the right hand as for numbers below 5.

Table 1.3. Montring strategies in the "exact" task of numerosities/postures 0 to 10 listed by total number of trials (top rows) and by predominantly produced configuration by subjects (bottom rows).

		From left thumb	From left index	From left middle	From right thumb	From right index	From right middle	Other (details)	Other 2 (details)
0	**Trials**	-	-	-	-	-	-	**364** (no fingers)	-
	Subjects	-	-	-	-	-	-	**37** (no fingers)	-
1	**Trials**	64	27	0	**173**	80	0	0	0
	Subjects	8	2	0	**19**	8	0	0	0
2	**Trials**	43	35	0	**135**	124	0	0	0
	Subjects	5	5	0	**15**	13	0	0	0
3	**Trials**	68	9	0	**213**	29	4	1 (TI-T)	0
	Subjects	8	1	0	**25**	3	1	0	0
4	**Trials**	1	80	-	45	**176**	-	7 (TI-TI)	2 (IM-IM)
	Subjects	0	9	-	5	**22**	-	1 (TI-TI)	0
5	**Trials**	110	-	-	**244**	-	-	1 (IM-TIM)	0
	Subjects	12	-	-	**26**	-	-	0	0
6	**Trials**	115	10	0	**188**	37	0	0	0
	Subjects	12	1	0	**20**	4	0	0	0
7	**Trials**	90	17	0	**171**	57	0	1 (RP-TIMRP)	0
	Subjects	11	2	0	**17**	7	0	0	0
8	**Trials**	78	0	5	**205**	0	0	49 (IMRP-IMRP)	0
	Subjects	10	0	1	**22**	0	0	5 (IMRP-IMRP)	0
9	**Trials**	25	75	-	48	**169**	-	0	0
	Subjects	3	10	-	5	**20**	-	0	0
10	**Trials**	-	-	-	-	-	-	**370** (all fingers)	-
	Subjects	-	-	-	-	-	-	**37** (all fingers)	-

Note. Starting finger given in the heading refers to the finger of the hand showing less than a full hand (except for number 5 where it shows the full hand), i.e., for numbers ≤5 the hand matches the starting hand, for numbers >5 it does not. Bold: predominant configurations across participants. Details (in "Other" columns) list the fingers of the left hand [hyphen] fingers of the right hand with T: thumb, I: index, M: middle, R: ring, P: pinkie, e.g.: TI-TI means thumb and index finger of both hands.

Consistency of montring postures within each task

First, we addressed the *intra-individual* level of montring consistency, inspecting variations within participants. The individual predominant finger configurations per numerosity were identified (cf. previous section) for each task. For each participant each produced configuration was classified as identical[15] or different from the respective predominant finger configuration. Cases where participants produced two different configurations equally often for a given numerosity were omitted.[16] Individual proportions of identical configurations per numerosity were calculated and intra-individual consistencies correspond to mean proportions of identical configurations across subjects (see Table 1.4).

For the *inter-individual* analysis, we first identified the predominant configuration for each numerosity across all participants. Each participant's individual predominant configuration was classified as identical or different from this inter-individually predominant configuration. The proportion of participants complying with the predominant configuration was calculated and inter-individual consistencies correspond to mean proportions across numerosities. For the inter-individual analyses, only postures 1 to 9 were used for reasons of comparability between the tasks (because postures 0 and 10 each only appeared in two of the three tasks).

Intra-individual consistencies were high with means between 91% and 98% (or 100% for postures 0 and 10), while inter-individual consistencies were low with means around 55%. See Table 1.4 for details.

Consistency of montring postures and starting hand across tasks

To determine intra-individual consistency across tasks the predominant finger configurations per subject and numerosity per task were compared. Specifically, a binary variable "consistency" coded whether the predominant configurations of always two tasks were identical (per subject and numerosity). We determined a consistency-index for each of the three task pairs for each numerosity.

Mean consistencies of predominant finger configurations across tasks ranged between 79% and 97% (or 100% for postures 0 and 10), see Table 1.5 for details.

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[15] Identical finger configurations are classified following Wasner et al. (2014b) as involving the same fingers as well as the same hand.

[16] This affected five cells in the "exact" task, four cells in the "smaller" task, and two cells in the "bigger" task.

Table 1.4. Percentages (standard deviations given in brackets) of intra-individually (top) and inter-individually (bottom) consistent finger postures.

	Posture	Task: Exact (%)	Task: Bigger (%)	Task: Smaller (%)
	0	100 (0)	-	100 (0)
	1	94.46 (12.78)	93.58 (12.25)	96.58 (9.14)
	2	94.40 (10.53)	95.51 (11.37)	91.06 (13.15)
	3	97.84 (6.11)	94.71 (10.25)	91.82 (15.10)
Intra-individual	**4**	96.09 (10.38)	97.09 (8.15)	95.27 (10.33)
	5	96.05 (9.08)	97.57 (9.25)	94.39 (10.87)
	6	96.69 (6.76)	93.31 (12.33)	96.22 (9.33)
	7	96.08 (8.79)	94.26 (11.55)	96.33 (11.27)
	8	96.79 (7.61)	90.84 (14.26)	94.98 (13.03)
	9	94.72 (12.53)	95.59 (8.66)	97.06 (7.43)
	10	100 (0)	100 (0)	-
Inter-individual[17]	**$\overline{[1-9]}$**	55.00 (9.14)	54.66 (11.22)	55.18 (6.13)

Table 1.5. Proportions of consistent finger configurations between the tasks. 95%-confidence intervals given in square brackets.

Posture	Proportion consistent finger configuration [95%-confidence interval]		
	Exact – Bigger (%)	**Exact – Smaller (%)**	**Bigger – Smaller (%)**
0	-	100 [100, 100]	-
1	83.78 [72.97, 94.59]	89.74 [82.05, 100]	79.49 [69.23, 92.31]
2	84.21 [73.68, 97.37]	89.47 [81.58, 100]	91.89 [83.78, 100]
3	89.47 [81.58, 100]	89.47 [81.58, 100]	89.19 [81.08, 100]
4	91.89 [83.78, 100]	97.30 [94.59, 100]	91.89 [83.78, 100]
5	89.47 [81.58, 100]	85.00 [75.00, 97.50]	82.05 [71.79, 94.87]
6	78.95 [65.79, 92.11]	89.19 [81.08, 100]	78.95 [65.79, 92.11]
7	89.19 [81.08, 100]	83.78 [72.97, 97.30]	94.59 [89.19, 100]
8	92.11 [84.21, 100]	86.84 [78.95, 97.37]	94.59 [89.19, 100]
9	89.74 [82.05, 100]	92.11 [84.21, 100]	92.11 [84.21, 100]
10	100 [100, 100]	-	-

[17] Admitting hand-based variations as matching finger configurations gives consistencies (in %, *SD*s in brackets) of 80.03 (13.28), 79.71 (12.65), and 80.68 (11.79) for the "exact", "bigger", and "smaller" task, respectively.

Furthermore, the starting hands were compared across tasks. Each posture was identified as a "left-starting" or "right-starting" posture. The percentage of "left-starting" postures per task, subject and posture was analysed in a repeated-measures ANOVA with the within-subject variables Task (exact/smaller/bigger) and Posture (1-9). There were significant main effects for Task, $F(1.47, 52.94) = 4.187$, $p = .031$, $\eta^2 = .004$, and Posture, $F(1.28, 46.25) = 22.495$, $p < .001$, $\eta^2 = .15$, as well as a significant interaction effect of Task x Posture, $F(4.40, 158.48) = 2.679$, $p = .029$, $\eta^2 = .002$ (see Figure 1.2).

Contrasts between the three tasks, averaged over all postures, revealed that the mean frequency of a left starting hand in the "bigger" task was significantly lower than in the "smaller" task, $t(72) = 2.772$, $p = .019$, only marginally lower than in the "exact" task, $t(72) = 2.106$, $p = .096$, and that there was no significant difference between the "exact" and the "smaller" task, $t(72) = 0.666$, $p = .784$ (see Figure 1.2).

In a post-hoc test all involved contrasts between tasks per posture were analysed. There was a significantly higher percentage of "left-starting" postures for the "smaller" than the "bigger" task for posture 5, $t(267.96) = 3.989$, $p < .001$, for posture 6, $t(267.96) = 5.223$, $p < .001$ and for posture 7, $t(267.96) = 2.650$, $p = .023$, as well as for the "exact" than the "bigger" task for posture 6, $t(267.96) = 4.291$, $p < .001$ and a marginally higher percentage for the "exact" than "bigger" task for posture 5, $t(267.96) = 2.136$, $p = .085$; all other *p*s > .1 (see Figure 1.2).

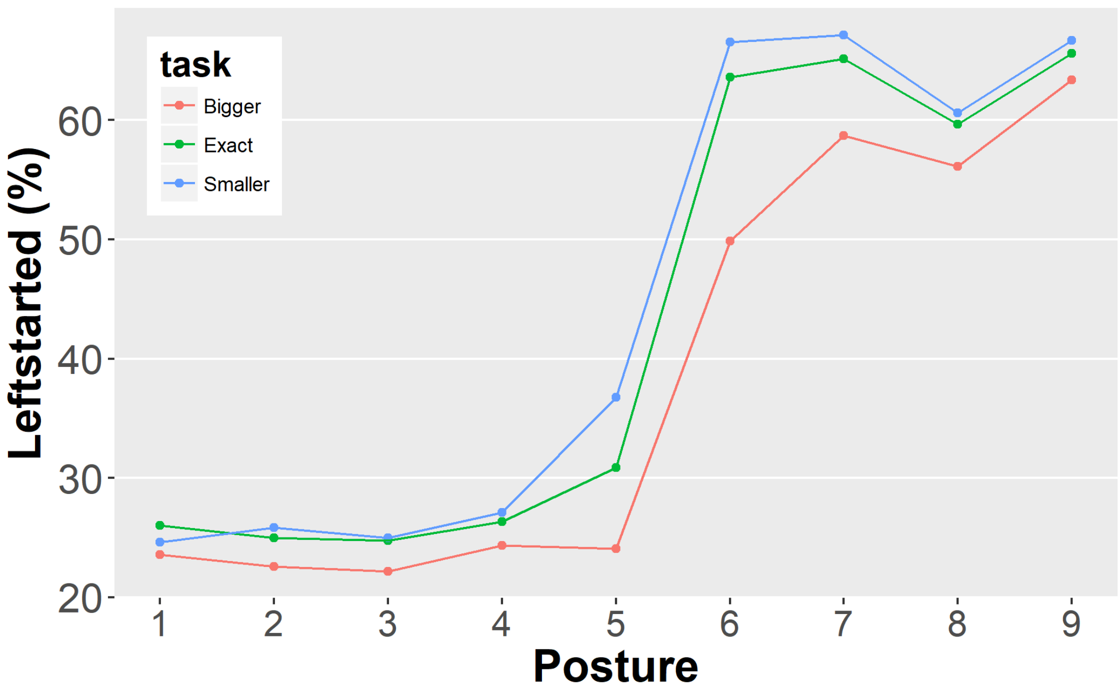

Figure 1.2. Percentage of left-started finger postures per task and posture.

Consistency of montring postures with the dominant hand, with the starting hand in finger counting, and with the enquired montring configurations

Having attained multiple measures of montring and counting habits as well as hand dominance, we furthermore investigated whether these measures captured (partly) overlapping concepts. The dominant hand was given by the results from the handedness questionnaire administered after the experiment. According to the handedness questionnaire, four participants were classified as left-handers (mean handedness score = -13.50, range = -7 to -17) and 32 participants were classified as right-handers (mean handedness score = 14.94, range = 10 to 20), and one participant with a handedness score of only 3 was excluded from this analysis because of the very weak hand preference. All other participants had handedness scores with an absolute value between 7 and 20 (with 20 being the maximum score attainable).

The starting hand in finger counting was defined as the hand on which participants started counting during the assessment of their counting habits at the end of the experiment, and the explicitly enquired montring configurations were analogously defined as the montring configurations that were produced when participants were asked to gesture numbers 1-4 at the end of the experiment. Cases in which participants weren't able to decide which configuration they preferred were excluded. The predominant starting hand was addressed separately for postures smaller than or equal to 5 and for postures larger than 5 (i.e., postures usually involving one vs. two hands, respectively).

For determining the consistency with the dominant hand, with the starting hand in finger counting, and with the explicitly enquired montring configurations, we coded in each case whether or not the dominant hand, starting hand in finger counting, and enquired montring configurations matched the predominant starting hand or finger configuration, respectively, during the experiment. Montring configurations 1-4 were addressed separately and we additionally addressed the hand which was used for montring. Again, consistency-indices with 95%-confidence intervals were determined. Table 1.6 and 1.7 present all results.

Table 1.6. Percentages of consistency between starting hand of the montring postures during the experiment (rows) and dominant hand / starting hand in finger counting as assessed at the end of the experiment (columns). 95%-confidence intervals given in square brackets.

Predominant starting hand during experiment	**Explicit assessment at the end of experiment**	
	Dominant hand	**Starting hand**
Postures ≤ 5	83.33 [72.22, 97.22]	81.08 [70.27, 94.59]
Postures > 5	47.22 [30.56, 63.89]	62.16 [45.95, 78.38]

Table 1.7. Percentages of consistent finger montring configurations and montring hands between the assessments. 95%-confidence intervals given in square brackets.

Predominant configuration / hand during experiment	Explicit assessment at the end of experiment	
	Montring configurations	**Montring hand**
Montring 1	86.11 [75, 100]	86.49 [78.38, 97.30]
Montring 2	75.68 [62.16, 89.19]	89.19 [81.08, 100]
Montring 3	94.44 [88.89, 100]	86.49 [75.68, 97.30]
Montring 4	94.59 [89.19, 100]	81.08 [70.27, 94.59]

Reaction time analyses

Both mean RTs and slopes were analysed for the different tasks. As a comprehensive analysis, we ran a linear mixed effects model with the fixed factors Task (exact/bigger/smaller) and Posture (1-9)[18] and the random factor Subject with by-subject random slopes for Task, Posture, and their interaction. Contrasts for the factor Task were set to treatment contrasts with the "exact" task as the control level.

Reactions in the "smaller" task (*M* = 849.43ms, *SD* = 276.54ms), but not in the "bigger" task (*M* = 769.46ms, *SD* = 235.57ms) were on average significantly slower than in the "exact" task (*M* = 684.86ms, *SD* = 254.98ms). RTs significantly increased with increasing Posture in this model, and the significant interactions show that the RT slopes over the postures are significantly steeper both in the "bigger" and the "smaller" task than in the "exact" task (see Table 1.8 and Figure 1.3).

Table 1.8. Results of the linear mixed effects-analyses of RTs, *t*-values exceeding 2 are classified as significant (cf. Baayen, 2008).

Effect (fixed)	**β**	***SE***	***t***
Task: Bigger	37.573	35.845	1.048
Task: Smaller	114.805	28.837	3.981
Posture	7.650	2.941	2.602
Bigger x Posture	9.765	3.381	2.888
Smaller x Posture	10.157	3.538	2.871

[18] Postures 0 and 10 were again excluded from this specific analysis, because they each could only appear in two of the three tasks and complexity effects are to be expected which would thus influence the RT slopes of the "smaller" and "bigger" task differently.

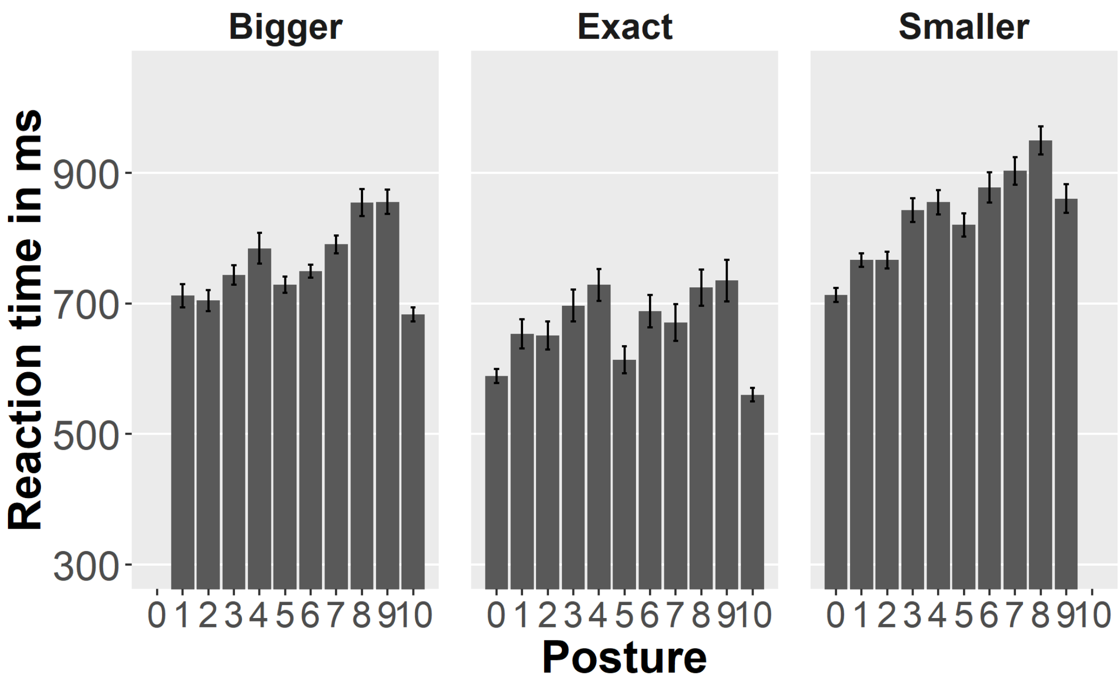

Figure 1.3. RTs per task and finger posture. Error bars represent within-subject standard errors as suggested by Cousineau (2005).

Assuming that the mean RTs of each task are mainly determined by task difficulty and that the regression slopes of each task are mainly determined by a quantity effect arising from the task, the residuals of the different postures from individual regression slopes should indicate additional influences arising from the required response. Such an influence does not necessarily reflect mental number processing, but might arise from the required posture's motor complexity or from visual features of the presented target number.

Motor complexity effects would be indicated by larger residuals for more complex postures than for less complex postures, irrespective of the task. Influences from the visually presented target number would be indicated by larger (absolute) residuals in the "bigger" and "smaller" task than in the "exact" task for particular target numbers.

A linear regression was calculated per person and per task and the residuals of each posture from the resulting regression slopes were analysed. First of all, a one-sample *t*-test compared mean residuals per subject of motorically less complex postures (i.e., postures 0, 5, and 10) against zero to address a possible complexity effect (i.e., longer RTs due to the anticipation/preparation of more complex finger postures) and revealed that these postures had significantly shorter RTs than predicted by their regression slope, $t(36) = -5.248$, $p < .001$.

A 3 x 9 ANOVA with the within-subject factors Task (exact/bigger/smaller) and Posture (1-9) on residuals was calculated to address influences from visually presented target numbers. Results showed significant main effects of Task, $F(1.57, 56.55) =$

10.73, $p < .001$, $\eta^2 = .006$, and Posture, $F(4.07, 146.44) = 6.95$, $p < .001$, $\eta^2 = .08$, as well as a significant interaction, $F(8.13, 292.79) = 4.51$, $p < .001$, $\eta^2 = .06$.

Post-hoc contrast analyses on all tasks and postures revealed that the only two significant differences were in posture 9: the negative deviation from RTs as predicted by the regression slope was significantly larger in the “smaller” than in the “exact” task, $t(614.1) = 6.771$, $p < .001$, and the “bigger” task, $t(614.1) = 7.106$, $p < .001$; all other *p*s > .1 (see Figures 1.3 and 1.4).

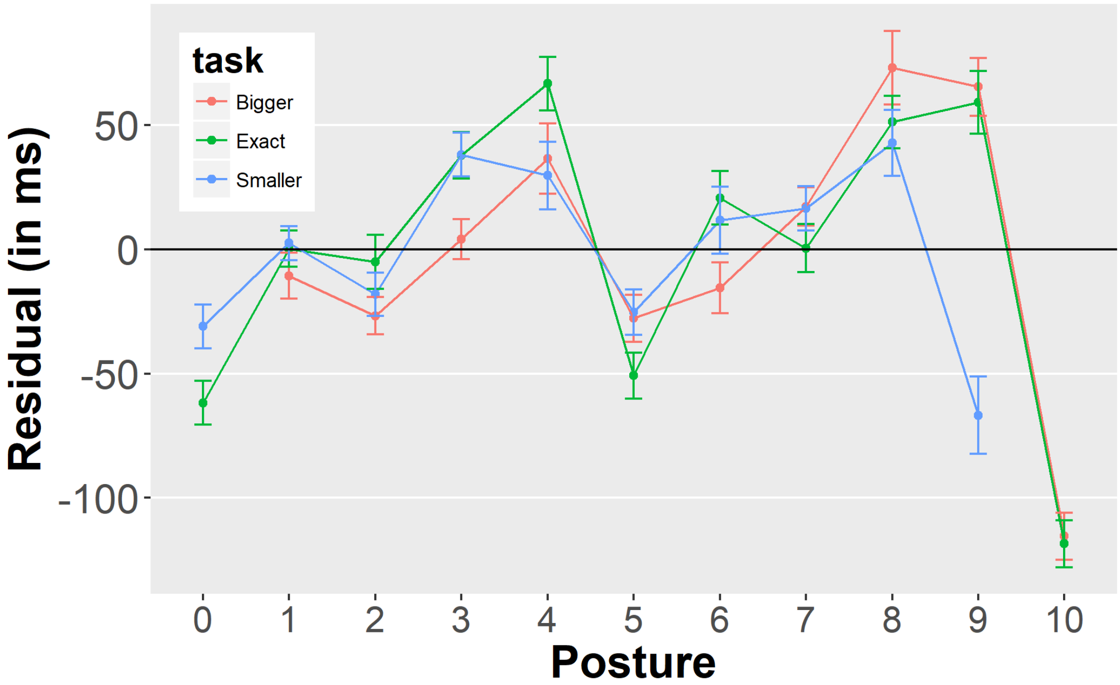

Figure 1.4. Residuals from the linear regression slopes per task and finger posture. Error bars represent within-subject standard errors as suggested by Cousineau (2005).

Confusion matrix

To investigate the produced errors, confusion matrices were created for each task. That is, only trials with incorrect responses were used for these analyses. Two error types were of special interest: 1) producing five fingers less or more, as in missing or adding one full hand from/to the correct posture (“split-five” errors) and 2) producing one finger less or more (“split-one” errors).

First, a 3 x 6 ANOVA with the within-subject factors Task (exact/smaller/bigger) and Absolute Difference from correct posture (± 1-6) was conducted on total number of respective errors. Differences 7 through 10 were excluded, because they appeared only once or never at all.

Results showed a significant main effect of Absolute Difference, $F(1.51, 54.34) = 66.08$, $p < .001$, $\eta^2 = .44$, but not of Task, $F(1.43, 51.48) = 0.36$, $p = .625$, and also no significant interaction of the two factors, $F(2.43, 87.61)$, $= 0.65$, $p = .552$; see Figure 1.5.

Post-hoc contrasts pairwise compared all differences (averaged over tasks). Difference 1 occurred more frequently than all other Differences, all $t(180) > 11$, all $p < .001$, and Difference 5 occurred more frequently than Difference 2, $t(180) = 3.031$, $p = .033$, than Difference 3, $t(180) = 3.395$, $p = .011$, and than Difference 6, $t(180) = 4.274$, $p < .001$; all other *p*s > .164 (see Figure 1.5).

Next, a 3 x 2 ANOVA with the within-subject factors Task (exact/smaller/bigger) and Difference (+1 / -1) was conducted on total number of respective errors. There was no significant main effect of Task, $F(1.39, 50.03) = 0.44$, $p = .573$, and only a marginally significant main effect of Difference, $F(1, 36) = 3.54$, $p = .068$, $\eta^2 = .01$, but a significant interaction of the two factors, $F(1.84, 88.18) = 13.93$, $p < .001$, $\eta^2 = .08$.

Post-hoc pairwise contrasts per task and difference showed that Difference -1 occurred more often than Difference +1 in the "bigger" task, $t(108) = 2.207$, $p = .029$, and vice versa in the "smaller" task, $t(108) = -5.150$, $p < .001$, and that there was no significant difference in the "exact" task, $t(108) = -0.307$, $p = .760$. That is, the neighboured posture which matched the visually presented number (i.e., with the respective Difference of +1 or -1) was produced significantly more often in the "bigger" and "smaller" task. The lack of a main effect of Task in the ANOVA furthermore shows that the amount of errors involving the absolute difference 1 did not depend on the task, but that it was only the distribution between +1 and -1 which was heavily influenced by the task.

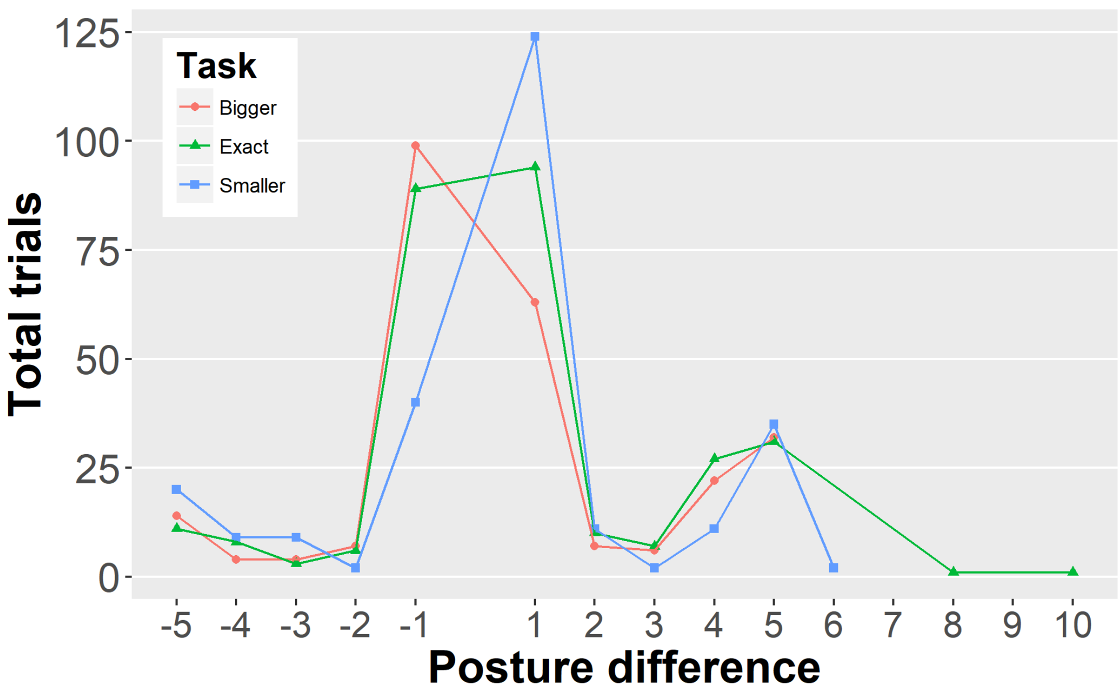

Figure 1.5. Visualization of the confusion matrix with frequencies (y-axis) of produced postures that deviated from the correct posture by a certain number of fingers (x-axis) in the three tasks (see legend).

Discussion

In this experiment, participants' finger montring behaviour was repeatedly recorded as well as RTs to initiate montring. We primarily analysed the consistency in finger configurations as well as signatures of mental number processing in manual posture production. Montring postures were produced in three contexts: 1) show the visually presented number with the hands, 2) and 3) show one less or one more than the presented number with the hands. In general, we found that when exactly the presented number was to be produced, the predominant montring strategy among participants was to use the left hand as sub-base-five, that is, an empty left hand for numbers up to 5 and a full left hand for numbers beyond 5, and to stretch out the right thumb for number 1 and 6, thumb and index finger for number 2 and 7, thumb, index and middle finger for number 3 and 8, all fingers except the thumb for number 4 and 9, and the full hand for number 5 and 10. Participants were not fully consistent both inter-individually (different people had different predominant strategies) and intra-individually (the predominant strategy was not the only one produced by the same persons). However, intra-individual consistencies were all above 90% and therefore higher than inter-individual consistencies which were around 55%. This low consistency is due to finger-based as well as hand-based (or both) variations, but in any case speaks against a single strong culturally predominant montring strategy.

Interestingly, the consistency of predominant finger configurations across tasks was not perfect. That is, adding or subtracting 1 in some cases changed the finger configurations that were used to gesture the number. Even more interestingly, in particular the starting hand of postures was affected by the different tasks: postures in the "smaller" task involved a left starting hand significantly more often than in the "bigger" task. This difference was particularly pronounced in postures 5, 6, and 7. This shift in starting hand might reflect that the task of adding or subtracting a number also induced an attentional shift. Assuming a mental number line with increasing numbers from left to right, participants' attention might have shifted along the line in the direction required by the task, carrying the shifted attention into the outside world and influencing the selection of the starting hand of the finger posture. However, from our data we cannot conclusively determine whether this spatial shift stems from (automatic) bottom-up factors or a (possibly conscious) top-down strategy where adding 1 also invokes a rightward shift.

Concerning the same analysis, the main effect of finger posture furthermore reflects the starting hand preference reported above: right starting hand for numbers up to 5 and left starting hand beyond 5. That is, mostly the same hand is used to produce the "fine motor" part of postures. Further analyses showed that for numbers up to 5, this hand is mostly the dominant hand, while for numbers beyond 5 there was no transparent connection of starting hand and dominant hand. The same is true when comparing the starting hand of montring postures with the starting hand in finger counting as assessed at the end of the experiment.

As to the comparison of the predominant montring configurations during the experiment and at the assessment at the end of the experiment, the finger configurations and starting hand mostly coincided. This probably reflects participants' consistent montring behaviour – however, we cannot exclude the possibility that repeatedly posturing during the experiment also influenced the assessment at the end of the experiment. Interestingly, montring posture 2 was produced with matching configurations in only about 76% of the cases, suggesting that the traditional measure of asking participants only once to demonstrate montring behaviour is not always reliable.

RT analyses revealed that adding the minimal mathematical task changed RT patterns substantially: for the “smaller” task mean RTs were significantly slower and there was a significantly larger increasing RT slope over increasing postures than for the “exact” task. Increased mean RTs probably reflect the general task difficulty level. The steeper slope indicates a stronger quantity effect.

The analysis of residuals then showed that those postures with only empty and/or full hands (i.e., postures 0, 5, and 10) had significantly shorter RTs than predicted by the slopes. These postures are motorically less challenging because they don’t involve fine motor adjustments as the selection and movement of single fingers within a hand. This advantage for less complex postures suggests that motor complexity accounted for some part of the RTs. On the other hand, one could argue that posture 10 might be easier to initiate because the visually presented Arabic number 10 was better detectable, being the only double-digit number. However, RTs for posture 10 were also faster in the “bigger” task where the Arabic number 9 was presented. Nevertheless, there seems to be an additional advantage for visual number 10: while for all other postures residuals were comparable, there was a significant difference for posture 9: in the “smaller” task negative residuals (in contrast to positive residuals in the other tasks) indicate a processing advantage for trials involving visual number 10 (in contrast to visual numbers 9 and 8 in the “exact” and “bigger” task, respectively).

Interestingly, montring errors were not randomly produced but more often showed a deviance from the correct number by 1 and by 5. That is, in erroneous responses postures most often deviated by either one single finger or one full hand. Moreover, when the error distance was 1, the error direction (i.e., showing one less versus one more than the required posture) was influenced by the task. It may not be surprising that more often the visually presented number was erroneously presented (i.e., one more in the “smaller” task and one less in the “bigger” task), it is however interesting that only the distribution of errors changed substantially, but that the total number of that kind of errors did not rise.

Overall, the results indicate that the “exact” task was the easiest and the “smaller” task was the most difficult and that difficulty induced an increase of mean RTs, of the slope gradient of RTs over postures, and an altered error distribution while not increasing the number of produced errors. Moreover, the simple mathematical operation involved in two of the tasks significantly influenced the selection of the starting hand.

General Discussion

The present study investigated details of finger montring in different contexts. First, we addressed the consistency between montring and counting configurations for numerosities up to 4. Consistency rates ranged from 15% (posture 4) to 71% (posture 3). Our results replicate Wasner et al.'s (2014b) finding that montring and counting configurations vary intra-individually to different degrees from each other on a hand-based and/or finger-based level. The proportions of consistencies – while very similar to

Wasner et al.'s (2014b) for numbers 3 and 4 – however differed more strongly from their results for numbers 1 and 2.

Then, we scrutinised montring configurations which were produced repeatedly and under different conditions. Participants were asked to produce finger postures in a fashion natural to them according to a visually presented number and the following tasks required them to produce one less ("smaller" task) or one more ("bigger" task) than the visually presented number. We primarily addressed two main questions: 1) Are people consistent in their montring behaviour for repeated posture production? 2) Does manual production of montring postures reflect signatures of mental number processing?

To address the first question, we first identified participants' predominant montring postures. The main predominant montring behaviour was to use the left hand as a sub-base-five – for indicating 0 or 5 – and to use the right hand for the fine motor part of the posture, that is, for showing the remaining single fingers. While inter-individually participants varied quite strongly in their predominant configurations, intra-individually they were very consistent in their montring behaviour within each task: on average they used their predominant configurations in 90-100% of the cases. Between tasks however, average intra-individual consistencies often dropped to around 80%. That is, the task of adding or subtracting 1 before producing the number influenced the shape of the produced finger configurations. Although all intra-individual montring consistencies were still well above chance level, the drop of consistency indicates additional influences from mental number processing, which will be discussed shortly.

We furthermore investigated whether our measure of individual predominant configurations matched the traditional measure of asking participants only once to demonstrate montring behaviour. Only for montring posture 2, the two measures diverged significantly with matching configurations in about 76% of the cases. Following these results, we would be quite confident that the traditional measure reliably yields the preferred montring configurations for postures, 1, 3, and 4, but not for posture 2.

To investigate the second main question of the experiment – that is, signatures of mental number processing in manual production of montring postures – we primarily analysed RTs as well as specific errors. These will be discussed in detail below, but first, we now address the drop of intra-individual consistencies mentioned above which indicate additional influences from mental number processing. Specifically, the task of adding or subtracting 1 before manually producing the number systematically shifted the starting hand of the finger configurations. One explanation for this novel finding might be an attention shift on a mental number line when adding or subtracting 1 from the visually presented number. That is, participants possibly took a mental step to the left or to the right on the number line and transferred this spatial reallocation of their attention onto the selection of the starting hand in their task to produce a finger posture. Measurable interactions of body movements and attentional shifts along the mental number line have been reported before. For example in a random number generation task where participants moved their head alternately to the left and right, generated numbers were biased towards smaller numbers for left head-turns (Loetscher et al., 2008). That is, participants' attention probably followed their physical head-turns along a mental number line, thereby biasing responses. Similar processes might have been at play in the present study, only ‘the other way round’. In Loetscher et al.'s (2008) study the voluntary body movements affected attention on the mental number line and thereby the selection of the response number. In our study, the very simple subtraction and addition problems biased the attention towards the left or right, respectively, on the mental number line and this in turn affected the voluntary body movement which was in our case the selection of the starting hand.

Alternative explanations of this novel finding might be delivered by the linguistic markedness hypothesis (cf. Nuerk, Iversen, & Willmes, 2004) or the polarity correspondence account (Proctor & Cho, 2006). Both theories involve opposed item pairs (linguistically un-/marked or associated with a "+"/"-" polarity, respectively) where the coupling of items "on the same side" brings forth processing advantages compared with a coupling of opposing items. In our case, the addition in the "bigger" task as well as a right starting hand would be linguistically unmarked or corresponding to the "+" polarity, respectively, whereas the subtraction in the "smaller" task as well as a left starting hand would be linguistically marked or corresponding to the "-" polarity, respectively. These matching combinations, having a processing advantage, would therefore be chosen more often than non-matching combinations, which would also result in the observed rightward shift in the "bigger" task.

Another signature of mental number processing is the quantity effect, which we expected to find in the RTs' regression slopes, while mean RTs of each task should merely reflect unspecific task difficulty. Indeed, RTs were systematically influenced by the tasks. Expectedly, mean RTs increased with task difficulty with the "smaller" task being the most difficult of the three tasks. More intriguingly, the slope gradient over postures also increased with task difficulty. The RT slope was steeper in the "bigger" than in the "exact" task and steepest in the "smaller" task. The steeper slopes in the tasks where 1 had to be added or subtracted remind of a problem size effect, which is a typical finding in the research of simple arithmetic and constitutes longer RTs and more errors the larger the digits involved in the calculation (e.g., Zbrodoff, 1995). The problem size effect is more pronounced in subtraction problems than in addition problems (Campbell & Xue, 2001; Curtis, Huebner, & LeFevre, 2016), which would explain the (descriptively) steeper slope in the "smaller" task than "bigger" task in our data. The problem size effect seems to be the best explanation for the systematic RT slope differences between the three tasks. Consequently, "showing one more" or respectively "showing one less" than the visually presented Arabic number apparently involved the same processes as simple calculation with two Arabic numerals as operands and verbal responses (as in Barrouillet & Thevenot, 2013; Curtis et al., 2016).

Besides the problem size effect, which was reflected in the RT slopes over postures, we furthermore found a complexity effect and a visual effect on RTs. The complexity effect was reflected in RT residuals and became most obvious in postures that were motorically the least challenging, because they only required full hand movements, that is, postures 0, 5, and 10. Those postures were produced significantly faster than the respective tasks' RT slopes predicted. The visual effect became evident in the "smaller" task for posture 9: RTs were faster than predicted by the slope and differed significantly from RTs of posture 9 in the "exact" and "bigger" task. That is, although the posture is quite complex, the easy visual detectability of the only two-digit number gave these trials an advantage. The residuals of all other postures did not differ significantly between tasks, which suggests that the influence of the specific visual target number is minimal (except for the case of visual number 10): RTs were mainly determined by a combination of the problem size effect (i.e., specific RT slopes) and the complexity effect (i.e., residuals from the tasks' specific slopes per target posture).

Further signatures of mental number processing were reflected in the produced errors. Most incorrect postures deviated from the correct target posture by 1. Although these are "numerically plausible errors" (cf. Domahs et al., 2008), it is interesting to find them in a task that did not require any mental arithmetic, but only the translation from an Arabic number symbol into a finger montring posture. That is, it was not only the case that the visually presented numbers were rashly produced in the "bigger" and "smaller" tasks, but just as many split-one errors occurred in the "exact" task. However, the distribution indeed bent towards the one mentioned above for the "bigger", and even more strongly for the "smaller" task.

Moreover, there were also significantly more split-five errors than most other numerical distances. Domahs et al. (2008) already reported split-five errors in mental addition and subtraction. Although in their study pupils only showed this effect at the beginning of second grade and not anymore at the end of second grade, the present data reveal that the assumedly underlying process of adding or missing "a full hand" actually takes place in the literal sense in adults.

The present study joins the group of studies disagreeing with the high proportion of left-starters reported in Lindemann et al.'s (2011) study. The reason is probably the different method used in their online questionnaire (Wasner et al., 2014a). Asking participants to hold the empty hands in front of oneself before starting to count gives participants a visual cue – possibly activating their left-to-right mental number line more strongly – as well as more time to reflect upon "sensible" finger counting habits. Experiment 2 of the present study required participants to produce number postures as fast as possible and most participants used their right hand to show numbers up to 5 (which, in finger counting, would be synonymous with a right starting hand). Participants visually perceived their own hands at least peripherally the entire time which suggests that visual perception of the hands is not necessarily the factor inducing a left starting hand. Thus, it was probably the speed component making them prefer their right hand for small postures. Considering that 83% of the participants predominantly used their dominant hand for postures up to 5, this endorses Wasner et al.'s (2014b, p. 436) statement that "right-starters [prefer] to use the dominant (right) hand for all finger movements that require more refined motor skills which—in the case of finger counting or montring—are necessary for the numbers from 1 to 5 (…)". Apparently, the urge to use the motorically more skilled (i.e., dominant) hand for small numbers decreases when more time is given to ponder over one's habits, or rather about the best way to display numbers with the hands.

The complexity effect reported in the present study is worth some more considerations. Although we don't have an objective measure of individual motor complexity to correlate with RTs, postures which require only movements of the full hands arguably are less complex than those postures requiring single fingers to move independently. However, motor complexity is of course subjective as it depends on individual dexterity and bodily properties regarding finger constitution. Following the embodied cognition hypothesis, numerical cognition (partly) relies on finger counting experience. It is therefore conceivable that specific finger dexterity might account for a part of the specific associated number concepts. Previous studies have already reported a general one-to-one association between number concepts and fingers (Di Luca et al., 2006; Sixtus et al., 2018). An influence of specific fingers' dexterity on the associated numbers' processing efficiency should be a next step to test the depth of numbers' embodiment in fingers.

In summary, we replicated previous findings that finger counting and finger montring configurations vary from each other to different degrees. Intra-individual consistencies within montring configurations on the other hand were very high when postures had to be produced repeatedly. However, selection of finger configurations, and especially the starting hand of finger configurations, was significantly influenced by the task of adding or subtracting 1 from a number before producing it, which might reflect spatial attention shifts induced by movements on the mental number line. Furthermore, RTs apparently were determined by a combination of each posture's motor complexity, a problem size effect arising from the task, and a visual effect for the only two-digit Arabic number 10. Finally, the higher frequency of errors involving postures deviating from the correct target posture by 1 and by 5 reflects the erroneous addition or omission of a single finger or a full hand. This matches previous findings in mental arithmetic where these errors occurred disproportionally often (Domahs et al., 2008). The present results thus provide further evidence for a tight link between bodily representations and "abstract" mathematical tasks still in adults.

Chapter 3

Study 2: Finger posing primes number comprehension

Based on:

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Abstract

Canonical finger postures, as used in counting, activate number knowledge but the exact mechanism for this priming effect is unclear. Here we dissociated effects of visual versus motor priming of number concepts. In Experiment 1, participants were exposed either to pictures of canonical finger postures (visual priming) or actively produced the same finger postures (motor priming) and then used foot responses to rapidly classify auditory numbers (targets) as smaller or larger than 5. Classification times revealed that manually adopted but not visually perceived postures primed magnitude classifications. Experiment 2 obtained motor priming of number processing through finger postures also with vocal responses. Priming only occurred through canonical and not through non-canonical finger postures. Together, these results provide clear evidence for motor priming of number knowledge. Relative contributions of vision and action for embodied numerical cognition and the importance of canonicity of postures are discussed.

Introduction

Cognitive scientists are revising their long-standing belief that cognitive processes are independent from bodily states. Evidence is rapidly accumulating that body and mind are indeed interacting in various ways (for recent reviews, see e.g., Coello & Fischer, 2016). A strong version of the "embodied cognition" stance claims that features of the body shape cognition permanently, in that both sensory and motor activations which were present during knowledge acquisition remain associated with that knowledge and become mandatory parts of all knowledge retrieval. The present study examines this claim.

One domain of embodied cognition that has recently gained much attention is numerical cognition (Lindemann & Fischer, 2015). Numbers, traditionally seen as a paradigmatic case of symbols with amodal cognitive representations, are no longer thought of as abstract conceptual entities: they were learned and internalised through the use of fingers, thus featuring systematic sensory and motor associations with the body (Butterworth, 1999a; Fischer & Brugger, 2011; Fuson, Richards, & Briars, 1982; Knudsen, Fischer, Henning, & Aschersleben, 2015). Not only children employ finger postures to represent numbers; adults use them to convey quantities to others, e.g., when verbal communication is difficult (Pika et al., 2009) or when the verbal system is occupied (Lucidi & Thevenot, 2014). Even blind adults rely on finger postures during number processing when their vision was intact during number learning (Crollen et al., 2014).

The mechanisms of embodied number knowledge are currently not well understood. In the case of finger counting, multi-modal (visual, motor and proprioceptive) associations between fingers and numbers may develop through repeated co-occurrence (Butterworth, 1999a; Fuson et al., 1982; Fuson, 1988) and this is reflected in shared cortical regions for both finger discrimination and number processing (Andres et al., 2012; Rusconi et al., 2005; Sato et al., 2007; Tschentscher et al., 2012). For example, Tschentscher et al. (2012) found that visually presented numbers 1 through 5 evoked activity in the observer's hand motor cortex, selectively for the hemisphere contralateral to the hand on which this person would begin to count.

Behavioural studies confirm the close coupling between specific numbers and fingers. Di Luca et al. (2006) required participants to classify the numbers 1 through 10 by pressing buttons with all ten fingers according to different finger-number mappings. The mapping conforming to the participants' finger counting habits produced the fastest responses. In a masked priming study, Di Luca and Pesenti (2008, Experiment 2) presented pictures of finger configurations subliminally, followed by Arabic digits that were classified as smaller or larger than five. In congruent trials, finger configuration and target digit were both either larger or smaller than five and this led to faster digit classification than incongruent trials. Importantly, this congruency effect only consistently emerged for canonical finger configurations (i.e. those actually used for counting), consistent with an embodied number representation. Badets et al. (2010) found a comparable facilitating finger-number priming effect in arithmetic with supraliminal presentations of finger configurations: participants solved addition problems faster when the correct outcomes were presented after each response as canonical finger configurations than when they were presented as rod configurations.

So far, finger postures have only been introduced as visual stimuli. This raises the important question of whether their effect on number processing reflects visual recognition of familiar stimuli or a covert motor simulation[19] (Jeannerod, 2006) of the observed posture. Finger postures – which are readily imitated even by neonates (Nagy, Pal, & Orvos, 2014) – are automatically simulated by adults: Brass, Bekkering, Wohlschläger, and Prinz (2000) showed that merely seeing a rising finger interfered with the observer's own downward finger movement, thus indicating spontaneous visuo-motor priming. Glover and Dixon (2013, Experiment 2) reported evidence that motor priming also takes place through imagined movements alone without the need for visual perception altogether. The authors studied perseveration effects for grasp mode (vertical or horizontal grasp). They found that posture selection relied on motor codes rather than visual perception (Experiment 1) and that even motor imagery led to perseveration of grasp mode (Experiment 2), indicating that visual perception and also proprioception do not augment the priming induced by motor codes alone. This study, however, does not inform about the effects of pure visual perception or proprioception.

Both motor and proprioceptive information are influential for conceptual number processing. It is often assumed that numbers are mentally represented as positioned on a mental number line with larger numbers to the right of smaller numbers (in Western cultures; e.g., Dehaene, 1992). Motor and proprioceptive information has been shown to shift attention along this mental number line: for example, in a random number generation task, participants produced more small numbers when turning their head to the left than when turning it to the right (Loetscher et al., 2008); the proprioceptive experience of leaning to the left induced smaller numerical estimates (Eerland et al., 2011); tapping movements in left or right peripersonal space resulted in respectively stronger or weaker underestimations of the midpoint between two three-digit numbers (Cattaneo, Fantino, Silvanto, Vallar, & Vecchi, 2011). Apart from these spatial associations, several studies recently demonstrated an association between motor-related and numerical magnitudes as for instance illustrated by the link between grasping actions and number processing (Andres et al., 2004; Lindemann et al., 2007; Ranzini et al., 2011). It has for example been shown that grip openings were initiated faster in response to large numbers while grip closures were initiated faster in response to small numbers (Andres et al., 2004). Also power grip actions were initiated faster when preceded by large numbers while precision grip actions were initiated faster when preceded by small numbers (Lindemann et al., 2007). Similarly, Ranzini et al. (2011) showed that visual presentation of graspable objects (i.e., objects associated with grasping movements) as well as the actual, task-irrelevant action of holding an object amplified a numerical magnitude effect (i.e., faster responses to small than large numbers).

Finger counting has even tighter links to mental number representations than the above mentioned movements and grips, as finger counting is a compound of visual, motor and proprioceptive experiences of the hands with displaying numbers. In accordance with the embodied cognition stance, we expect that finger postures exert

[19] We understand motor simulation with Jeannerod (2006, p. 129) "as the off-line rehearsal of neural networks involved in specific operations such as (…) acting. In other words, [motor] simulation is what makes it possible to (…) activate motor mechanisms without executing an action".

priming effects on number processing largely via motor and proprioceptive rather than visual mechanisms.

In order to test this hypothesis, the present study examined visual and motor contributions to the finger priming effect in number processing. Experiment 1 compared the influence of both visual and motor codes on magnitude classification relative to a fixed reference value using a go/no-go number classification task, while Experiment 2 further investigated number priming through motor codes in a magnitude comparison task. We will henceforth label the combination of initial activation of motor codes through manual adoption of finger postures and ongoing proprioceptive feedback[20] as "motor priming", while conditions with exclusively visual presentation of finger postures will be labelled as "visual priming".

Experiment 1

When comparing the impact of visual and motor priming from the hands on number processing, one possible outcome could be that visual priming is more effective than motor priming because of spontaneous motor simulation in the visual priming condition. Thus, the visual prime would effectively be rendered a visuo-motor prime (cf. Brass et al., 2000), providing both visual and motor inputs to the same number concept. If, on the other hand, motor simulation does not possess priming capabilities, but visual perception and active movements do, then both visual and motor priming might emerge similarly strongly. However, if it is mainly (covert) motor simulations induced by pictures of canonical finger configurations that produces their priming effect, then actively adopting those same postures should arguably induce much stronger activation of related number concepts, even when the postures are not visually available. The fact that the perception of numbers activates the motor area of the hand that is responsible for the respective numbers during finger counting (Tschentscher et al., 2012) suggests a tight motoric link between fingers and numbers. In the light of this reasoning, as well as Glover and Dixon's (2013) findings, we expected the motor condition to elicit stronger priming effects than the visual condition.

Method

The experiment was conducted in accordance with the ethical standards expressed in the Declaration of Helsinki. It consisted of a magnitude classification task in which participants indicated via foot pedals whether an auditorily presented number was smaller or larger than five. Before each block of 10 number comparisons, a single finger posture was introduced as a prime stimulus. This posture was either shown throughout the trials and visually processed (visual priming) or it had to be adopted out of view by the participant (motor priming). No-go trials ensured participants' attention towards the visual stimuli. Instructions were given purely visually and not, for instance, by manipulating the participant's fingers; this was done to avoid tactile stimulation of the fingers, which is also known to trigger numerical concepts (Krause et al., 2013). The implied counting direction was manipulated to ensure equally distributed spatial attention to the left and right sides of the display (in the visual priming condition) and of

[20] Desmurget, Vindras, Grea, Viviani, and Grafton (2000) estimated proprioceptive information from the unseen hand to remain cognitively available for at least 15 seconds.

one’s own body (in the motor priming condition). Also, no-go trials were introduced to ensure the same amount of attention to the display in both priming conditions. Experimental software, raw data and analysis scripts for both experiments are available via the Open Science Framework platform at https://osf.io/rwgh6.

Participants

Thirty-one undergraduate students at Potsdam University (20 female, 11 male) took part in Experiment 1. All reported to be right-handed, were native German speakers and received course credit for participation. One participant had to be excluded from analyses due to technical problems during data collection.

Apparatus and experimental set-up

Participants were seated at a table with a computer monitor (60 cm screen diagonal; 60 Hz refresh rate) mounted on top of a custom-made rack with a height of 102 cm (see left panel of Figure 2.1 for illustration). They were instructed to place their hands on a surface underneath the rack. Participants' lower arms and hands were shielded from view with a dark cloth that was attached to the rack. The experimenter was positioned behind the set-up and monitored participants’ hand postures throughout the experiment.

Auditory stimuli were presented via headphones. Responses were given with the left or right foot on two custom-made pedals connected via USB, positioned under the table. Stimulus presentation and response recording were controlled by a custom-made program based on the free Python library *Expyriment* (Krause & Lindemann, 2014).

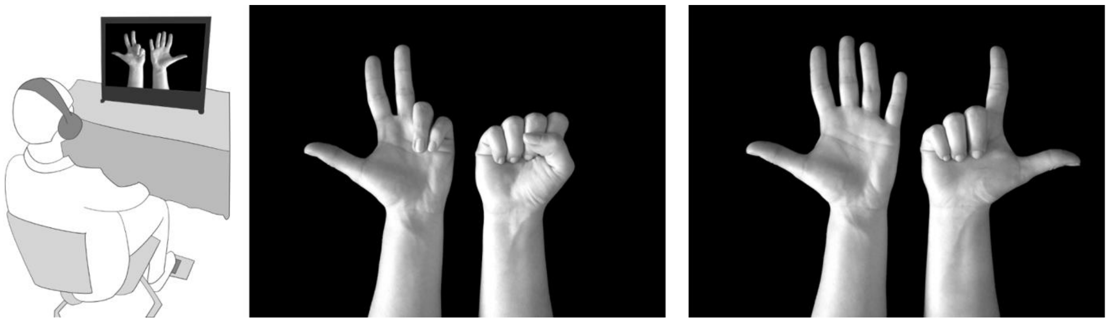

Figure 2.1. Experiment setup and sample stimuli. The left panel shows the setup with a visual finger prime “8” with a right full hand. The participant classified auditorily presented numbers with two foot pedals. The experimenter (not visible) sat behind the rack to monitor the participant’s finger postures. The central and right panels show further example stimuli with a left starting hand.

Stimuli

Target stimuli for the magnitude classification task consisted of eight spoken German number words (1 to 9 except 5) with a duration of 500 ms each. A 440 Hz tone (500 ms duration) served as error feedback for incorrect and slow responses. Visual prime stimuli were colour photographs of pairs of hands on a black background (see Figure 2.1). Depending on the postures, the hands subtended visual angles of 10-16° vertically and 13-19° horizontally; they wore no rings or wrist bands/watches. Palms were always oriented toward the participant. The stimulus set comprised all 18 canonical finger counting postures representing the numbers from 1 to 9. That is, each number was represented by two finger postures resulting from different counting directions, i.e., either left-to-right (with 1 associated with the left thumb extended) or right-to-left (with 1 associated with the right thumb extended; see Figure 2.1).

Motor prime stimuli were manual postures. They were instructed via the same photographs as in the visual condition, only with the hands coloured green. During data collection they were replaced by two rectangular grey blocks, matching the average size of the finger counting postures. In no-go trials the hands (in the visual condition) or the rectangles (in the motor condition) turned red.

Procedure

A practice phase familiarised participants with all finger postures. Green-coloured pictures of all 18 hand postures were presented once in randomised order and participants were instructed to imitate the postures. The experimenter monitored responses and corrected participants as necessary. Each participant also performed a short training of the auditory magnitude classification task alone to learn the foot pedal responses.

During data collection, each mini-block of ten trials started with the visual presentation of a green finger posture. In the *motor priming* condition, the participant adopted this posture and pressed a foot pedal when ready. A double beep tone was then played to indicate the start of the next 10 auditory magnitude classification trials and the screen showed two grey rectangles during data collection. In the *visual priming* condition, participants placed both hands palm down flat on the table and pressed the foot pedal when ready. Again, a double beep tone sounded and the green instruction stimulus (which was not to be imitated) changed its colour to natural and remained visible as visual prime throughout the following 10 trials.

The remaining procedure was identical across the two priming conditions: an auditory number word was presented and participants indicated whether the number was smaller or larger than 5 by pressing the left or right foot pedal according to the instructed response mapping. Responses had to be given within 1500 ms. Importantly, in both conditions no-go trials were quasi-randomly inserted (see Design section) to ensure that participants attended and processed the visual stimuli: the colour of the displayed hands or rectangles turned red with the onset of the auditory target and participants had to refrain from making foot responses. An error tone followed incorrect or too slow responses. Reaction times (RTs) were defined as the durations from target number onset until a pedal was depressed. After a random inter-trial interval (350-750 ms) the next trial started. After 10 trials a new finger posture was instructed (in the motor condition) or shown for the next 10 trials (in the visual condition). The experimenter verified the required finger posture through visual inspection and marked trials with incorrectly performed postures.

Design

The stimulus-response mapping (i.e., left vs. right foot pedal for small vs. large numbers) changed in the middle of the experiment for each participant. The order of the stimulus-response mappings was randomised across participants (24 participants whose data were analysed started with the mapping right pedal for small numbers). Within each of the two response mappings, there were two blocks with different priming conditions: visual and motor priming; their order was balanced across participants (16 participants whose data were analysed started with the motor condition and 14 with the visual condition).

Each of the four resulting experimental blocks comprised 80 trials. Each mini-block of 10 trials consisted of all 8 target numbers (go trials) plus 2 additional, randomly chosen target numbers (no-go trials). All target numbers were presented with each of the eight finger postures for numbers 2, 3, 7 and 8 in both counting directions. Thus, there was a total of 320 trials: 2 response panel mappings x 2 finger prime modalities x 4 finger postures x 2 counting directions x 10 numbers (8 target numbers [1-4, 6-9; go trials] + 2 random target numbers [no-go trials]). The first trial within a mini-block of 10 trials never consisted of a no-go trial; apart from this, the trial order in each mini-block was randomised. Additionally, each of the four blocks began with 10 randomly chosen warm-up trials that were not further analysed. The entire experiment lasted approximately 30 minutes.

Results

For RT analyses, only go trials were used. We excluded all trials with incorrectly adopted finger postures (1.15 %), slow responses (RTs > 1500 ms; 1.85 %) and erroneous responses (2.45%). Errors were too infrequent to be further analysed. Average RTs and error rates are depicted in Figure 2.2.

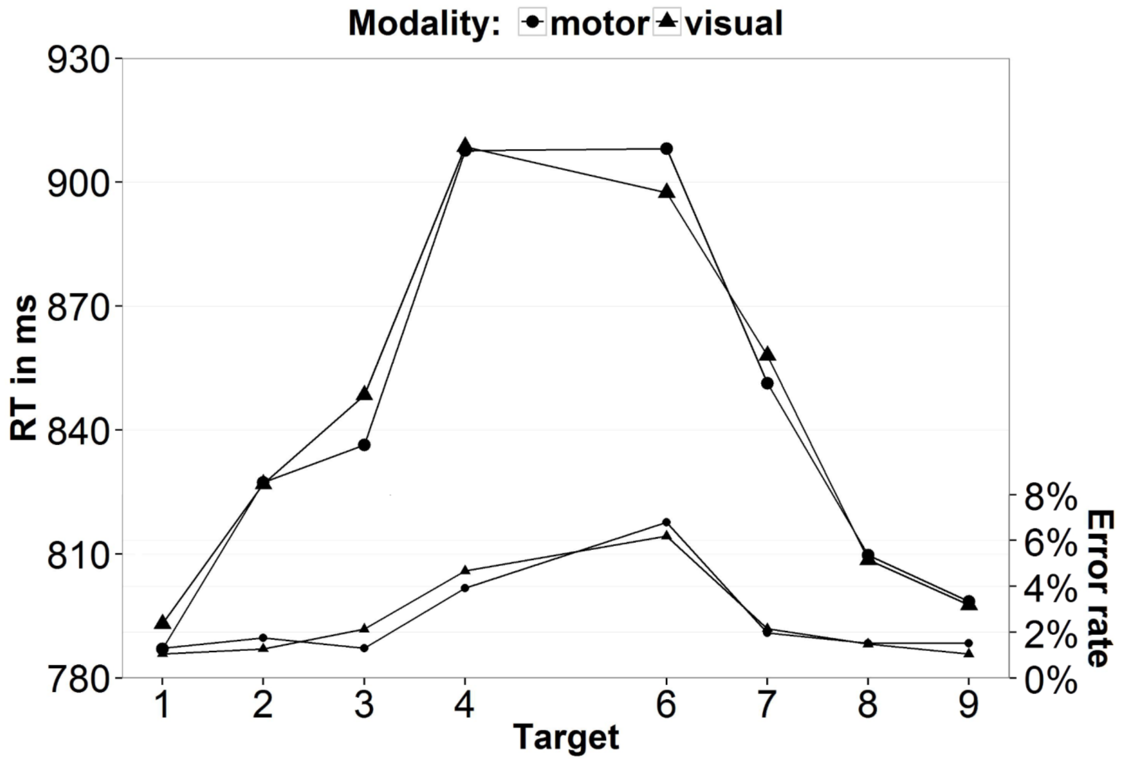

Figure 2.2. RTs for trials with correct responses (large symbols) and error rates (small symbols) per auditory target number (x-axis), separately for each prime modality.

Signatures of number processing

We first examined typical signatures of numerical processing such as the SNARC effect[21] and the distance effect (Hinrichs, Yurko, & Hu, 1981). Afterwards, we addressed our specific question about visual vs. motor contributions to the priming of number concepts by finger postures. Effect sizes for *t*-tests were computed as Cohen's d_z (cf. Rosenthal, 1991). Standard deviations (*SD*s) for (differences of) RTs are given in ms.

SNARC effect. We conducted a 2 (Prime Modality: visual vs. motor) x 2 (Response Side: left vs. right) x 2 (Target Magnitude: small numbers 1-4 vs. large numbers 6-9) repeated-measures analysis of variance (ANOVA) on the RTs. Results showed a main effect of Response Side, $F(1, 29) = 6.03$, $p = .020$, $\eta^2_p = .17$, indicating that responses given with the right foot pedal (839 ms, $SD = 88$) were faster than those given with the left foot pedal (851 ms, $SD = 83$). Importantly, over both prime modalities a reliable interaction between Response Side and Target Magnitude emerged, $F(1, 29) = 38.41$, $p < .001$, $\eta^2_p = .57$, signalling the presence of a SNARC effect: small target numbers were classified faster with the left foot pedal (826 ms, $SD = 86$) than with the right foot pedal (863 ms, $SD = 92$), $t(29) = 4.42$, $p < .001$, $d_z = 0.81$, and vice versa for large target numbers (left: 875 ms, $SD = 87$; right: 815 ms, $SD = 92$), $t(29) = 6.36$, $p < .001$, $d_z = 1.16$. Moreover, there were no main effects or interactions of the factor Prime Modality, all *p*s > .1.

Distance effect. The distance effect refers to slower classification of numbers closer to the reference value in magnitude classification tasks (e.g., Hinrichs et al., 1981). We conducted a 2 (Prime Modality: visual vs. motor) x 4 (Distances of auditory targets from the reference number 5) repeated-measures ANOVA on RTs. As expected (see Figure 2.2), responses were faster for larger distances (distance 1: 910ms, $SD = 95$, distance 2: 853 ms, $SD = 91$, distance 3: 819 ms, $SD = 85$, distance 4: 798 ms, $SD = 89$), $F(3,87) = 170.05$, $p < .001$, $\eta^2_p = .85$. Paired *t*-tests confirmed that every increase in numerical distance led to a significant reduction of decision latencies: distance 1 against 2: $t(29) = 14.93$, $p < .001$, $d_z = 2.73$; 2 against 3: $t(29) = 6.43$, $p < .001$, $d_z = 1.17$; 3 against 4: $t(29) = 4.18$, $p < .001$, $d_z = 0.76$). Again, an interaction with or main effect of the factor Prime Modality did not reach significance, both *Fs* < 1.

Category Priming

Following Di Luca and Pesenti (2008), trials where prime and target were both smaller or both larger than 5 were defined as congruent with respect to response category, all others trials as incongruent. A 2 (Magnitude Category Congruency: congruent vs. incongruent) x 2 (Prime Modality: motor vs. visual) repeated measures ANOVA on RTs showed no reliable main effect of Magnitude Category Congruency, $F(1, 29) = 2.66$, $p = .114$, or Prime Modality, $F(1, 29) < 1$, $p = .948$, but a significant interaction between these two factors, $F(1, 29) = 4.83$, $p = .036$, $\eta^2_p = .14$. Paired *t*-tests showed that for the motor condition, responses in congruent trials were significantly faster (837 ms, $SD = 90$) than those in incongruent trials (850 ms, $SD = 79$), $t(29) = 2.25$, $p = .032$, $d_z = 0.41$. In the visual condition, there was no significant difference

[21] The SNARC effect (spatial-numerical association of response codes; Dehaene, Bossini, & Giraux, 1993) refers to a pervasive association of smaller numbers with left space and larger numbers with right space in Western cultures (for recent review, see Fischer & Shaki, 2014).

between congruent (846 ms, *SD* = 87) and incongruent trials (842 ms, *SD* = 90), $t(29) = 1.25$, $p = .221$ (see Figure 2.3). A post-hoc power analyses revealed that based on our sample size of 30 subjects, an alpha level of .05 and an intended power of 80%, the design allowed us to detect main effects and interactions of small to medium size, $\eta^2_p = 0.04$.

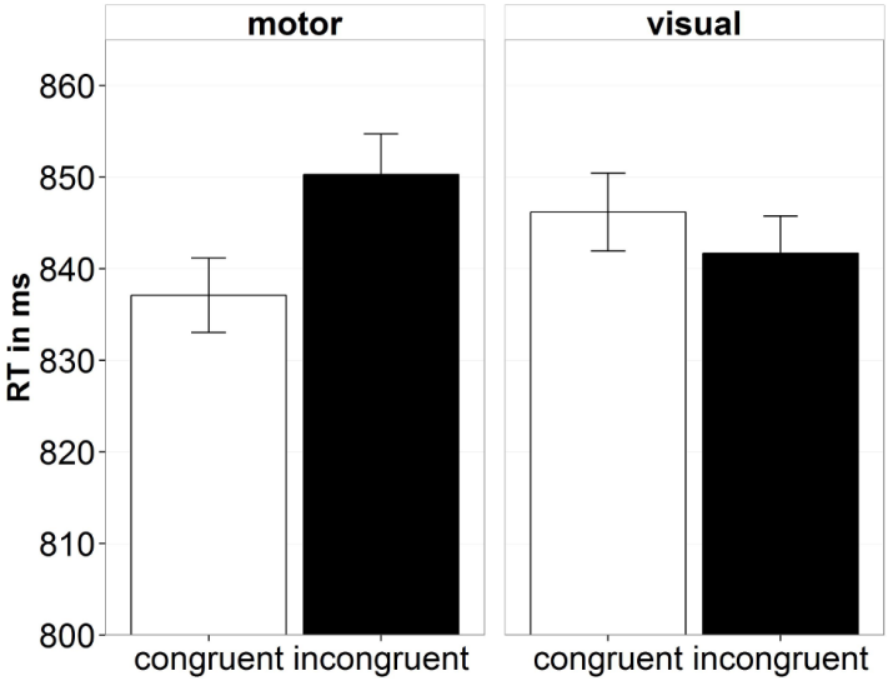

Figure 2.3. Mean RTs in ms for congruent (white) and incongruent (black) conditions for Magnitude Category congruency in the motor (left panel) visual (right panel) priming modality. Error bars represent within-subject standard errors as suggested by Cousineau (2005).

Motor and visual primes were either adopted or presented for the rather long period of 10 trials. Therefore, we also analysed the priming properties over time: we computed "priming slopes" of each condition, that is, the RT effect (i.e., RT difference in ms of incongruent minus congruent condition per subject, trial and modality) for each modality was regressed over the Trial Number (1 to 10). The resulting estimated regression equations were for the motor priming condition y = 8.69 + 1.01*Trial Number and for the visual priming condition y = –4.54 – 0.11* Trial Number. The individual slope coefficients were tested against zero (cf. Lorch & Myers, 1990). Neither in the motor nor in the visual condition this one-sample *t*-test became significant; both $t(29) < 1$.

Discussion

Experiment 1 studied performance in a magnitude classification task with finger posture primes and found evidence for faster number processing following congruent compared to incongruent motor primes. Importantly, our novel comparison between visual and motor priming conditions shed light on the relative contributions of visual and manual codes to this previously reported finger-based priming of number concepts. We showed that response selection was facilitated by actively adopting, but not by passively seeing, canonical finger counting postures matching the magnitude category of subsequently presented target numbers.

The lack of a persistent priming effect in the visual condition challenges the hypothesis that visually perceived body postures induce an effective motor simulation by the observer; it shows instead that active posturing provides additional and specific information, such as proprioceptive input, to the conceptual system beyond what is available through mere simulation. The presence of this proprioceptive information possibly explains the conflict between the visual priming effect reported by Di Luca and Pesenti (2008) and the lack of visual priming effects in the present study. Di Luca and Pesenti considered their effect to be visual in nature but we note that their participants actively moved their fingers to classify the numbers, thus including tactile and proprioceptive input from the hands in their task. In our visual priming condition participants' hands rested passively on a surface and the experimenter monitored compliance with this instruction. This might even have created a conflict, because when simulating own body movements, proprioceptive information is integrated (e.g., Lorey et al., 2009) and we instructed participants to hold their hands flat, that is, essentially in the posture corresponding to the number 10.

Even though the present study failed to find any effects of the visual presentation of hand postures, it cannot be excluded that visual priming might have affected the processing of numbers. Indeed, it is plausible to assume that the perception of a hand causes motor resonance (Brass et al., 2000; Schütz-Bosbach & Prinz, 2007) and thereby also induces priming of the number concept to a certain extent. However, crucially, the effect in the motor condition was significantly stronger than in the visual condition, revealing the dominance of priming through proprioception over priming through visual perception of postures. Likewise, the short visual presentation of the postures in the beginning of each mini-block of the motor condition might have caused a visual priming of the number concepts. Yet, the stronger priming in the motor condition illustrates the key role of proprioceptive information for the impact on number processing.

Having established a contribution from motor priming on number processing, the question arises of how robust motor priming of number concepts is across tasks, modalities, and response requirements. For example, previous work has shown that pictures of both canonical and non-canonical finger postures can prime magnitude concepts, but that canonical finger postures do so more pervasively (cf. Di Luca & Pesenti, 2008). On the other hand, an embodied view of numerical cognition that assumes active motor experience to be the source of embodiment would predict that non-canonical finger postures (with regard to numerical meanings) should not activate number concepts at all. We therefore report below a replication of our main finding in a design that examined also non-canonical postures and that required visual magnitude comparison instead of auditory magnitude classification.

The second experiment furthermore allowed us to address a concern regarding a possible account of our finding through posture naming. Specifically, we wished to ascertain that it was not merely verbal transcoding of the adopted finger postures into number names which activated the specific number concepts. Thus, we reasoned that verbalizing the target numbers[22] would suppress possible sub-vocal verbalization strategies for the finger postures.

Experiment 2

Experiment 2 aimed to replicate the motor priming effect with a substantially different methodology. First, we changed the task from auditory magnitude classification, which is relative to a fixed standard, to visual magnitude comparison, which requires the comparison of two new numbers in each trial (cf. Moyer & Landauer, 1967). Secondly, we tried to eliminate strategic verbal recoding by disguising the focus of the study on finger counting by mixing canonical and non-canonical postures and by avoiding all references to finger counting. Furthermore, we also replaced foot responses with verbal responses to interfere with verbal recoding. Verbally responding has the additional advantage of being non-lateralised, thus enabling us to test whether motor priming requires lateralised responses, perhaps because the finger stimuli involve lateralised effectors. The embodied cognition stance predicts that only adopting canonical postures should prime number concepts.

Method

Participants

Twenty-seven participants (19 female, 8 male) took part in Experiment 2 for either course credit or payment. Two participants were subsequently excluded from analyses: one reported during debriefing that the verbal responses were meaningful in her native language (from Polish approx. "these" and "this"), which might influence RTs and confound effects due to finger postures; the other because post-experiment testing indicated that "canonical" postures of the experiment were not actually canonical for her. All reported to be right-handed and had normal or corrected-to-normal vision. They were German native speakers and naïve as to the purpose of the experiment.

Apparatus and experimental set-up

Participants sat in front of a monitor (viewing distance of about 60 cm; 43 cm screen diagonal, 60 Hz refresh rate) with both hands resting on a table in front of them. The left hand made a loose fist throughout the experiment and the right hand was out of sight behind a board, about 5 cm in front of a 54 mm wide x 33 mm tall circular button ("PowerMate"; Griffin Technology, Nashville, USA). Verbal response latencies were recorded with a headset microphone connected to a voice key device ("SV-1 Voice Key"; Cedrus Corporation, San Pedro, USA). For errors, tones sounded from speakers that were positioned behind the monitor. The experiment was again controlled using the *Expyriment* software (Krause & Lindemann, 2014).

Stimuli

Motor primes consisted of three canonical and three non-canonical finger postures with 2, 3, or 4 extended fingers (see Figure 2.4). Arabic numerals between 1 and 5 (text size = 36 pixels, sans serif font type) were displayed in light grey at the centre of a black display; they comprised about 1° of the participant's visual field.

[22] Corrigendum: in this task *responses* (not *target numbers*) were verbalised.

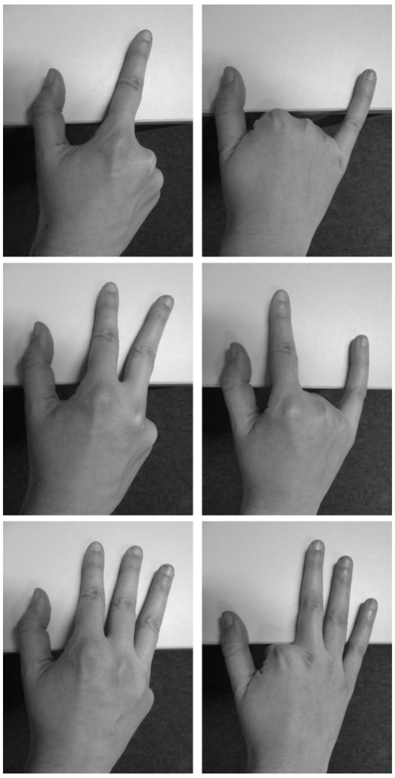

Figure 2.4. Canonical finger postures (left) and non-canonical finger postures (right) with 2, 3, or 4 extended fingers.

Procedure

Participants were not told about the meaning of the finger postures and no reference was made to finger counting at any time. They were asked to take off rings to avoid any additional stimulation on their fingers.

At the beginning of each mini-block the participant adopted the finger posture that the experimenter manually demonstrated. Each trial was started by the participant pressing the button with the right hand and then immediately re-adopting the finger posture, resulting in a motor prime that was produced out of view at the edge of the table. Next, a fixation cross was shown for a random period of time between 1000 and 1500 ms until the reference number (2, 3, or 4) appeared for 400 ms. After a 300 ms blank-screen, the target number appeared, being either smaller or larger than the reference number by one. It remained visible until a response was given.

Participants decided as fast and accurately as possible if the target was larger or smaller than the reference number by uttering the syllable “tah” or “toh”. Those (for German speakers meaningless) syllables were chosen because they have the same length, they were easily distinguishable for the experimenter who entered the responses, and they start with the same plosive consonant to ensure the most precise detections of the voice onset with the voice key device. RT was defined as the time from onset of the target number until the beginning of the verbal response. The experimenter entered the response identity or the occurrence of recording problems (microphone malfunction, coughing etc.) via the keyboard. Trials with incorrect responses and false RTs due to recording problems were repeated at the end of the mini-block.

After the experiment, participants stated their assumptions about the objectives of the study and reported their handedness, using two (translated) questions from Annett (1970): "Show me how you would butter bread" and "Show me how you would deal out playing cards". Finally each participant's manner of finger counting was recorded by asking "Show me how you would count from one to ten with your hands" and observing the response.

Design

Each trial comprised a sequence of two visual numbers: a reference number (2, 3, or 4), and the following target number (1 through 5), the latter being smaller or larger than the former by exactly 1. Target numbers 1 and 5 did not have a corresponding finger posture and thus only served as fillers, so that participants could not reliably predict the correct response for reference numbers 2 and 4. In total, the experiment contained 288 trials: 6 number combinations x 6 finger postures (3 canonical, 3 non-canonical) x 8 repetitions. The experiment was structured into mini-blocks of 12 trials, presenting every one of the six possible reference-target combinations twice, in a random order. Using 24 mini-blocks, each combination appeared 48 times. The experiment was preceded by at least three mini-blocks (or more if required) with only non-canonical finger postures 2, 3, and 4 in a random order. This training ensured that participants could execute the non-canonical postures effortlessly.

Results

The data of two subjects had to be excluded (see Participants section). Only one of the remaining 25 participants guessed the true objective of the experiment; when referring to hand postures, three participants mentioned the (number of outstretched) fingers, the others either had no assumptions or at most assumed that the postures were supposed to generally disturb the comparison task.

Training trials and trials with erroneous RTs due to false microphone activation were deleted before further analyses. The error rate amounted to only 1.71%, so no error analyses were conducted. In contrast to Experiment 1, Experiment 2 had no pre-programmed RT limit. Therefore, RTs exceeding the mean ± 2 *SD*s per participant were excluded from analyses; this excluded a further 4.13% of the data. Also, only trials with target numbers 2, 3, and 4 were analysed because 1 and 5 had no corresponding finger postures (see Design section). Table 2.1 shows mean RTs for each finger posture, target number and posture condition.

Table 2.1. Mean RTs in ms (standard errors in parentheses) by canonicity, finger posture and target number.

	Canonical			Non-canonical		
Posture	**Target 2**	**Target 3**	**Target 4**	**Target 2**	**Target 3**	**Target 4**
2	735 (44)	766 (45)	751 (39)	767 (50)	764 (42)	772 (48)
3	756 (53)	779 (47)	771 (41)	762 (52)	779 (47)	774 (41)
4	763 (51)	770 (46)	739 (37)	774 (50)	789 (47)	772 (45)

A repeated measures ANOVA on RTs with the factors Target (2 vs. 3 vs. 4), Posture (2 vs. 3 vs. 4) and Canonicity (canonical vs. non-canonical) revealed no significant main or interaction effects, all *p*s > .29, except for a marginally significant main effect of Canonicity, $F(1, 24) = 4.14$, $p = .053$, $\eta^2_p = .15$, due to 14 ms faster responses with canonical compared to non-canonical postures.

Congruency effect

Congruency is here defined as a match of target number with the number of extended fingers of the right hand; incongruent trials involve finger postures and targets that do not represent the same number. We hypothesised that canonical finger postures would elicit a congruency effect (faster RTs for congruent than incongruent trials) whereas non-canonical finger postures should not. This was indeed the case: with canonical postures, RTs were significantly faster for congruent (751 ms, $SD = 161$) than incongruent trials (764 ms, $SD = 179$), $t(24) = 2.39$, $p = .025$, $d_z = 0.48$. RTs of trials with non-canonical postures were not significantly influenced by congruency (congruent: 771 ms, $SD = 184$; incongruent: 773 ms, $SD = 182$), $t(24) < 1$ (see Figure 2.5). A post-hoc power analyses revealed that based on our sample size of 25 subjects, an alpha level of .05 and an intended power of 80%, the design allowed us to detect medium to large effects of $d_z = 0.58$.

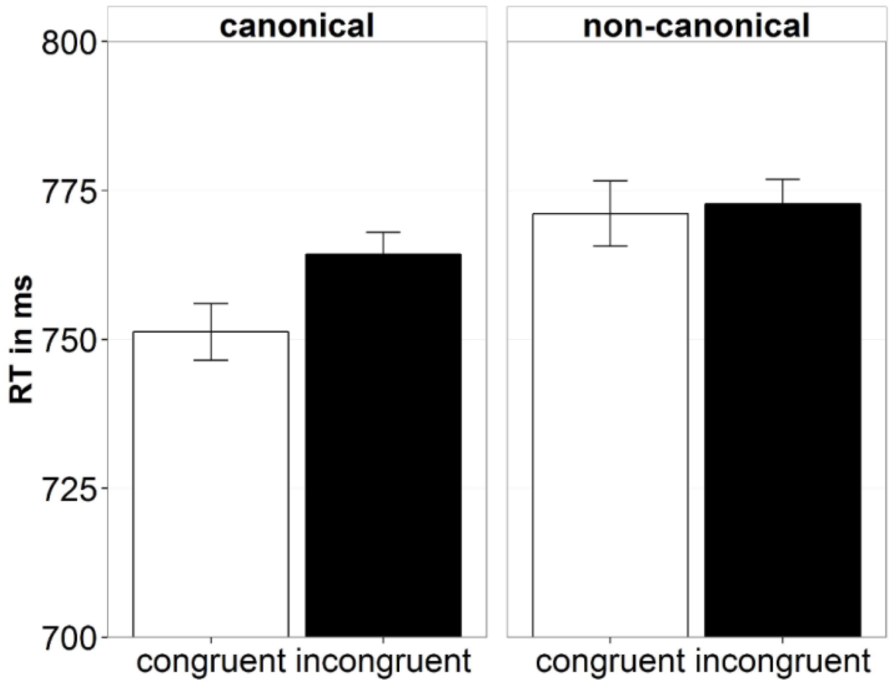

Figure 2.5. Mean RTs in ms for congruent (white) and incongruent (black) conditions with canonical finger postures (left panel) and non-canonical finger postures (right panel). Error bars represent within-subject standard errors as suggested by Cousineau (2005).

Again, we also analysed the priming properties over time: the RT effect (i.e., RT difference in ms of incongruent minus congruent condition per subject, trial and canonicity) for canonical and non-canonical postures was regressed over the Trial

Number (1 to 12). The individual slope coefficients were tested against zero (Lorch & Myers, 1990). Neither for canonical nor non-canonical postures this one-sample *t*-test became significant; both $t(24) < 1$.

Starting hand

Participants adopted all postures with their dominant hand, which was not necessarily identical with their starting hand in finger counting. Out of the 25 participants, six started counting with the left hand, 18 with the right hand, and one was uncertain, but all of them counted from the thumb of the starting hand to the pinkie of the other hand, except for one who used the right hand twice from thumb to pinkie when counting to ten. We excluded the latter participant from a repeated-measures ANOVA with the within-subject factors Canonicity (canonical vs. non-canonical posture) and Congruency (congruent vs. incongruent condition), and the between-subject factor Starting Hand (left vs. right). Except for a main effect of Canonicity, $F(1, 22) = 9.44$, $p = .006$, $\eta^2_p = .30$, no significant effects emerged, all $p > .1$.

Discussion

Experiment 2 replicated, in a novel task and with verbal responses, the main finding of Experiment 1 that adopting canonical finger counting postures primes numerical concepts, thereby leading to faster responses in congruent conditions. It also confirmed the prediction of embodied numerical cognition that non-canonical finger postures do not possess this priming capability. The result was obtained with non-lateralised verbal responses, thus ruling out the need for lateralised responses to match lateralised finger stimuli as an important ingredient for motor priming of number concepts. The verbal responses engaged the participants' verbal apparatus and thus arguably prevented, to some extent, transcoding of finger postures into number names. Together with the participants' absence of insight into the purpose of the experiment this evidence goes some way toward excluding a strategic verbalization account of the priming effect.

Contrary to expectation, the habitual starting hand in individual finger counting did not play a role in motor priming of number concepts. However, this null effect might be due to the relatively small number of left-starters in our sample. Moreover, recent work by Wasner et al. (2014b) showed that, depending on situated factors, either hand can be used to initiate finger counting, thus challenging the notion of a habitual starting hand.

General Discussion

The present study investigated the priming mechanism underlying the association between numbers and fingers in adults. In Experiment 1, participants classified auditorily presented target numbers according to their magnitude as larger or smaller than five while either seeing or manually adopting finger counting postures. The objective of this manipulation was to compare the effectiveness of visual and motor priming of number processing through finger postures. We obtained several novel and theoretically important results: decision latencies for classifying auditorily presented target numbers in the magnitude classification task were faster when their magnitude category matched the current finger counting posture. Importantly, however, this priming effect was only present when participants manually adopted category-congruent postures and not when they merely viewed pictures of the same postures. This finding clarifies that the highly overlearned associations between finger postures and numerical concepts of adult subjects are not primarily based on visual representations of the hand, but instead highlights the importance of motor codes and proprioceptive feedback from manual behaviour for these embodied representations. This involvement of motor codes is in accordance with number processing theories (e.g., Fischer & Brugger, 2011) which postulate that the development of numerical concepts is shaped by the acquisition of bi-directional associations between number words or symbols and motor experiences as it is, for instance, the case, when fingers are used to support counting in early childhood (Butterworth, 1999a; Knudsen et al., 2015; Lindemann & Fischer, 2015). Importantly, the small error rates, the presence of a SNARC effect and the numerical distance effect, which were all equally present in the visual and motor priming conditions, indicated that participants processed the target numbers semantically.

Experiment 2 replicated the finding that adopting canonical finger counting postures yields faster response latencies in semantically congruent compared to incongruent conditions. Participants decided whether a visually presented target number was larger or smaller than a previously presented reference number while adopting canonical or non-canonical finger postures. Importantly, the numerical meaning of the finger counting postures was obscured by the non-canonical filler-postures and almost no participant realised their true connection to the task. The requirement to respond verbally furthermore discouraged verbal recoding of finger postures and thus addressed the concern that any priming effect in the first experiment was due to strategic verbalization. Overall, the study highlights the importance of proprioceptive information in manual action for the retrieval of number knowledge that was previously learned through finger movements.

What might be a plausible mechanism for motor priming of number concepts? Our results of Experiment 1 suggest categorical response priming: participants responded faster when the category of the target number (small/large) matched the category of the manually adopted finger posture in a given mini-block. This finding is in line with a wide range of previous studies on numerical size priming through task-irrelevant primes, even when they are presented in different notations than the target stimuli (e.g., Dehaene et al., 1998; Di Luca & Pesenti, 2008; Naccache & Dehaene, 2001). The literature on response priming indicates that effects of dichotomous semantic stimulus categories—even when presented subliminally—are driven by a pre-activation of motor codes associated with a task-irrelevant stimulus feature or prime, due to an instructed response mapping of a similar but task-relevant stimulus feature (e.g., Reynvoet, Gevers, & Caessens, 2005; for a review on response priming see Kiesel, Kunde, & Hoffmann, 2007). The response time effects in the present study hence indicate that finger postures are automatically associated with numerical concepts so that they pre-activate the response that is related to those numerical concepts.

On the other hand, attentional shifts along the mental number line, induced by producing small or large numbers, could explain the results pattern: focussing on the ‘small’ or ‘large side’ of the number line would facilitate responses to numbers from that side. Previous studies found that attentional shifts on the mental number line influence numerical estimations (e.g., Cattaneo et al., 2011), so it is conceivable that category congruency is mediated by a spatial dimension.

The present study furthermore provides evidence for the notion that a particular finger counting posture is coupled with a specific numerical concept by demonstrating priming effects of specific numbers that are not caused by the compatibility between dichotomous categories of stimuli and responses (Experiment 2). We interpret this finding as evidence for the notion that an adopted finger posture is not only associated with a broad relational dichotomy of *small* or *large*, but that on top of that, sensorimotor representations of specific counting postures are linked to equally specific concepts of cardinality. Non-canonical finger postures with the same amount of outstretched fingers did not elicit this priming effect, thus highlighting the importance of the specific posture for a specific numerical concept.

It remains an open question whether visual and motor-based priming are based on essentially the same or different cognitive mechanisms. Observers automatically mirror perceived actions of others by activating their own motor representation (e.g., Brass et al., 2000). This mechanism has been labelled as 'motor resonance' and has been proposed as the basis of action understanding (for a review see Fischer & Zwaan, 2008). In the context of research on motor resonance in action observation, the present data suggest that motor representations are involved in the retrieval of numerical meanings of finger postures. These motor activations are triggered by action observation and are presumably the crucial ingredient for the emergence of apparently visual priming effects in previous studies using finger posture primes (e.g., Badets et al., 2010; Di Luca & Pesenti, 2008). We therefore want to stress that the absence of the visual priming effect in the present study should not necessarily be taken as evidence against the existence of visual priming of number processing by hand postures in general. Moreover, it is plausible to assume that visual processing of finger postures results in motor resonance or motor simulation (Brass et al., 2000; Jeannerod, 2006; Schütz-Bosbach & Prinz, 2007), which might in turn have induced additional activation of the associated number concept. However, crucially, the present study reveals that the priming effects due to proprioception are stronger.

In conclusion, our findings of finger posture priming of number concepts are consistent with the embodied view of number cognition, according to which sensory and motor activations are a crucial part of knowledge representations and their retrieval. Our experience of actively performing counting postures while acquiring number knowledge in childhood is probably a crucial source of this association. The present results highlight the importance of the manual (i.e., motor and proprioceptive) codes activated by finger counting experiences for establishing such life-long links between fingers and numbers.

Chapter 4

Study 3: Incidental counting: speeded number naming through finger movements

Based on:

Sixtus, E., Lindemann, O., & Fischer, M. H. (submitted). Incidental counting: speeded number naming through finger movements.

Abstract

The first steps in numerical cognition are usually done in conjunction with fingers. Following the assumption that abstract concepts stay associated with the sensory-motor information that was present during their acquisition and consolidation, mental number representations should always be associated with the respective finger counting components. We tested whether finger movements that imply finger counting actually prime the corresponding number concepts in adults. All participants counted number 1 with their thumb and incremented sequentially to number 5 with their pinkie. In the experiment, participants sequentially and repeatedly pressed five buttons from thumb to pinkie. Each button press triggered the visual presentation of a random number between 1 and 5 that had to be named aloud, resulting in 20% counting-congruent and 80% counting-incongruent finger-number mappings. Average naming latencies were significantly shorter for congruent than incongruent finger-number combinations. This result provides further evidence that number representations are strongly associated with finger counting experience, making fingers an effective tool for number comprehension.

Introduction

Hands and fingers play an important role in mental number representation, as evidenced by both neuroscientific and behavioural studies. A neuroanatomical link was identified in overlapping cerebral areas for finger and number representations (left angular gyrus, cf. Rusconi et al., 2005; horizontal part of the intraparietal sulcus and posterior superior parietal lobule, cf. Andres et al., 2012; Tschentscher et al., 2012). Also, hand muscles, but not arm and foot muscles showed increased corticospinal excitability when transcranial magnetic stimulation was applied to the primary motor cortex during counting (Andres et al., 2007). Behavioural studies provide further evidence that hands and numbers interact (Badets et al., 2012; Di Luca et al., 2006; Imbo et al., 2011; Sixtus et al., 2017). Imbo et al. (2011) found that moving participants' hands during a counting task reduced their performance in a numerical task. Importantly, the hand movements were external to the numerical task, thereby possibly exerting unspecific interference over associated number concepts. It is thus conceivable that number-congruent movements, would facilitate number processing. The question then arises what makes a movement number-congruent.

The present study aims to investigate the cognitive consequences of number-congruent movements as defined by the congruency between fingers and numbers. The following paragraph will explain the underlying idea which relies on two pre-experimentally established associations between fingers and numbers.

The first association is based on the spatial interaction between the cognitive representation of numbers and the physical alignment of fingers. It is explained by the idea that numbers are mentally represented along a mental number line (MNL) with small numbers to the left of larger numbers (in Western cultures; Dehaene, 1992). A spatially congruent movement associates left-side movements with small numbers and right-side movements with large numbers. Indeed, such a facilitating effect is commonly reported, especially in the form of the so-called SNARC effect (spatial-numerical association of response codes; Dehaene et al., 1993): left-sided responses are faster to small than large numbers and right-sided responses are faster to large than small numbers. The SNARC effect is thought to be independent from the hands or properties of the body because responses given with crossed hands show the same spatial congruency effect (Dehaene et al., 1993; but see Wood, Nuerk, & Willmes, 2006). This effect was also reported within one hand: fingers which were located further to the left were associated to smaller numbers and fingers located further to the right were associated to larger numbers, regardless of finger identity (Brozzoli et al., 2008).

The second association between fingers and numbers is embodied: numbers become embodied through habitual finger counting where each of the successively extended (or folded, depending on finger counting habits) fingers is consistently used in conjunction with a specific number (name), thus establishing the association of interest. A study by Di Luca et al. (2006) supports this claim: participants responded to numbers with various finger-to-number mappings; responses were fastest when the mapping conformed to the participants' finger counting habits – faster also than with a spatial, MNL-conforming (i.e., increasing left-to-right) mapping.

Extending this evidence, Riello and Rusconi (2011) reported a co-existence of both spatial and embodied effects. In their study, participants responded to numbers with button presses of the index and middle fingers in four separate conditions, using either their left or right hand with the palms either up or down. All participants indicated to count with number sizes increasing from thumb to pinkie. Thus, for the left hand in a palm up-position and for the right hand in a palm down-position, MNL- and finger counting directions coincided. Intriguingly, it was only for those response configurations that a SNARC effect was present. In the other configurations the congruency benefit of interest was seemingly cancelled out by the competing spatial and embodied number representations.

The two studies reported above show that active finger involvement influences mental number processing. Additionally, there is evidence for effects of passive finger involvement on mental number processing (e.g., Di Luca & Pesenti, 2008; Sixtus et al., 2018). Sixtus et al. (2018) showed that tactile finger stimulations pre-activated associated mental number concepts. Di Luca and Pesenti (2008) furthermore showed that passive subliminal visual presentation of finger postures primed mental number processing. Interestingly, however, Sixtus et al. (2017) found that the active production of finger postures had a greater impact on mental number processing than the passive (supraliminal) visual perception of the same finger postures, which emphasises the special role of active finger involvement for the association between fingers and numbers.

In the present study, we extend previous work in several ways. Participants pressed buttons with their fingers while their hand was oriented palm down and named subsequently appearing numbers. This motor priming task measured the strength of finger-number associations implicitly by avoiding explicit finger-number assignments. Consistent with the above literature, we hypothesised that finger movements should co-activate the counting-congruent embodied number representations (comparable with Di Luca et al., 2006) so that counting-congruent finger-number pairs should elicit faster verbal responses than incongruent ones (as Sixtus et al., 2018 found for passive tactile finger stimulations). However, if there was an equally strong spatial-numerical association (as in Riello & Rusconi, 2011), the anticipated motor priming effect should only appear for the right hand, where the embodied and spatial finger-number associations coincide. Importantly, we also assessed finger counting habits and tested whether a congruency effect depended on the starting hand in finger counting, that is, the hand which was spontaneously used for numbers one to five which were part of the present experiment.

Method

The experiment was conducted in accordance with the ethical standards expressed in the Declaration of Helsinki. It consisted of a number naming task in which participants sequentially pressed buttons with the fingers of one hand, thereby triggering the display of Arabic numerals on the computer screen. Buttons were pressed such that the order of the fingers pressing the buttons conformed to usual Western finger counting habits – ascending from thumb to pinkie.

Participants

Thirty students at Potsdam University took part in the experiment for course credit or money. All but four participants counted from one to ten on their thumb to pinkie by starting on the thumb of one hand and ending on the pinkie of the other hand.

One counted from thumb to pinkie of the right hand twice. The remaining three participants did not have clear finger-number mappings for numbers one to five or did not use the same order of fingers for both hands and were thus excluded from congruency analyses. The final sample was composed of 26 German native speakers and one English native speaker (19 female, 8 male, mean age = 23.56, *SD* = 4.53). Twenty-three were self-reportedly right-handers and four were left-handers.

Apparatus and experimental set-up

Participants were seated at a table with a computer monitor (60 cm screen diagonal; 60 Hz refresh rate) and a standard keyboard. The keyboard save five buttons (‘f’, ‘g’, ‘h’, ‘j’, and space) was covered by a sheet of paper and the uncovered buttons were centred in front of the participant. Verbal responses were spoken into a microphone (‘t.bone EM-9900‘; Thomann GmbH, Burgebrach, Germany) that was connected to an audio interface (‘U46 XL‘; ESI Audiotechnik GmbH, Leonberg, Germany). They were detected by a voice key device (‘SV-1 Voice Key‘; Cedrus Corporation, San Pedro, USA) connected to the audio interface’s phones output. A custom-made program based on the free Python library *Expyriment* (Krause & Lindemann, 2014) controlled stimulus presentation and recording of voice onset times.

Stimuli

Target stimuli consisted of Arabic digits 1 to 5 (text size = 35 pixels, sans serif font, light grey colour on a black background) that were positioned at the centre of the computer screen.

Procedure

Participants were instructed to put each finger of one hand on the respective button of the computer keyboard in front of them. Instructions on the computer screen informed them whether the left or right hand was to be used in the following block (order balanced over participants). Starting with the thumb, the fingers had to press down buttons on the keyboard consecutively in the order [thumb – index finger – middle finger – ring finger – pinkie]. Directly following each button press a number appeared on the screen that had to be read out aloud as quickly as possible in the participant’s native language. Reaction times (RTs) were measured from the appearance of the number until the verbal response was detected by the voice key device. The number disappeared as soon as a response was detected. After a random delay between 250 and 500 ms a fixation dot appeared at the centre of the screen. As soon as the dot had appeared, the participant could press the next button in the sequence with the appropriate finger to evoke the next number. After every 50 trials there was a short pause. In the middle of the experiment participants were instructed to change hands.

A short message appeared on the computer screen whenever an incorrect finger was used, when it took too long to press the next button (when the dot was presented for over 1500 ms) or when the next button was pressed before a voice response was detected. A message then also informed about which finger had to be used next.

The experimenter monitored the entire experiment and noted trial numbers for wrong responses or false voice onset registrations, due to external noise or the participant using a weak voice.

Finger counting habits were assessed with two methods for each participant, a number-based and a syllable-based method. The number method consisted of asking participants to "Show me how you count from one to ten with your hands". The syllable method consisted of asking participants: "How many syllables does the children's song 'Alle meine Entchen' [popular German children's song] have until the word 'See'?" (correct response: 11). Participants were encouraged to use their hands in the few cases where they did not do it spontaneously. The English speaking participant, who did not know the song, was instead asked about the number of syllables of the first verse of the song "What shall we do with a drunken sailor" (correct response: 10). In all cases the starting hand and finger counting sequence were recorded. The order of assessments, which took place before or after the experiment, was counterbalanced across participants.

Design

Participants completed 500 experimental trials in total: 2 hands x 5 fingers x 5 numbers (1-5) x 10 repetitions. A short training of 20 trials (or more if required) was inserted at the beginning and when changing hands. Order of hands was counterbalanced across participants. Target numbers were distributed quasi-randomly with the only restriction that the same number could not turn up more than twice in a row. The entire experiment took approximately 30 minutes.

Results

Raw data and the analysis script are available online via https://osf.io/nur86.[23] Trials where participants pressed a wrong button (0.58%) or failed to press the next button within 1500 ms (0.30%) were eliminated from the data. Note that these trials were immediately repeated in the experiment. Further error trials (that were not repeated) were excluded from analyses: errors consisted of incorrect verbal responses (0.30%), false voice onset registrations (2.74%), and missed verbal responses (0.72%), excluding 3.75 % of the trials. Then, trials with extreme RT values, which were presumably attributable to a lack of concentration, were eliminated (RT < 250 ms or > 1500 ms; 0.33%).

Next, results from the two methods of assessing the starting hand were compared. Table 3.1 lists the number of participants who started counting on the left or right hand under each method. One third of participants had nonmatching starting hands in the two counting tasks. Fishers' exact test revealed that the distribution of starting hands in the two tasks did not endorse the hypothesis that the two measures are interdependent, $p = .210$.

For the main analysis regarding the congruency effect, RTs were averaged per subject, hand, finger, and target number. Congruent trials included finger-number pairs thumb-1; index finger-2; middle finger-3; ring finger-4; and pinkie-5. All other trials were defined as incongruent. The 2 x 2 ANOVA thus included the within-subject factors Congruency (congruent / incongruent) and Hand (left / right). There was a significant main effect of Congruency, $F(1, 26) = 9.80$, $p = .004$, $\eta^2_p = .27$. RTs for congruent trials (679.51 ms, $SD = 87.65$ ms) were shorter than for incongruent trials

[23] Note that the current analysis script deviates due to modifications that were made in the course of the review process (publication: see doi.org/10.5334/joc.49).

(686.34 ms, *SD* = 89.78 ms; see Figure 3.1). There was no significant main effect of Hand, $F(1, 26) = 2.26$, $p = .145$, and no significant interaction of Congruency and Hand, $F(1, 26) < 1$.

In addition, we performed two further ANOVAs, each including one of the measures of the starting hand in finger counting, to find whether one (or both) of them captured a finger counting habit which influenced the association between fingers and numbers. The first 2 x 2 x 2 ANOVA included the same within-subject factors as before and the between-subject factor Starting hand numbers (left / right). There again was a significant main effect of Congruency, $F(1, 25) = 5.71$, $p = .025$, $\eta^2_p = .19$. There were no significant main effects of Hand, $F(1, 25) = 2.14$, $p = .156$, Starting hand numbers, $F(1, 25) = 2.73$, $p = .111$, and no significant interaction effects, all *F*s < 1.

The second 2 x 2 x 2 ANOVA included the same within-subject factors as before and the between-subject factor Starting hand syllables (left / right). There again was a significant main effect of Congruency, $F(1, 25) = 10.72$, $p = .003$, $\eta^2_p = .30$. There were no significant main effects of Hand, $F(1, 25) = 2.07$, $p = .162$, Starting hand syllables, $F(1, 25) < 1$, and no significant interaction effects, all *p*s > .231.[24]

Table 3.1. Number of participants with left/right starting hand in the two counting tasks.

		Starting hand for syllables		
		Left	**Right**	**Total**
Starting hand for numbers	**Left**	5	3	8
	Right	7	15	22
	Total	12	18	30

Note. Five participants were left-handers. One of them started both syllable and number counting with the left hand, two started only syllable counting with the left hand, two started only number counting with the left hand, and none started both with the right hand.

[24] All results were statistically identical whether or not the data of the English native speaker were included and we report the full data.

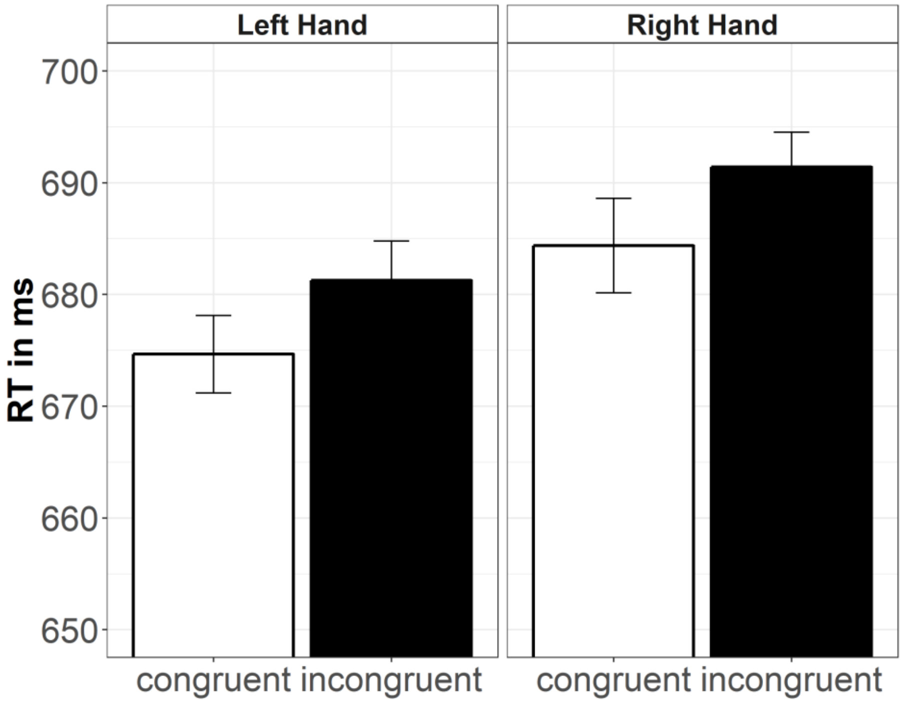

Figure 3.1. Reaction times in ms for congruent an incongruent finger-number pairs for the left hand (left) and right hand (right). Error bars represent within-subject standard errors as suggested by Cousineau (2005).

Discussion

The main objective of the present study was to investigate whether and how finger movements affected number processing. We focused on embodied number representations, that is, pre-experimentally established finger-number associations that comply with finger counting habits. Repeatedly performing finger movements in this habitual order resulted in speeded naming latencies for counting-congruent finger-number pairs. The underlying mechanism presumably involved priming of the associated number concepts through finger movements. This observation complements previous findings of passive finger stimulations activating associated number concepts (Sixtus et al., 2018) and supports embodied accounts of cognition according to which all knowledge, even supposedly 'abstract' numerical knowledge, remains associated with the sensory and motor activation that was present during its acquisition (Barsalou, 2008; Fischer, 2012; Fischer & Coello, 2016; Pulvermüller, 2013).

Importantly, the congruency effect in our task did not depend on the starting hand in finger counting, or on the active hand during the experiment, or on their interaction. Interactions with the starting hand would have been expected if the starting hand were an intra-individually stable trait. Interactions with the active hand were predicted from the spatial associative account according to which the congruency benefit is limited to those conditions where fingers are spatially oriented in alignment with the left-right increasing MNL. We discuss these additional observations and their implications in turn.

Regarding the starting hand, it might have been expected that the effect only appeared in the hand spontaneously used for numbers one to five which were part of the present experiment. This was not the case. As evident from the independence of the results from the two different measures of starting hand, both hands can be assigned to small or large numbers (one to five or six to ten, respectively) rather flexibly (see also Wasner et al., 2014a, 2014b). Due to this flexibility, both hands presumably habitually represent both small and large numbers, resulting in measurable associations between the investigated small numbers and fingers of both hands. The independence of starting hand between the two measures is in itself an interesting finding. Wasner et al. (2014a, 2014b) already reported flexible finger-number mappings; however, they used different participants for related tasks that all included counting with the fingers (Wasner et al., 2014b) or they used very different tasks for the same participants, whereof only one consisted in counting with the fingers (Wasner et al., 2014a). The present results further emphasise the situatedness of the starting hand in finger counting, because participants were inconsistent in their starting hand with only about half an hour lying between the two measures and with the only difference being the items to be counted.

Regarding the active hand, it might have been expected that the congruency effect would be stronger on the right than left hand because only for the right hand did the finger counting direction coincide with the direction of the MNL, that is, smaller numbers on the left and bigger numbers on the right. The congruency effect for the left hand appears to conflict with Riello and Rusconi's (2011) results where finger counting direction needed to be spatially aligned with the MNL for the congruency effect to appear. However, the two studies differ in their definitions of congruency: Riello and Rusconi (2011) measured the SNARC effect, looking for a more general space-magnitude congruency, and thereby coded whole magnitude dimensions (smaller or larger than five) to single fingers, while we coded discrete finger-number congruency, that is, one number per finger. This indicates that while general magnitude processing may depend on finger-space alignment, specific finger-number associations do not.

Moreover, Riello and Rusconi (2011) found a reliable spatial-numerical association only in the parity task while it "fell (…) far from significance in the magnitude task [4 ms; $F(1,46) = 1.131$, $P > 0.10$]" (p. 6). This aspect of their results indicates that the level of number processing might be important, with better sensitivity for implicit compared to explicit magnitude processing (cf. Shaki & Fischer, 2018). Arguably, our present naming task imposed even less semantic number knowledge retrieval compared to a parity task, thus increasing sensitivity of the measurement.

The present study complements the work of Di Luca et al. (2006) by revealing the bi-directional relationship between finger movements and mental number representations: in Di Luca et al.'s (2006) experiment, the number was given and responses were finger movements while in the present experiment, finger movements were given and responses were vocalised number names. Furthermore, the present study reveals the implicit link between numbers and fingers: in their experiment the task explicitly assigned numbers to fingers, which was not the case in the present experiment where numbers appeared quasi-randomly with only 20% finger-number congruent trials scattered over the experiment.

One limitation of the present study is that fingers were only moved in a sequence matching finger counting. This leaves the possibility that the effect did not emerge through finger-number associations, but through a sequence effect independent from finger identity. We tried to minimise such an effect by having always 50 uninterrupted trials per mini-block so that the thumb was not only moved first, but also sixth, eleventh etc., the index not only second, but also seventh, twelfth etc.… It is nevertheless still possible that the leap from the pinkie back to the thumb induced a resetting of participants' internal counter to 'one', which could have been induced by the spatial leap and not by finger identity. With this study alone we can therefore not conclusively distinguish between an effect of finger-number associations and a sequence effect. However, there are other studies indicating towards finger-number associations without the need of the fingers being in a sequence: when stimulated on the index, middle, or ring finger two, three, or four times, responses regarding the amount of stimulations were more accurate and faster on the counting-congruent fingers (Sixtus et al., 2018). The present study extends this finding by showing that also actively produced finger movements prime number concepts. A follow-up study could set out to replicate the present results using another fixed sequence or even random finger movements instead of the counting-congruent sequence.

Taken together, the present study provides further evidence that number representations are strongly associated with finger counting experience. This persistent association indicates that fingers are an effective tool for understanding numbers.

Chapter 5

Study 4: Stimulating numbers: signatures of finger counting in numerosity processing

Based on:

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Abstract

Finger counting is one of the first steps in the development of mature number concepts. With a one-to-one correspondence of fingers to numbers in Western finger counting, fingers hold two numerical meanings: one is based on the number of fingers raised and the second is based on their ordinal position within the habitual finger counting sequence. This study investigated how these two numerical meanings of fingers are intertwined with numerical cognition in adults. Participants received tactile stimulation on their fingertips of one hand and named either the number of fingers stimulated (2, 3, or 4 fingers; Experiment 1) or the number of stimulations on one fingertip (2, 3, or 4 stimulations; Experiment 2). Responses were faster and more accurate when the set of stimulated fingers corresponded to finger counting habits (Experiment 1) and when the number of stimulations matched the ordinal position of the stimulated finger (Experiment 2). These results show that tactile numerosity perception is affected by individual finger counting habits and that those habits give numerical meaning to single fingers.

Introduction

Finger counting has shaped both our ontogenetic and phylogenetic development of numerical reasoning (Coolidge & Overmann, 2012). Fingers are used for counting in most cultures - they are ten tiny tools, literally always at hand to help children internalise the number sequence from 1 to 10. Later in life fingers are still used for handling numerosities, e.g., when signalling the size of a set (Pika et al., 2009) or when keeping track of the number of verbal items (e.g., syllables in a sentence; Lucidi & Thevenot, 2014) or of items in a verbalised list. These acts of finger counting imbue fingers with numerical meaning. Given that Western finger counting habits usually comprise a one-to-one correspondence of fingers to numbers, fingers have a cardinal meaning that simply corresponds to the number of active (e.g., raised) fingers. Similarly, fingers have an ordinal meaning that is determined by a finger's specific position within the counting sequence and thereby depends on the order in which fingers are used for counting. While the cardinal meaning is objectively quantifiable, the ordinal meaning depends on individual finger counting habits. Both the cardinal and ordinal meaning exist irrespective of whether counting with the fingers consists of extending them outward, folding them inward and/or touching them with another finger.

The present study aims to investigate compatibility effects between finger counting experience and the representation of numerical meanings of fingers. Experiment 1 focusses on the specific sets of fingers that are used in conjunction with different numerosities. It has been shown for the manual production of finger postures that those postures that comply with individual finger counting habits prime comprehension of the associated numbers while other finger postures involving the same number of fingers do not (Sixtus et al., 2017). One could argue that the specific sets of fingers that a person habitually uses have evolved into finger symbols representing the specific numerosities and therefore provide a processing advantage over other sets of fingers involving the same number of fingers. Experiment 1 investigates whether finger counting habits influence the perception of cardinal tactile numerosities – when determining the amount of stimulated fingers, does it play a role *which* fingers are being stimulated, and *how*?

The cardinality of counting-congruent sets of fingers is never fully dissociable from the ordinal meaning of the fingers involved in the count. Specifically, the most recently activated finger in the counting sequence receives significance as the one discriminating it from the next smaller or larger number and, more importantly, it is active (being moved, touched, or just acutely thought of) at the exact moment when this particular number is named (or thought of). This is especially relevant in situations of sequential (as opposed to simultaneous) finger activations. Potential effects of different kinds of finger sets are therefore inherently confounded with ordinal finger meanings.

Experiment 2 removes the potential symbolic component of the stimuli and controls the cardinal meaning of finger sets by stimulating one single finger multiple times in each trial. Stimuli thereby represent the ordinal aspect of finger meanings and Experiment 2 thus explores the impact of the position of the stimulated fingers (within the hand, i.e., within the habitual counting sequence) on tactile numerosity processing. Cardinality might still be involved to some degree, as people are habitually using theses single fingers in combination with the "lower" fingers in finger counting and might thereby co-activate these other fingers. Moreover, an ordinal meaning of fingers is achieved by counting sets of fingers and stopping at the finger in question. Nevertheless, single fingers provide reduced overt numerosity information as compared to full sets of fingers and we are interested in whether this partial information suffices to interact with number processing. An influence of both the specific finger sets (Experiment 1) and the specific single fingers (Experiment 2) on number processing would be predicted by an embodied cognition stance on number processing; according to this view, the sensorimotor experience that was present during concept acquisition (e.g., learning about numbers through finger counting) remains a fundamental part of conceptual representations throughout life (cf. Fischer & Brugger, 2011). Therefore, finger representations and number representations should co-activate each other. The literature regarding the processing of cardinal meanings of finger sets so far shows inconsistent results, as will be indicated by the following section (for broader reviews, see Domahs, Kaufmann, & Fischer, 2012).

Krause et al. (2013) found that the cardinal meaning of finger sets is mentally processed similarly to the cardinal meaning of Arabic numbers. Participants in their study verbally compared a visual Arabic number with the amount of tactually stimulated fingers in a same-different task. The authors reported a numerical distance effect during cross-modal number presentation: the numerical distance effect is a typical signature of analogue mental number processing: when two different numbers are compared, responses are slower and more error-prone the smaller the numerical distance between the two numbers is (Moyer & Landauer, 1967). This is usually ascribed to mental representations of adjacent numbers being more similar to each other when compared to more distant numbers. Cohen et al. (2014) furthermore found that judgements concerning the amount of tactually stimulated fingers were faster and more accurate when the stimulated sets of fingers consisted of neighbouring fingers than when they consisted of non-neighbouring fingers. While Cohen et al. (2014) did not report an advantage for the simultaneous stimulation of counting-congruent finger configurations (i.e., neighbouring fingers that include the thumb for participants who start to count on their thumb) as compared to other neighbouring configurations, Krause et al. (2013) did. However, in Krause et al.'s (2013) first experiment the counting-incongruent sets of fingers differed substantially from the counting-congruent sets: the latter were sets of neighbouring fingers including the thumb and the former were sets of neighbouring fingers including the pinkie. In their second experiment Krause et al. (2013) used sequential instead of simultaneous stimulations; congruency was defined by the stimulation direction relative to the mid-sagittal plane. Both hands were always prone, so congruent stimulation ran from the thumb outwards and incongruent stimulation ran inwards towards the thumb. Surprisingly, the authors found only a trend towards an influence of counting congruency on response times. Note, however, that in this case the specific sets of stimulated fingers did not vary and were always counting-congruent, because congruency was defined only by the stimulation direction. This also means that effects of counting congruency (finger sets in Experiment 1 and stimulation direction in Experiment 2) were only found for simultaneous and not for sequential stimulations.

To summarise, both the specific sets of fingers and the directionality of sequential stimulations (i.e., stimulating the fingers of the prone hand "outwards" or "inwards") contribute to counting congruency in finger counting, but it has not yet been studied how these conditions interact. Moreover, it has not been conclusively investigated whether the effect of counting congruency is linked to the timing of the stimulations (i.e., sequential or simultaneous stimulations). The present study took up the ideas of different conditions regarding finger sets, directionality, and timing and combined them in a within-subject design.

Furthermore, sets of fingers always also include ordinality information conveyed by the involved single fingers. The natural spatial distribution of the fingers carrying this ordinal information partly disagrees with another spatial representation of numbers: it is often assumed that numbers are cognitively represented on a spatially oriented mental number line (MNL) with increasing numbers from left to right (in Western cultures). This cognitive representation is probably culturally induced (through schooling, the depiction of number- and timelines, etc.). A typical consequence is the so-called spatial-numerical association of response codes (SNARC) effect, which constitutes faster responses to small numbers with left-side responses and faster responses to larger numbers with right-side responses (Dehaene et al., 1993). Brozzoli et al. (2008) found that these spatial-numerical associations of the fingers interacted with number processing, but that the ordinal meaning of the fingers did not. In a tactile detection task, Arabic numbers ("1", "2", "4" or "5") served as visual primes and participants stepped on a foot-pedal to report tactile finger stimulations to the thumb or pinkie of the right hand. Their hand was either in a supine or prone position such that thumb and pinkie were the left- and rightmost fingers. Stimulations on the left-side fingers of the hand were detected faster after seeing small numbers and right-side stimulations were detected faster after seeing larger numbers, irrespective of the identity of the stimulated finger. The results are therefore in line with the notion of a spatial MNL that is unaffected by (ordinal) finger-number associations as derived from finger counting habits.

In contrast, finger-number associations did affect magnitude classification in an experiment conducted by Riello and Rusconi (2011). In two separate tasks participants classified Arabic numbers as smaller or larger than 5, or as odd or even. Responses were given by pressing buttons with the index or middle finger of either the left or right hand, in an either supine or prone position. Thus, depending on the condition, the number-to-button arrangement could be compatible with the MNL (i.e., spatial arrangement: increasing numbers from left to right), or with finger counting habits (i.e., anatomical arrangement: increasing numbers from thumb to pinkie); that is, each arrangement conformed to either none, one, or both of these compatibilities. Interestingly, the typical SNARC effect only emerged when there was no conflict between MNL- and finger counting representations, i.e. for the left hand in a supine position and for the right hand in a prone position. These results suggest similarly strong embodied (finger counting-based) and spatial representations of numbers that cancel each other when in conflict. Thus, the embodied ordinal meaning of single fingers influenced response efficiency at least to some degree.

Finally, a study by Di Luca et al. (2006) provides evidence for a stronger association between the individual fingers and their ordinal meaning than a purely spatial-numerical association would predict. Participants rested each finger on a button and pressed one of these ten buttons in response to Arabic numbers (1-10). The finger-number assignment varied between blocks. Results showed that responses were faster when each finger was assigned to the number it represents within the individuals' finger counting habits than with any other finger-number assignments - even a MNL-compatible assignment with numbers increasing from left to right was less efficient. Di Luca et al.'s (2006) findings speak for a strong embodied representation of numbers that has been established through finger counting, and not so much for a purely spatial association which would be a consequence of the MNL.

How can these seemingly contradictory results be explained? An important difference between the three reported studies consists in the task-relevance of the numbers. In the first study (Brozzoli et al., 2008), number primes were completely task-irrelevant and any finger stimulation required the same response. In the other two studies (Di Luca et al., 2006; Riello & Rusconi, 2011), however, different target numbers required different responses and numbers had to be processed according to finger-assignment or magnitude. It seems as if a certain processing of numbers is necessary to evoke a measurable influence of the ordinal meaning of fingers on number processing. We therefore made semantic number processing an explicit task requirement in the present study.

In this study, Experiment 1 first investigated whether the processing of the numerosity of stimulated finger sets is affected by finger counting habits. Experiment 2 then addressed the role of the position of fingers within the hand, that is, within the individual counting sequence for number processing.

Experiment 1: Single stimulations across multiple fingers

In the present Experiment we varied the set of stimulated fingers (one marker of finger counting-compatibility). We introduced three different finger set variants (one was finger counting-compatible and two were finger counting-incompatible) for each of three different numbers of stimulated fingers and we manipulated the timing of finger stimulations (i.e., sequential or simultaneous stimulation). For sequential stimulations we also varied the stimulation direction (another marker of finger counting-compatibility). Participants' task was to verbally indicate the number of stimulated fingers per trial. It is conceivable that number of stimulations is the only predictor of response efficiency (i.e., the fewer, the easier). In contrast, an embodied cognition perspective predicts that finger counting-compatible stimulations should be processed faster and more accurately than finger counting-incompatible stimulations.

Method

The datasets analysed during the current study (Experiment 1 and 2) are available via the Open Science Framework platform at https://osf.io/w5aey.

Participants

Thirty-one participants took part in the study in return for course credit or money. All participants gave their informed consent before data acquisition. Data from four participants were excluded from analyses because of voice key malfunctions during data acquisition. All remaining participants (25 females, 2 males, mean age: 21.85 years, *SD* = 3.30) were native German speakers, one was left-handed and one reported no hand preferences. All performed finger counting from thumb to pinkie, as was determined at the end of data collection by asking participants to show how they count on their fingers from one to ten.

The experiment was conducted in accordance with the ethical standards expressed in the Declaration of Helsinki.

Apparatus and experimental set-up

The tactile stimulation device was custom-made from piezoelectric Braille cells (Metec AG, Stuttgart, Germany; see also van Ede, Jensen, & Maris, 2010). Each fingertip can be stimulated separately: there are ten stimulation fields, i.e., five per hand (one per finger). Each stimulation field consists of eight little plastic pins (arranged in two groups of four), which rise and lower as programmed with approximately millisecond precision. In this study, stimulations were always delivered jointly by all eight plastic pins of the stimulation fields to the fingertips resting on them. Wooden boxes around each device prevented participants from seeing their hands and hearing the clicking sound of the moving pins. Holes in the boxes allowed participants to put the hands inside and to place them on the stimulation devices in a prone position. The devices are built such that the position of the stimulation fields can be adjusted to individual finger lengths. Responses were given verbally into a microphone (t.bone EM-9900, Thomann GmbH, Burgebrach, Germany) that was connected to an audio interface (U46 XL, ESI Audiotechnik GmbH, Leonberg, Germany); response times were registered by a voice key device (SV-1 Voice Key, Cedrus Corporation, San Pedro, USA) also connected to the audio interface.

Stimuli

Target stimuli were tactile stimulations on different fingertips of all ten fingers. Stimulations were delivered by the pins emerging once per stimulated finger. Stimulations occurred either simultaneously or sequentially on 2, 3, or 4 fingers of the same hand and the stimulated fingers were either adjacent or not (see Table 4.1). In the sequential condition, fingers were stimulated both in the counting-compatible and counting-incompatible direction (e.g., both thumb-index and index-thumb).

Table 4.1. All counting-compatible and counting-incompatible finger set variants (columns) for each numerosity tested (rows). Pins up-durations (in ms) in the sequential conditions are also given to document control over duration cues (pins down-durations were always 60 ms).

Number of fingers stimulated	**Pins up-durations per single stimulation (ms), sequential condition**	**Finger set variants**		
		Counting-compatible (FSC+)	**Counting-incompatible A (FSC-)**	**Counting-incompatible B (FSC-)**
2	100, 173, 180	T I - - -	T - M - -	- I - R -
3	47, 100, 173	T I M - -	T - M R -	- I - R P
4	47, 60, 100	T I M R -	T - M R P	T I - R P

Note. FSC: Finger Set Compatibility; T=thumb, I=index finger, M=middle finger, R=ring finger, and P=pinkie. '-' indicates no stimulation.

For sequential stimulations, different stimulation length patterns occurred pseudo-randomly, so that neither overall nor individual stimulation lengths would reveal the correct responses.[25] Only the times of 'pins up' varied while pauses between two 'pins up'-events lasted always 60 ms. Table 4.1 lists the pins up-durations. Each trial included only one of the pins up-durations (e.g., four times 47 ms stimulation with three 60 ms pauses in-between). The resulting overall stimulus lengths including pins up- and pins down-events were for the sequential stimulation of two fingers 260, 406 or 420 ms, of three fingers 261, 420 or 639 ms, and of four fingers 368, 420 or 640 ms. For simultaneous stimulations, the respective pins were always raised for 100 ms, which is equivalent to the overall stimulus length.

During training, the (German) feedback "Korrekt!" (engl.: *correct*) or "Richtig gewesen wäre [actual number of stimulations]" (engl.: *The correct response would have been* [actual number of stimulations]), appeared on the computer screen for 500 ms.

In the verbal baseline phase after the experimental blocks the Arabic numbers 2, 3, and 4 were presented on the computer screen in a sans serif font (FreeSans, Free Software Foundation, Boston, USA) with a text size of 30 pixels.

Design

There were two blocks per hand, each hand receiving one block of sequential stimulations and one block of simultaneous stimulations, with their order balanced over participants. Furthermore, half of the participants started with the right hand, the other half with the left hand.

There were 486 experimental trials in total, 324 trials in the sequential blocks: 2 hands (left / right) x 3 numerosities (2 - 4) x 3 finger set variants (one counting-compatible and two counting-incompatible variants; see Table 4.1) x 2 directions (thumb-to-pinkie / pinkie-to-thumb) x 3 stimulation length patterns x 3 repetitions. In the simultaneous blocks there were 162 trials: 2 hands (left / right) x 3 numerosities (2 - 4) x 3 finger set variants (one counting-compatible and two counting-incompatible variants; see Table 4.1) x 9 repetitions. Stimulation lengths were not varied in the simultaneous blocks because the overall stimulation length and the number of stimulations were not confounded here.

Before each experimental block there was at least one training block comprising 18 trials: for sequential stimulation blocks each finger set (3 numerosities x 3 finger set variants) in both 'directions', and for simultaneous stimulation blocks each finger set twice . Pins up-durations in the training of the sequential conditions were chosen so as to hold overall lengths equal – 180 ms for 2, 100 ms for 3 and 60 ms for 4 stimulations.

A verbal baseline phase following the last experimental block was introduced to control for the different individual pronunciations of the different number words. The baseline phase comprised a total of 30 trials, containing each number (2, 3, 4) 10 times in a random order.

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[25] All individual stimulation durations range from 47 to 180 ms and all total stimulation durations range from 260 to 640 ms. Although participants might learn that 47 ms could never involve two stimulations, we chose not to use the shortest individual stimulation length for two stimulations because that would have resulted in a very short (154 ms) total stimulation length which would have given away the numerosity without requiring actually counting the number of individual stimulations. Furthermore, additional analyses showed that there was no training effect selectively for stimulation conditions involving 47 ms-stimulations.

Procedure

The participant placed the left or right hand (as specified by the instructions on the screen) on the tactile stimulation device with all five fingertips on the stimulation fields. The other hand was placed comfortably on the table so that both hands were in a prone posture. Before each trial, a fixation dot appeared on the screen for a random duration between 700 and 1200 ms. Then, two, three, or four fingers were stimulated (as described in the Stimuli section). Participants responded verbally by saying the perceived number of stimulated fingers as quickly and accurately as possible. Responses were entered by the experimenter via the keyboard. Then the next trial began after an inter-trial interval of 300 ms. The procedure in the training and experimental blocks was the same, except that the feedback after each response (see Stimuli section) was given during training only. The training was repeated until an accuracy level of at least 70% (measured per 18 trials of the training block) was reached. During the experimental blocks, a short message appearing every 18 trials on the screen informed participants about their performance (i.e., percentage of correct responses) in the past 18 trials. After this message the experiment resumed after the participant said that he or she was ready and the experimenter pressed a button. A verbal baseline phase followed the experimental blocks, measuring the baseline reaction times for saying the different numbers. Before each baseline trial, a fixation dot appeared for a random duration between 700 and 1200 ms. Then, the target number (2, 3, or 4) appeared on the screen until a response was registered by the voice key: participants responded by reading out the number name as quickly as possible. After 1000 ms, the fixation dot reappeared for the next trial.

After data collection the experimenter assessed the participant's finger counting habits. The participant was asked to count from one to ten with the fingers and the experimenter noted down the order in which the fingers were used.

Analyses

Verbal response times (vRTs) were defined as the duration from the moment when participants can know the correct response for sure until the onset of the verbal response. For two and three stimulations in the sequential stimulation condition vRT measurements therefore start at 60 ms after the end of the last stimulation, because at this point it becomes clear that no further stimulation is going to occur. For four stimulations as well as for all numerosities in the simultaneous stimulation condition vRT measurements start at the onset of the last or all, respectively, stimulation(s), because no further stimulation can occur after that. In the verbal baseline phase vRTs start at the onset of the visual number. In some trials the voice key registered unrelated noises as responses, resulting in a bimodal frequency distribution of the vRTs with the first peak at about 100 ms and the intersection of the curves at about 250 ms. vRT analyses therefore excluded all trials with registered response latencies below 250 ms (9.56% of the experimental trials and 5.80% of the baseline trials). Slow responses (experimental trials with vRTs longer than 2000 ms: 1.12%, and baseline trials with vRTs longer than 1200 ms: 0.52%) were also excluded from vRT analyses. Only trials with correct responses were considered for vRT analyses. The vRTs used in the analyses were adjusted for voice key sensitivity regarding individual pronunciation of the different number words: first, naming latencies of the baseline condition were aggregated per subject and response (mean latency for reading number 2 ("zwei") was 644 ms, SD = 91 ms, for number 3 ("drei") it was 574 ms, SD = 99 ms, and for number

4 (“vier”) it was 603 ms, *SD* = 81 ms). Then the difference between those values and the mean naming latency per subject (averaged over all numbers) was calculated. This difference value was then subtracted from every verbal RT from the experimental trials from the corresponding subject and response. vRTs will henceforth always refer to the resulting adjusted vRT scores. vRTs and accuracy were analysed separately.

Analyses of vRTs and accuracy made use of (generalised) linear mixed effects. The contrasts for all factors were set to summation contrasts and *t*-values equal or larger than 2 were considered as statistically significant for the linear mixed effects models (Baayen, 2008) as well as *p*-values falling below 0.05 for the generalised linear mixed effects models.

Finger Set Compatibility (FSC) was defined as follows: finger counting-compatible finger set variants (FSC+) consisted of all neighboured fingers starting from the thumb, and all other configurations were finger counting-incompatible (FSC-; see Table 4.1). Direction Compatibility (DC) existed only in sequential stimulations and was defined as follows: for sequential stimulations in a counting-compatible direction (DC+), the fingers were stimulated in the direction from thumb to pinkie and for sequential stimulations in a counting-incompatible direction (DC-), the fingers were stimulated in the reverse direction, i.e., from pinkie to thumb. Numerosity (NUM) ranged from two to four stimulated fingers.

Fixed effects in the linear mixed effects models (vRT analyses) and the generalised linear mixed effects models (accuracy analyses) were FSC (FSC+ / FSC-), NUM (2-4 stimulated fingers) and DC (DC+ / DC-; for sequential stimulations only).[26] All vRT analyses included all interaction terms. As random effects the intercepts for Stimulation length patterns (for sequential stimulations only) and Subject were included. To select a sufficient random effect structure, the fixed factors and their interaction terms were included step-wise as random slopes and kept within the model when they significantly improved model fit to receive the most parsimonious model. For the sequential stimulation condition, by-Subject slopes for FSC, NUM, and the interaction term of the two were included. For the simultaneous stimulation condition, by-Subject slopes for NUM were included.

The same approach was taken for the accuracy analyses. The same fixed and random effects were included – however, for the sequential stimulation condition only the interaction terms for FSC x DC and FSC x NUM were included as it turned out that the generalised linear mixed model did not converge with all interaction terms included. For accuracy analyses in the sequential condition, by-Subject slopes for FSC were included and for the simultaneous condition, by-Subject slopes for NUM were included.

Results

The overall accuracy was 79.72% (see Table 4.A.1 in the Appendix for vRTs and accuracy per set of fingers).

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[26] To keep the size of the model reasonable, only factors of theoretical interest were modeled. For instance, the factor Hand (left / right) was not included. Moreover, including Hand as a fixed factor would not bring about any significant main effects or interactions in the complete models except for a three-way interaction of DC:Hand:NUM in the sequential condition.

Sequential condition: vRT analyses

The linear mixed effects model revealed significant main effects of FSC, DC, and NUM as well as significant two-way-interactions of FSC x NUM and DC x NUM (see Table 4.2).

FSC+ (648 ms, *SD* = 127 ms) elicited shorter vRTs than FSC- (668 ms, *SD* = 127 ms). With increasing numerosity, vRTs increased as well (2 stimulated fingers: 624 ms, *SD* = 124 ms 3 stimulated fingers: 682 ms, *SD* = 141 ms, 4 stimulated fingers: 691 ms, *SD* = 149 ms). vRTs were longer for DC+ (671 ms, *SD* = 128 ms) than DC- (653 ms, *SD* = 125 ms). The interaction FSC x NUM reveals that the increasing slope over the three numerosities is significantly steeper for the FSC+ than the FSC- condition. The same is true for the DC x NUM interaction: the slope over numerosities is steeper for the DC+ than the DC- condition. See Figure 4.1 for illustration.

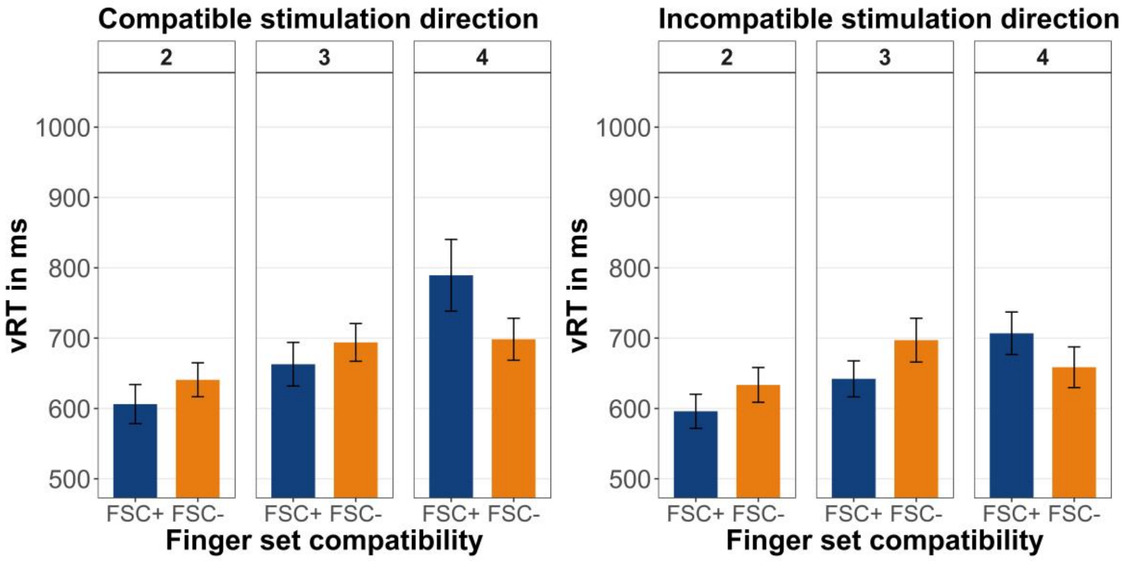

Figure 4.1. Average vRTs for finger counting-compatible (FSC+, blue bars) and finger counting-incompatible (FSC-, orange bars) sets of fingers per numerosity (given in each panel heading) for compatible stimulation direction (DC+, left panels) and incompatible stimulation direction (DC-, right panels) in the sequential stimulation condition. Error bars represent within-subject standard errors as suggested by Cousineau (2005).

Sequential condition: accuracy analyses

The generalised linear mixed effects model revealed that all main and interaction effects included in the model were significant (see Table 4.2).

Accuracy for FSC+ was on average 78.05%, *SD* = 10.36%, and for FSC- it was 84.38%, *SD* = 8.38%. Nevertheless, taking into account all factors, the model estimated accuracy higher for FSC+ than for FSC-. Accuracy was lower for DC+ (80.50%, *SD* = 7.57%) than for DC- (84.04%, *SD* = 8.70%). With increasing numerosity, accuracy decreased (2 stimulated fingers: 90.64%, *SD* = 8.84%; 3 stimulated fingers: 85.49%, *SD* = 9.61%; 4 stimulated fingers: 70.68%, *SD* = 14.71%). The interaction FSC x NUM shows that the negative slope over increasing numerosities was steeper for FSC+ than for FSC-. The interaction FSC x DC shows that in the DC+ condition, the difference between FSC+ (73.53%, *SD* = 11.30%) and FSC- (83.98%, *SD* = 8.88%) was larger than the difference in the DC- condition (FSC+: 82.58%, *SD* = 11.17% vs. FSC-: 84.77%, *SD* = 9.09%). As Figure 4.2 illustrates, this dissociation of FSC effects is predominantly driven by the low accuracy for 4 stimulations in the finger set-compatible, stimulation direction-compatible condition (i.e., FSC+ and DC+).

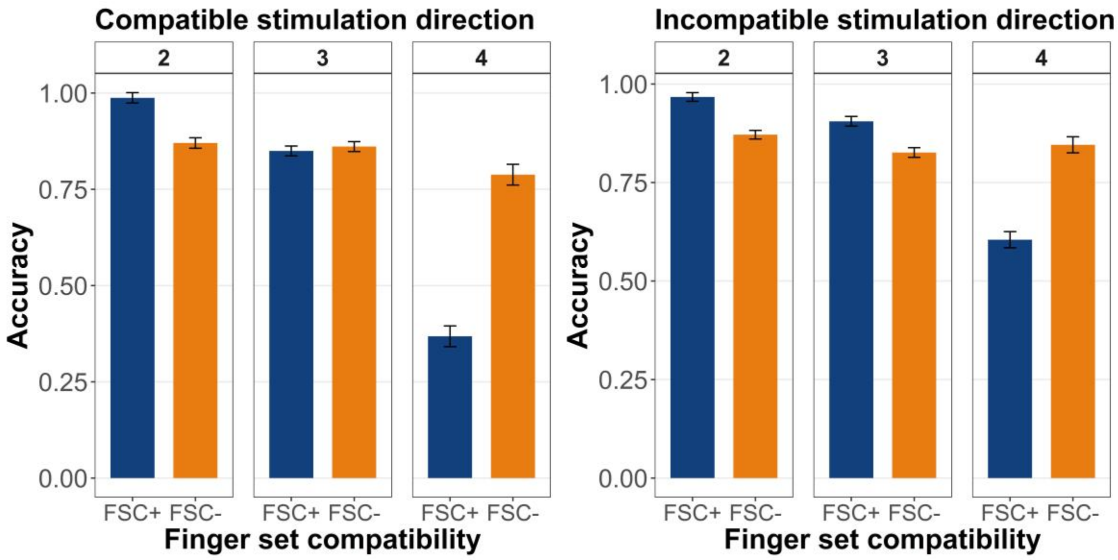

Figure 4.2. Average accuracy rates for finger counting-compatible (FSC+, blue bars) and finger counting-incompatible (FSC-, orange bars) sets of fingers (x-axis) per numerosity (given in each panel heading) for compatible stimulation direction (DC+, left panels) and incompatible stimulation direction (DC-, right panels) in the sequential stimulation condition. Error bars represent within-subject standard errors as suggested by Cousineau (2005).

Table 4.2. Results from sequential stimulation conditions. Left: results of the linear mixed effects-analyses of vRTs, *t*-values exceeding 2 are classified as significant (cf. Baayen 2008). Right: results of the generalised linear mixed effects-analyses of accuracy data, significance estimates given by *p*-values.

	vRT			**Accuracy**			
Effect (fixed)	**β**	***SE***	***t***	**β**	***SE***	***z***	***p***
FSC	-82.011	16.958	-4.836	3.037	0.187	16.278	<.0001
DC	-23.498	10.507	-2.236	-0.214	0.033	-6.390	<.0001
NUM	47.673	9.881	4.825	-1.187	0.053	-22.518	<.0001
FSC x DC	-5.408	10.506	-0.515	-0.182	0.033	-5.442	<.0001
FSC x NUM	27.004	5.626	4.800	-0.969	0.053	-18.433	<.0001
DC x NUM	12.221	3.575	3.418				
FSC x DC x NUM	3.393	3.575	0.949				

Note. FSC: Finger Set Compatibility, DC: Direction Compatibility, NUM: Numerosity.

Simultaneous condition: vRT analyses

The linear mixed effects model revealed significant main effects of FSC and NUM, as well as a significant interaction of FSC x NUM (see Table 4.3).

FSC+ (813 ms, *SD* = 126 ms) elicited shorter vRTs than FSC- (844 ms, *SD* = 128 ms). vRTs increased with increasing numerosity (2 stimulated fingers: 779 ms, *SD* = 119 ms; 3 stimulated fingers: 881 ms, *SD* = 142 ms; 4 stimulated fingers: 870 ms, *SD* = 156 ms). This slope was steeper for FSC+ than for FSC-. For illustrations see Figure 4.3 (left panels).

Simultaneous condition: accuracy analyses

The generalised linear mixed effects model revealed significant main effects of FSC and NUM, as well as a significant interaction of FSC x NUM (see Table 4.3).

Taking into account all factors, the model again estimated accuracy to be higher for FSC+ than FSC- (although descriptively the other way round; FSC+: 69.55%, *SD* = 10.98; FSC-: 77.15%, *SD* = 8.30%). Accuracy decreased with increasing numerosity (2 stimulated fingers: 92.17%, *SD* = 7.14%; 3 stimulated fingers: 76.95%, *SD* = 12.50%; 4 stimulated fingers: 54.73%, *SD* = 14.13%). This decreasing slope was again steeper for FSC+ than FSC-. See Figure 4.3 for illustrations (right panels).

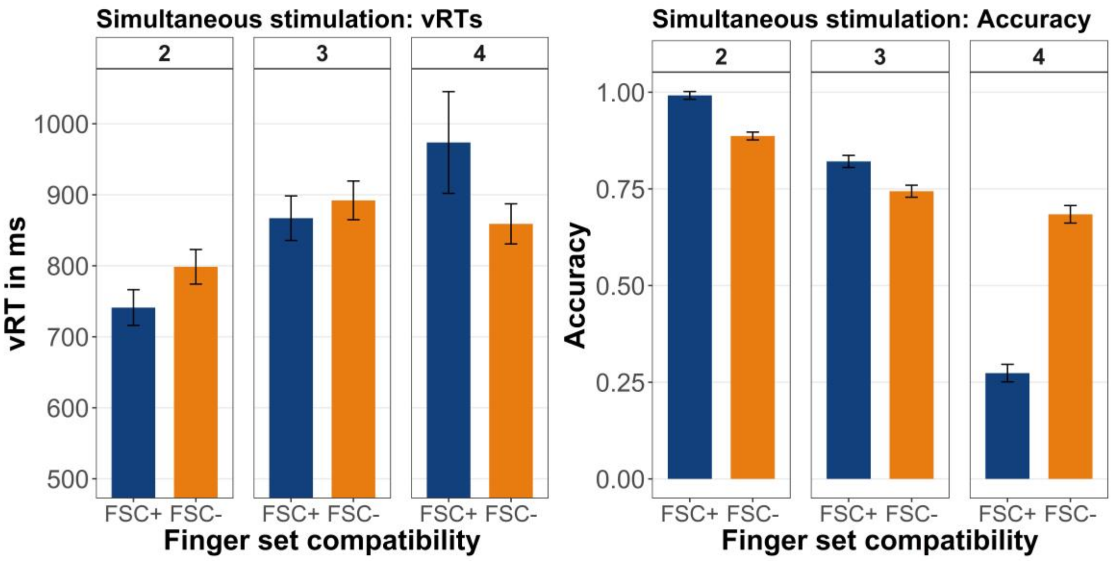

Figure 4.3. Average vRTs (left panels) and accuracy rates (right panels) for finger counting-compatible (FSC+, blue bars) and finger counting-incompatible (FSC-, orange bars) sets of fingers (on x-axis) per numerosity (given in each panel heading) in the simultaneous stimulation condition. Error bars represent within-subject standard errors as suggested by Cousineau (2005).

Table 4.3. Results from the simultaneous stimulation conditions. Left: results of the linear mixed effects-analyses of vRTs, *t*-values exceeding 2 are classified as significant (cf. Baayen, 2008). Right: results of the generalised linear mixed effects-analyses of accuracy data, significance estimates given by *p*-values.

	vRT			Accuracy			
Effect (fixed)	**β**	***SE***	***t***	**β**	***SE***	***z***	***p***
FSC	-111.704	17.416	-6.414	3.323	0.260	12.795	<.0001
NUM	69.191	101.383	6.664	-1.771	0.129	-13.757	<.0001
FSC x NUM	37.414	6.238	5.998	-1.056	0.074	-14.247	<.0001

Note. FSC: Finger Set Compatibility, NUM: Numerosity.

Discussion

In Experiment 1 numerosity information was conveyed via tactile stimulation of different numbers of fingertips. We were interested in the influence of the composition of the sets of stimulated fingers on processing speed of the conveyed numerosities, or more precisely, whether the specific set of fingers used in counting facilitates the recognition of the corresponding numerosity. Results indicate that there indeed is such an effect of finger counting experience: responses were both faster and more accurate when a finger counting-compatible set of fingers was stimulated than when a finger counting-incompatible set was stimulated. Although there was a significant interaction with numerosity – as described below – these results suggest that the stimulations delivered more information than the mere number of fingers: finger counting knowledge was co-activated and counting-compatible finger sets were easier to process.

Both for response times and accuracy, the main effect of Finger Set Compatibility interacted with Numerosity: the slope over numerosity (increasing vRTs and decreasing accuracy, respectively) was steeper for counting-compatible than for counting-incompatible sets. This effect was driven by the fact that numerosity 4 exhibited much more efficient responses for counting-incompatible than counting-compatible sets of fingers. A post-hoc explanation is that finger counting-incompatible sets of 4 stimulated fingers were easily identifiable: they were the only ones including stimulation of both thumb and pinkie and therefore ranged over a larger spatial distance than any other finger set. Therefore, in this condition subjects probably made use of a different strategy than actually counting the amount of stimulated fingers. This presumably non-numerical identification strategy exhibited faster and more accurate responses than the numerical pattern would predict, resulting in a flatter slope and thereby an interaction of Numerosity with Finger Set Compatibility. Overall, the results confirm our hypothesis that stimulating finger counting-compatible sets of fingers co-activates number concepts. Furthermore, the compatibility effect was present both for sequential and simultaneous stimulations.

Contradicting our hypotheses, responses were faster for stimulations from pinkie to thumb than from thumb to pinkie. This effect was probably caused by our specific setup: the prone hands were positioned in front of the participants. Therefore, the incompatible stimulation directions always moved towards the body midline, which probably made them more salient, because stimuli perceived as moving towards the body are naturally a larger potential threat than stimuli moving away from the body.

Looming stimuli have so far been shown to evoke faster reactions both in the visual (Franconeri & Simons, 2003; Moher, Sit, & Song, 2015; Takeuchi, 1997) and auditory domain (McCarthy & Olsen, 2017). This explanation is also supported by the fact that the effect was clearly driven by the Numerosity-4 trials which comprised the spatially longest and therefore most obvious "movement" towards the body.

Consistent with a size effect, vRTs increased and accuracy decreased with increasing numerosity. Similar results have been reported in the literature (e.g., Cohen et al., 2014; Cohen et al., 2016; Gallace, Tan, & Spence, 2008) and reflect the increasing imprecision of tactile perception and/or of larger numbers.

The specific finger sets chosen for the present Experiment might, however, have created a confound which weakens our interpretation of the processing advantage for counting-compatible finger sets. Compatible sets always consisted only of adjacent fingers, while incompatible sets always included non-adjacent fingers. Previous findings suggest that adjacent fingers are easier to process than non-adjacent fingers anyway (Cohen et al., 2014). However, it is also not a solution to look at counting-compatible versus incompatible sets of adjacent fingers, because this would create another confound: all counting-compatible sets include the thumb and index finger (in German finger counting) and regardless of counting-compatibility we can expect better performance for those fingers due to their higher sensitivity (Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995; Krause et al., 2013). It is therefore a good idea to approach the interaction of finger counting and numerosity representations also from another vantage point. This can be achieved in conjunction with our next objective to reduce the informative content of the stimulated fingers by stimulating only single fingers.

As mentioned before, fingers always possess an ordinal as well as a cardinal meaning. Regarding the usual finger counting sequence, the ordinal meaning of the "highest" stimulated finger – that is, the one farthest from the thumb and closest to the pinkie in Western finger counting – equals the cardinal meaning of counting-compatible finger sets, but not of counting-incompatible finger sets. It is therefore unclear whether the effect of finger set compatibility in Experiment 1 is actually dependent on the full finger set. It is also possible that the effect is driven by the single finger that is connected to the specific ordinal meaning, as it is or is not the "highest" stimulated finger in the counting-compatible or counting-incompatible finger set, respectively. Experiment 2 focusses on the position of single fingers within the hand and thereby within the habitual finger counting sequence. Is it sufficient to stimulate single fingers to activate the related number concepts? We address this question by controlling the numerosity conveyed by finger sets and stimulating only single fingers to pre-activate specific number concepts.

Experiment 2: Repeated stimulation of single fingers

In Experiment 2 the question is whether tactual stimulation of a single finger automatically activates its ordinal meaning. We addressed this question by administering temporally distributed tactile numerosities to specific fingers and measuring response efficiency because numerosity discrimination should improve when the tactile numerosity is pre-activated by the ordinal meaning of the stimulated finger.

Semantic processing was again ensured by the task of indicating the perceived numerosity.

We hypothesised that responses would be faster and more accurate whenever the tactually conveyed numerosity matched the ordinal meaning of the finger to which it was conveyed (i.e., two stimulations on the index finger, three on the middle finger or four on the ring finger). This would concur with the embodied cognition stance on mental number processing (Fischer & Brugger, 2011). On the other hand, small numerosities might be processed more easily when presented on the left-sided fingers of the prone hand and large numerosities when presented on the right-sided fingers of the prone hand, following the spatial-numerical mapping of the MNL (cf. Brozzoli et al., 2008).

Method

Participants

Twenty-seven participants took part in the experiment in return for course credit. All participants gave their informed consent before data acquisition. One was excluded from analyses because of misunderstanding the instructions. Of the remaining 26 participants, 20 were female and the mean age was 21.19 years (*SD* = 3.31). All but two were right-handed and all but one (Turkish) were native German speakers. All performed finger counting from thumb to pinkie, as was determined at the end of data collection by asking participants to spontaneously count on their fingers from one to ten.

The experiment was conducted in accordance with the ethical standards expressed in the Declaration of Helsinki.

Apparatus

The same tactile stimulation device as in Experiment 1 was used to stimulate participants' fingertips. In each experimental block one hand was placed onto the device, prone, through a hole in the box. Responses were given with the other hand via a button box with 4 exposed and unlabelled buttons (see Figure 4.4). The three response buttons were arranged equidistantly around a central 'hold-button'. The central button and the custom-made button box were connected to the computer via USB and emulated keys of a standard keyboard.

Figure 4.4. Experiment setup. Inside the wooden boxes (on the left and right sides) are the tactile stimulators (not visible; for a description see Section *Apparatus and experimental set-up* of Experiment 1). In the middle of the desk is the button box with the centred hold-button and three response buttons, as well as the instruction monitor.

Stimuli

Target stimuli were tactile stimulations on the fingertips of the index, middle, or ring finger. In each trial, the pins of the individual stimulation field emerged 2, 3, or 4 times. Three different stimulation patterns were applied to control for different aspects of the stimulations, so that numerosity could neither be derived from the durations of raised or lowered pins, nor from the overall duration of the stimulation. A) To keep individual lengths of both stimulations and pauses constant, pins were raised for 50 ms and lowered for 52 ms, resulting in overall lengths of 152, 254, and 356 ms for 2, 3, and 4 stimulations, respectively (Figure 4.5, Panel a); B) to keep the overall length of the stimulation constant as well as the lengths of the pauses, pins were raised for 152, 84, or 50 ms for 2, 3, or 4 stimulations, respectively, and lowered for 52 ms, resulting in an overall length of 356 ms for all three numerosities (Figure 4.5, Panel b); C) to keep the overall length of the stimulation constant as well as the lengths of the individual stimulations, pins were raised for 50 ms and lowered for 256, 103, or 52 ms for 2, 3, or 4 stimulations, respectively, also resulting in an overall length of 356 ms for all three numerosities (Figure 4.5, Panel c).

During the training phase, German feedback words appeared on the PC screen for correct and incorrect responses, the latter feedback also including the actual number of stimulations. Before each trial a fixation dot appeared on the screen for a random duration between 700 and 1200 ms.

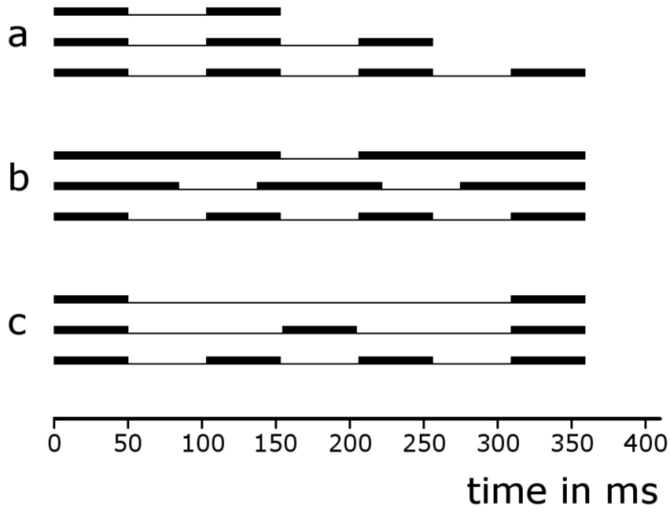

Figure 4.5. Different tactile stimulation patterns used. Each line represents one stimulation pattern; the black blocks represent the duration of raised pins. See text for details.

Design

Participants were tested on their left and right hands in two separate blocks. The order of hands was balanced over participants. There were two sub-blocks per hand of 108 randomised trials, i.e. 432 trials in total (2 hands x 2 blocks x 3 fingers x 3 numbers of stimulations x 3 stimulation patterns x 4 repetitions, all within participants). Half of the participants had to press the leftmost button for response "2", the middle button for "3", and the rightmost button for "4" and the other half of the participants had the reverse arrangement. At the very beginning and when switching hands there was a training block of 27 trials each (stimulating each finger with each number of stimulations and with each stimulation pattern).

Procedure

Instructions on the PC screen advised the participant to place the left or right hand on the tactile stimulation device with the fingertips on the stimulation fields containing the eight pins. The other hand was used for responses. The participant pressed the hold-button with the index finger of the response hand to initiate each tactile stimulation sequence. This requirement controlled the starting position of the responding finger. After the target stimulus had been delivered the participant had to press one of three buttons according to the perceived numerosity of tactile stimuli, also using the index finger of the response hand. This requirement ruled out that congruency effects originated at the responding hand. Participants were instructed to respond as quickly and accurately as possible. After giving the response, the index finger was returned to the hold-button for the next trial to start. Times were recorded both for lifting the finger from the hold-button and for pressing the response button.

At the very end of data collection, the participant was asked to count from one to ten with the fingers and the experimenter noted the order in which the fingers were used.

Analyses

Initial reaction time was defined as the duration from the onset of the last stimulation within a stimulation sequence (i.e. the onset of the 2nd, 3rd, or 4th stimulation) until the finger was lifted from the hold-button. Response time (RT) was defined as the initial reaction time plus the movement time until the response button was pressed. All trials with implausible reaction times (defined as initial reaction times shorter than 150 ms or longer than 2500 ms, as well as movement times longer than 1500 ms) were eliminated (1.36% of the data). Following visual inspection, RT data were log-transformed to account for heteroscedasticity and positive skew of the distribution (Kliegl, Masson, & Richter, 2010). RTs and accuracy were again analysed separately. For RT analyses, only trials with correct responses were used (for RTs and accuracy per finger-number combination see Table 4.A.2 in the Appendix).

The response condition (assignment of the responses to the response buttons: ascending left-to-right: [2 3 4] vs. ascending right-to-left: [4 3 2]) was added to the analysis as between-subject variable. *Finger-number congruency* was determined by the relationship between the finger and number of stimulations (congruent: 2 on index finger, 3 on middle finger, 4 on ring finger; incongruent: all other combinations). Additional analyses regarded the *MNL congruency* which was determined by the relationship of the spatial location of the stimulated finger with the number of stimulations (congruent: 2 on leftmost finger, 3 on middle finger, and 4 on rightmost finger). Note that finger-number congruency and MNL congruency are distinguished solely by the conditions with 2 and 4 stimulations on the index and ring finger of the left hand (all other conditions are both finger-number congruent and MNL-congruent, or incongruent, respectively), which is why those additional analyses regard only these conditions. Another additional analysis addressed a potential response bias, that is, the question whether participants in case of uncertainty (that led to errors) chose the number represented by the stimulated finger more often.

Linear mixed effects analyses and binomial generalised linear mixed effects analyses were again used for RT and accuracy data, respectively *(lme4*; Bates, Mächler, Bolker, & Walker, 2014) in R (R Core Team, 2016). The contrasts for all factors were again set to summation contrasts. Following Baayen (2008), *t*-values equal or larger than 2 were considered as statistically significant. *p*-values were considered as statistically significant when falling below 0.05. *t*-tests were used for the additional analyses.

The influence of finger-number congruency on RT or accuracy, respectively, was analysed. As fixed effects, Finger-Number Congruency (congruent / incongruent) and Hand (left / right) as well as the interaction term were included. As random effects intercepts for Subject, Response condition and Stimulation pattern were included. To select a sufficient random effect structure, the fixed factors and their interaction terms were included step-wise as random slopes and kept within the model when they significantly improved model fit to receive the most parsimonious model. The final model for RT data included by-subject and by-pattern random slopes for the effect of

Hand. The final model for accuracy data included by-subject random slopes for the effect of finger-number congruency and Hand.[27]

Results

The overall accuracy of the valid trials was 66.68%, which is comparable to the accuracy levels reported in the literature using tactile finger stimulation (Cohen et al., 2014, Experiment 1; Cohen & Henik, 2016).

The (generalised) linear mixed effect models revealed significant congruency effects (both for RTs and accuracy) and no significant effects for the hand and the interaction (see Table 4.4). Mean RTs were shorter for finger-number congruent trials (953 ms, *SD* = 208 ms) than for incongruent trials (975 ms, *SD* = 209 ms; see Figure 4.6, left panel). Mean accuracy in finger-number congruent trials (70.01%, *SD* = 20.24%) was higher than in incongruent trials (65.01%, *SD* = 23.09%; see Figure 4.6, right panel).

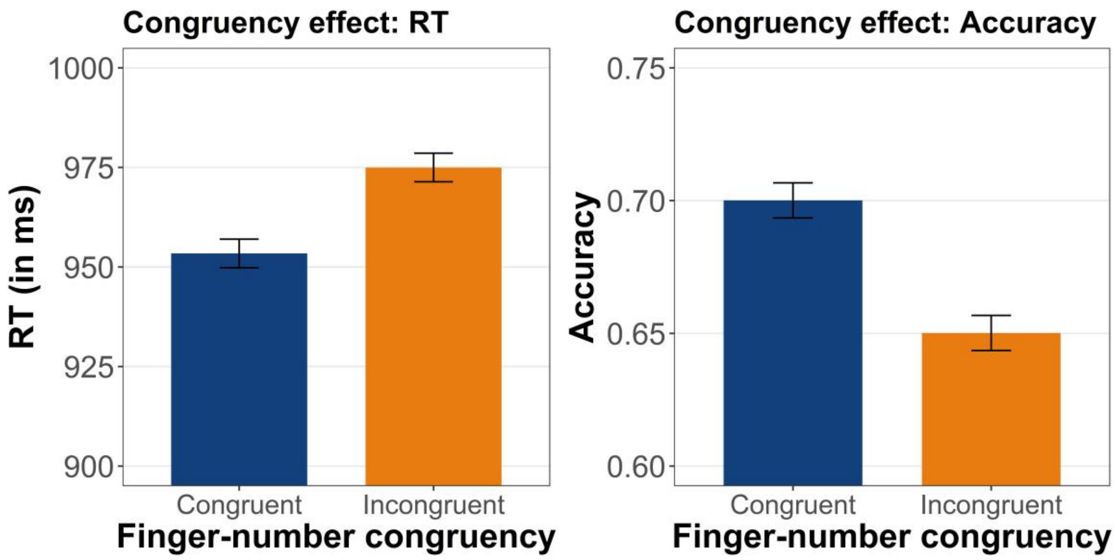

Figure 4.6. Congruency effects (x-axis) on average RTs (left panel) and accuracy rates (right panel). Error bars represent within-subject standard errors as suggested by Cousineau (2005).

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[27] The index finger of the opposite hand was always the responding finger, so one could expect interactions with stimulations to the index finger. We therefore coded a new factor “Response Finger” (i.e., index finger or not) and ran the (generalized) linear mixed models with the fixed factors Congruency, Response Finger, and their interaction and as random factors Subject, Response condition, and Stimulation pattern and with the random slopes determined as described above; there were no random slopes for the RT analysis and by-subject random slopes for Congruency and Response Finger as well as by-pattern random slopes for Congruency for the accuracy analysis. There were no significant interactions between Congruency and Response Finger for RTs or accuracy.

Table 4.4. Left: results of the linear mixed effects-analyses of log-RTs, *t*-values exceeding 2 are classified as significant (cf. Baayen 2008). Right: results of the generalized linear mixed effects-analyses of accuracy data, significance estimates given by *p*-values.

	RT			Accuracy			
Effect (fixed)	**β**	***SE***	***t***	**β**	***SE***	***z***	***p***
Con	-0.012	0.003	-4.23	0.127	0.033	3.861	<.001
H	-0.021	0.016	-1.28	0.036	0.040	0.919	.358
Con x H	0.002	0.003	0.73	0.004	0.023	0.192	.848

Note. Con: Congruency, H: Hand.

As reasoned above, to disentangle embodied finger-number congruency from spatial MNL congruency, analyses were restricted to data from 2 and 4 stimulations on the index and ring finger of the left hand. Finger-number congruent trials led to both faster and more accurate responses when compared to MNL-congruent trials. Paired *t*-tests revealed that finger-number congruent conditions elicited reliably more accurate responses (70.83%, *SD* = 10.28%) than MNL-congruent conditions (63.29%, *SD* = 14.22%), $t(25) = 2.46$, $p = .021$, $d_z = 0.48$, but that the RT difference between finger-number congruent (899 ms, *SD* = 145 ms) and MNL-congruent conditions (927 ms, *SD* = 135 ms) was only marginally significant, $t(25) = -1.91$, $p = .068$.

Next, error trials were examined separately to estimate a potential response bias, that is, a potential tendency to respond according to the ordinal meaning of the stimulated finger (finger-congruent responses). If responses were not influenced by the stimulated finger, erroneously responding “2”, “3”, or “4” should be distributed equally over the three fingers. However, a one-sample *t*-test revealed that the percentage of errors in favour of finger-congruent responses (38.02%) was significantly above chance level (33%), $t(25) = 4.40$, $p < .001$, $d_z = 0.86$.

Discussion

Experiment 2 investigated performance in a numerosity judgment task in which numerosity was tactually delivered to the fingertips through trains of mechanical stimulations. We compared discrimination performance for tactile numerosities that were delivered on fingertips in two conditions: stimulations were either counting-congruent or incongruent regarding the ordinal meaning of the finger within the finger counting sequence. Results showed that responses were both faster and more accurate for counting-congruent than for counting-incongruent finger-number combinations. Importantly, these results were not driven by MNL congruency: when MNL- and finger-number congruency did not coincide, response time was marginally lower and accuracy significantly higher for the finger-number congruent condition, indicating that adult number representations are shaped more strongly by finger counting than by spatial associations. As to the erroneous responses, a response bias was observed: participants decided above chance level in favour of a finger-congruent response. This indicates that, in case of uncertainty, the identity of the stimulated finger influenced response selection in that the counting-congruent number was preferred over the other possible choices. This bias reflects the importance of finger counting habits in our task and probably also contributed to the congruency effect in the accuracy data: when participants were uncertain, a finger-number congruent stimulation that pre-activated the correct mental number representation tipped the balance towards the correct response, while an incongruent stimulation would more often have provoked the respective finger-congruent, albeit incorrect response.

General Discussion

The present study investigated the impact of finger counting on the cognitive representations of sets of multiple fingers and specific single fingers. Results from the present study suggest that, for adults, determining the number of several fingers is easier when the set of fingers matches one's finger counting experience (Experiment 1) and that single fingers are mentally represented in relation to their purpose in finger counting (Experiment 2). Importantly, finger counting knowledge was activated simply by tactually stimulating participants' finger tips without the requirement of any motor response of the relevant fingers and also without the identity of the stimulated fingers being task-relevant. The results of Experiment 2 go beyond previous studies showing a close relationship between fingers and number knowledge. For example, it has been shown that passive hand movements interfere with mental counting (Imbo et al., 2011), that active finger movements interfere with addition and subtraction (but not multiplication; Michaux et al., 2013), and that larger numbers are rather assigned to the middle than index finger and vice versa for smaller numbers (Riello & Rusconi, 2011). The present experiment goes one step further and shows that finger-number correspondence is automatically activated. By directing attention to single fingers through tactile stimulation, their associated numerosities were processed more efficiently than the other numerosities. Evidently, through years of practice finger counting becomes more than just a one-to-one correspondence of numbers to fingers (see also Di Luca & Pesenti, 2011). Although finger identity was always task-irrelevant in the present study, it affected the processing efficiency of numerosities. In line with the embodied cognition stance on numerical cognition, finger representations seem to be an influential part of the seemingly abstract mental concept of numbers in adults.

The findings of Experiment 2 at first sight seem to be in conflict with those of Brozzoli et al. (2008) who reported purely spatial numerical associations without any measurable influence from finger counting habits. However, the present results endorse our previous explanation that a deeper semantic processing of numerosity than provided through mere visual perception (as in Brozzoli et al., 2008) seems to be necessary to evoke measurable finger-number interactions. Numerosity discrimination as required in the present study clearly requires deeper processing of numerosities than seeing task-irrelevant Arabic numbers. Finger-number interactions thus seem to depend on the task-relevance of the number identity. Interestingly, finger identity seemingly does not need to be task-relevant to pre-activate number processing. It is still possible that fingers need to be to focus of attention for this interaction to occur, however, the present study is not capable of resolving this matter. Our results are in line with those of Di Luca et al. (2006). Their task also required a deeper processing of numbers as they had to be memorised in combination with fingers. The authors reported those finger-number mappings to be most advantageous (in terms of RT) that corresponded to finger counting habits rather than to a purely spatial MNL. Importantly, while Di Luca et al.'s (2006) experiment required motor responses of the fingers, the present study shows that the mental activation of the specific finger representations through tactual finger stimulation suffices to interact with the associated mental number representations.

Also Experiment 1 showed that finger counting experience influenced the processing of numerosity information delivered through tactual finger stimulation. The lack of a compatibility effect of stimulation direction is actually in line with Krause et al. (2013) who reported no reliable influence of stimulation direction on response times. Our results even show an advantage for the counting-incompatible stimulation direction. This was probably caused by the fact that when stimulations were applied in the counting-incompatible direction, they moved towards the body midline and were thus perceived as looming, which typically results in processing advantages (Franconeri & Simons, 2003; McCarthy & Olsen, 2017).

Finger counting strategies vary inter-individually with a strong cultural influence: different cultures have different predominant strategies (e.g., Bender, 2009; Bender & Beller, 2012; Lindemann et al., 2011). It would therefore be very informative to apply the present paradigm cross-culturally. The embodied cognition account predicts that abstract concepts are shaped by bodily experience (e.g., Casasanto, 2009), that is, finger-number associations should be expected to reflect individual finger counting habits. Furthermore, some cultures that do not exhibit a one-to-one correspondence of numbers to fingers instead make use of finger symbols. That is, the cardinal value of the number of active fingers does not match the represented number. For example, in Chinese finger counting stretching out the thumb and index finger means 8. The Chinese start counting on the index finger and there is a one-to-one correspondence up to number 5; numbers 6-10 can be represented by finger symbols using one hand. This fact that Chinese can count numbers up to 10 on one hand has distinct effects on mental number processing times (Domahs et al., 2010; Morrissey et al., 2016). Testing Chinese adults (or others that do not make use of a one-to-one correspondence) with the design of Experiment 1 would enable us to dissociate between possibly conflicting representations of the cardinal versus symbolic meaning of those finger postures for numbers larger than 5.

In fact, it is likely that all sets of fingers used in counting become finger symbols representing numerosities to the proficient counter. Di Luca and Pesenti (2008) argued that finger counting configurations exhibit both iconic and symbolic features, which might support the development of appropriate number representations. Recognition of finger symbols is probably the mechanism behind the increased efficiency in Experiment 1 in identifying those finger sets that correspond to finger counting (see also Cohen et al., 2016). Cohen et al. (2016) even labelled this finger symbol, or finger pattern, recognition as "subitizing", which describes the fast, parallel numerosity determination for small quantities. Subitizing in this sense might also be a reason for the clearer less ambiguous finger-number interactions of Experiment 2: a parallel processing of a small set of items (here: fingers) might be less susceptible to numerical finger connotations than the serial processing involved in the numerosity identification of Experiment 2. In Experiment 2 the same symbol recognition mechanism as in Experiment 1 could not take place, because only single fingers were stimulated. Finger counting forms not only stable finger symbols representing numbers, but also stable finger-number associations.[28] The mental finger representation which is activated by

[28] Note that the Model of Analogue and Symbolic Codes (MASC) proposed in the General Discussion of the present thesis classifies both canonical finger postures and stable finger-number associations as part of the motor symbolic code for number.

reaching the *i*th finger in finger counting (e.g., when moving or touching it) is bound together with the synchronously activated mental number representation *i*. Activating one of the two representations will thereby always co-activate the other.

The existence of stable finger-number associations and symbol-number associations might play an important part in forming a mature representation of numbers. Rinaldi, Gallucci et al. (2016) found that children who were consistent in the order in which they used their hands for counting positioned numbers linearly on a number line, in contrast to children who were not consistent and who positioned numbers rather logarithmically. Although the authors do not report the specific counting fashion or the consistency in employing a specific order of the individual fingers, the influence of hand order consistency on maturity of number representations is a first indicator for the importance of consistency in finger counting habits. It is very conceivable that fixed finger symbols and finger-number associations strengthen mature number representations.

In conclusion, the present study provides evidence for the notion that finger counting habits shape the perception of the number meaning of sets of fingers in adults (see also Sixtus et al., 2017). Even more importantly, it also shows that finger counting imbues single fingers with numerical meaning, which in turn affects the results of mental numerosity discrimination processes. Together with previous findings in the field of numerical cognition, the present findings of persistent symbol-number and finger-number associations have implications for young children's acquisition of mature number concepts: irrespective of whether finger counting is a habit to be maintained or terminated within the first school years, consistency in finger counting might facilitate a fundamental grasp of numbers.

Appendix

Table 4.A.1. vRTs (left) and accuracy in percent (right) of Experiment 1 per set of fingers (standard errors in parentheses).

	vRTs			Accuracy		
	DC: compatible	**DC: incompatible**	**Simultaneous**	**DC: compatible**	**DC: incompatible**	**Simultaneous**
TI	606 (28)	596 (24)	741 (25)	98.77 (0.45)	96.71 (1.16)	99.18 (0.49)
TM	625 (28)	634 (28)	785 (23)	92.80 (2.95)	84.57 (3.39)	93.62 (1.10)
IR	666 (27)	638 (27)	823 (34)	81.28 (3.45)	89.71 (3.09)	83.74 (3.58)
TIM	663 (31)	642 (26)	867 (31)	84.98 (2.95)	90.53 (2.27)	82.10 (3.33)
TMR	692 (29)	679 (31)	858 (32)	91.15 (1.81)	85.19 (2.39)	84.57 (2.28)
IRP	690 (26)	720 (33)	933 (25)	81.07 (2.69)	80.04 (3.31)	64.20 (3.89)
TIMR	789 (49)	707 (30)	974 (66)	36.83 (4.60)	60.49 (4.97)	27.37 (4.57)
TMRP	682 (29)	665 (31)	869 (34)	79.01 (3.56)	84.57 (3.04)	62.14 (3.62)
TIRP	711 (32)	648 (28)	850 (27)	78.60 (3.47)	84.57 (3.04)	74.69 (3.21)

Note. DC: Direction Compatibility, T=thumb, I=index finger, M=middle finger, R=ring finger, P=pinkie.

Table 4.A.2. RTs in ms (left side) and accuracy in percent (right side) per finger-number combination (standard error in parentheses) of Experiment 2.

	RT			Accuracy		
Nr. of stimulations	**2**	**3**	**4**	**2**	**3**	**4**
Index finger	908 (26)	1004 (34)	985 (61)	83.86 (2.62)	67.31 (3.52)	50.10 (4.92)
Middle finger	934 (26)	989 (36)	976 (50)	79.20 (2.92)	68.82 (2.72)	45.91 (4.71)
Ring finger	936 (24)	1012 (38)	963 (55)	79.14 (3.10)	68.42 (2.95)	57.35 (4.44)

Chapter 6

General Discussion and the Formulation of a Comprehensive Model

The present thesis aims to systematically examine the role of finger counting experience in mental number representations. Over the past four studies I have taken a closer look at the interconnection of fingers and mental number representations. The main findings can be summarised as follows:

Study 1: Individuals were very consistent in their produced finger configurations when repeatedly showing numbers with their fingers (i.e., producing finger montring postures). However, situational factors systematically affected the choice of the starting hand as well as the problem size effect on reaction times, which were both influenced by the mathematical operation involved (addition vs. subtraction). Furthermore, most errors involved omitting or adding a single finger or a full hand.

Study 2: Production of finger counting postures (i.e., canonical finger configurations) primed related numerical concepts more strongly than visual perception of the same finger configurations and also than production of other finger configurations that are not usually used to represent numbers (i.e., non-canonical finger configurations).

Study 3: Successive finger movements primed related number knowledge. Numbers were on average named faster after movements of counting-congruent fingers, i.e., of fingers associated with the respective numbers through finger counting.

Study 4: Canonical finger configurations had a processing advantage as compared to non-canonical finger configurations when multiple fingers were tactually stimulated. Furthermore, stimulation of single fingers facilitated the detection of numerosities associated with the respective fingers through finger counting.

That is, the focus of investigation systematically moved from active finger posture production to passive finger stimulation, where the counting-congruency of finger postures or fingers with numbers was either task-relevant (involving the explicit instruction that specific finger postures stand for numbers) or task-irrelevant (the task neither emphasised nor depended on the association of fingers or postures with numbers) following these steps:

- Active production of finger montring postures (task-*relevant* finger configurations) – Study 1
- Active production or visual perception of finger counting postures (task-*irrelevant* finger configurations) – Study 2, Experiment 1
- Active production of canonical and non-canonical finger postures (task-*irrelevant* finger configurations) – Study 2, Experiment 2
- Active production of successive finger movements (task-*irrelevant* finger identity) – Study 3
- Passive stimulation of canonical and non-canonical finger configurations (task-*irrelevant* finger configurations) – Study 4, Experiment 1

- Passive stimulation of single fingers (task-*irrelevant* finger identity) – Study 4, Experiment 2

The main, pervasive finding was that different levels of finger activation co-activated numerical knowledge and influenced number processing. The results suggest that mental finger (posture) and number representations are deeply connected and that specific associations stem from finger counting experience.

In this last part of the present thesis I will discuss the presented studies' results as part of a bigger picture which has been painted by previous research. Above all, I will contemplate on my results in the light of a new model of magnitudes and symbolic codes representation, which highlights the fingers' special role in the acquisition of numerical knowledge and from which new predictions for research as well as recommendations for practical training of number skills can be derived.

The present results in light of Walsh's Theory Of Magnitude

In the Introduction I suggested that finger counting might function as a catalyser for binding mentally represented magnitudes with one another so that (mental representations of) external quantities can be processed by the generalized magnitude system (cf. also Andres, Di Luca et al., 2008) and/or that fingers might be represented as an own magnitude dimension. From the present studies with only adult participants I can only speculate about the former hypothesis in that it would make sense that the most used representational form of numbers during early childhood becomes a general (external and mental) representative for countable objects. That is to say, such a catalyser for binding objects and magnitudes does not necessarily have to be the fingers (but usually is). Study 1 of the present thesis also indicated that finger postures are more than their apparent number of involved fingers: the production of finger postures was determined by their immanent exact as well as approximate numerical meanings. The exact nature was especially indicated by high intra-individual consistency in number-specific finger configurations. The approximate nature of finger postures was indicated by the relatively high incidence of errors that involved the production of the neighbouring numerosity. That is, fingers seem to have the capacity to bind multiple numerical meanings with one another. Moreover, fingers also satisfy many of the basic counting and arithmetic principles of "abstract" numbers in that they directly convey the "how-to-count principles" of a one-to-one correspondence, stable order, and the cardinal principle when fingers are raised one after the other in a consistent (Western) finger counting way (Andres, Di Luca et al., 2008; Di Luca & Pesenti, 2011; Gelman & Gallistel, 1978; Roesch & Moeller, 2014).

As to the latter hypothesis that fingers might constitute their own magnitude dimension, it is helpful to recapitulate general characteristics of the magnitude dimensions within the generalized magnitude system first. The main feature is that all are prothetic dimensions in the sense that they can be "more" or "less". A second characteristic is that overlapping activations have been reported for processing magnitudes within the different dimensions: Walsh (2003, 2015) proposed the inferior parietal cortex to be the locus of the generalized magnitude system. This entails interferences between the concepts when tasks require the processing of more than one of the given dimensions. A third precondition for an additional dimension would naturally be that it is not identical to an already existing one.

As to the first mentioned characteristic (prothetic dimension), obviously also the number of involved fingers and the number represented through the finger posture (which do not necessarily coincide in all finger counting systems) are prothetic, because they can be or represent “more” or “less”: Study 1, Study 2 (Experiment 2), and Study 4 (Experiment 1) provided evidence for habitual and consistent bi-directional associations between finger postures and mental number representations; Study 3 and Study 4 (Experiment 2) showed that also single fingers are associated with specific number concepts. Study 2 (Experiment 1) furthermore showed that finger counting postures are associated with magnitude categories (see also Sixtus, Lindemann, & Fischer, 2014; for single fingers see also Riello & Rusconi, 2011).

Regarding the second mentioned characteristic (overlapping activations and interference effects) – although the neuroscientific foundations of finger counting have not been the object of investigation of the present thesis – cortical overlap between finger and number representations has already repeatedly been reported elsewhere (as elaborated in the introductory *Neuroscientific evidence*-sections; e.g., Roux et al., 2003; Rusconi et al., 2005). What is more, interferences between the concepts were indeed present in the studies of the present thesis: in Study 1, mathematical reasoning (i.e., simple addition or subtraction) influenced finger posture production; in Study 2 through 4, finger postures, finger movements, and finger perception (stimulation) influenced number processing. These findings strongly indicate a close relationship between the concepts, which could well be explained by cortical overlap.

The third precondition (exclusivity of each dimension) needs clarification of the magnitude inherent in the dimensions. Fingers per se are not a magnitude dimension, as aren’t time and space. Everything has to be regarded in relation to something else or according to specified criteria to become a magnitude. One certain time of the day has no magnitude unless it has been associated with some numerical value or one knows which time that is in relation to the whole day; a duration only becomes a magnitude because a starting- and end point have been specified; one certain point in space has no magnitude unless it is seen, for example, as some amount of space further to the left or right, above or below some other point; a certain distance or area only becomes a magnitude because its margins have been specified. The same is true for fingers: they can gain numerical meaning by becoming associated with magnitudes, they can be related to other fingers, and they can be counted as specified circumscribed objects. Finger-number associations, canonical finger postures, and fingers as countable objects (i.e., the number of fingers) are candidates for the “new” magnitude dimension. However, the mere number of fingers does not add anything new to the already existing dimension of *number*, so that one already disqualifies, which leaves associations of single fingers or postures with numbers. Single fingers become associated to numerical values due to the co-activation in active finger counting. Especially Study 3 and Study 4, Experiment 2, showed that this one-to-one association is indeed present in adults. Riello and Rusconi (2011) furthermore found that beyond this one-to-one mapping whole magnitude categories were mapped onto single fingers. These examples show that single fingers indeed offer magnitudes beyond their purely numerical or spatial features. Regarding finger postures, those from cultures with a one-to-one finger-to-number-mapping are deeply confounded with the numerical and spatial aspect of the number of involved fingers. However, some finger counting systems involve folding the fingers instead of stretching them out, or even finger symbols with no obvious translation between postures and numbers for the untrained eye. Chinese, for example, stretch out the thumb and pinkie for number six, the thumb and index finger for number eight and numbers seven and nine involve finger shapes other than simple outstretching. Therefore, also finger postures offer magnitudes beyond their purely numerical (i.e., number of involved fingers) or spatial features.

To sum up, numerical finger-values and finger postures are associated to magnitudes beyond their spatial characteristics and absolute number of items (i.e., outstretched fingers). The precondition of exclusivity, as I have been calling it, seems therefore fulfilled. Does this mean that fingers and finger postures qualify as an additional dimension within the generalized magnitude system? One remaining problem, which disqualifies fingers' and postures' magnitudes from being an additional dimension of the generalized magnitude system, is that they do not exist unless they have been willingly associated with magnitudes and they vary inter-individually, too. This is not the case for duration (time), spatial extent (space), and numerosity (number), whose magnitudes exist in the physical world whether or not they are processed by an individual's magnitude system.[29]

However, with the present thesis specifically focusing on finger counting habits, I have so far neglected one aspect of finger postures that they have in common with other "bodily magnitudes": the amount of sensorimotor activation during finger posturing is also a magnitude. And this one, while sharing the described features with other magnitudes from the generalized magnitude system, is not of symbolic nature. I therefore argue that finger postures do indeed involve general magnitudes of approximate nature. Krause (2014) and Krause et al. (2014) also proposed that motor magnitudes like the sensorimotor activation involved in force production were part of the generalized magnitude system. Moreover, sensorimotor activation involved in grasping (Andres et al., 2004; Andres, Ostry et al., 2008; Badets et al., 2012; Lindemann et al., 2007; Namdar et al., 2014), gesturing (Beattie & Shovelton, 2006; Holler & Stevens, 2016), body posturing (e.g., Carney, Cuddy, & Yap, 2010) would also be placed within this dimension of the generalized magnitude system.[30] The

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[29] Note that spatial and temporal *position* therefore also disqualify from being part of the generalized magnitude system.

[30] Walsh (2015, pp. 556–557) stated "that we learn about space and time through action and that associations between space, time, and magnitudes relevant for action (such as size, speed, and, under some conditions, luminance and contrast) will be made through action. When we later learn about number, the neurons with capacity to represent quantity are those that have information about the continuous variables learned about motorically" and "that discrete number evolved on the back of an analog quantity system necessary for computing the metrics of action". That is, the initial role of sensorimotor activation is presumably to interpret magnitudes that exist in the physical world which can thereby transform into numerical information. This information can then be symbolically coded (cf. TCM/QCM). A consequence of sensorimotor activation being the measuring instrument of external magnitudes is that concurrent motor activity (or concurrent sensory input) distorts the measurement. This is probably a source of interference effects known from embodied cognition research. Nevertheless, sensorimotor activation and number as well as space and time are processed relying on ATOM's underlying common metric and thereby constitute "magnitude dimensions" from the generalized magnitude system.

approximate nature of finger postures' motor activation is supported by Study 1 of the present thesis, where errors that involved the production of the neighbouring numerosity occurred more often than any other errors. Such an approximate motor activation, which was indicated by errors by one, co-exists with the exact symbolic motor activation, which was indicated by a) high intra-individual consistency in number-specific finger configurations, b) high accuracy, and c) high incidence of errors by five which is a "symbolic error" and not an "approximate error", because it results from postures being symbols: more attention is paid to the hand responsible for the "fine motor" part of the motor symbol, sometimes forgetting to open or close the full other hand, which is the "basic" part of the motor symbol; that is, such an error results in a posture which is symbolically similar, but very different in terms of motor activation. In conclusion, I propose that fingers as numerical representatives do not constitute their own magnitude dimension, but that their involved sensorimotor activation is represented as an approximate magnitude by the generalized magnitude system.

The earlier deliberations regarding fingers' and finger postures' (symbolic) magnitudes, however, were not in vain: they show that they do have a special role in mental number representations. The fulfilment of the first two mentioned characteristics (i.e., prothetic quality and similar cerebral processing site with interference effects) indicates that they possess a direct link to general magnitudes. Their symbolic function disqualifies them from being a general magnitude dimension, but it strongly suggests to go further into the question of whether fingers should become a part of Dehaene's (1992) (hitherto) triple-code model (TCM).

The present results in the light of Dehaene's Triple-Code Model

As mentioned before (cf. Introduction), some researchers have argued that fingers should extend Dehaene's (1992) model into a quadruple-code model (Di Luca & Pesenti, 2011; Moeller et al., 2012; Roesch & Moeller, 2014). Based on the deliberations from the previous paragraph I argue that the fingers' special role does not result from a distinct representational format alone, but from their integration in more than one of the interacting codes as well as their direct link to multiple dimensions of the generalized magnitude system, which directly corresponds with the analogue code of the TCM (which will become the QCM: quadruple-code model), as will be elaborated at a later point. The involvement of fingers in the QCM as part of the analogue code and as another symbolic code are described in the following.

Fingers are analogue representations of magnitude

The absolute number of fingers involved in a finger posture is an analogue magnitude that can be subitized, estimated, and compared like other analogue magnitudes as positions on number lines and number of dots in dot clouds. (This overlap with mere numerosity, which disqualified fingers from being their own magnitude dimension within the generalized magnitude system, allows them to be perfectly fine analogue representations of magnitudes.) The fingers' magnitudes have even something more to offer: they can be directly bodily experienced and manipulated. This enables the analogue code to receive magnitude information also through motor resonance, proprioception (cf. Study 2), and tactile information (cf. Study 4). An interesting side effect of fingers as part of the analogue code is that now there is a direct analogue output format in the form of the number of fingers involved in a finger posture (cf. Study 1). Furthermore, with fingers as a part of the analogue code, numbers can now also be processed and manipulated with the help of mental finger representations. Evidence for this notion is for example given by findings that number comparisons are slower when at least one of the numbers to be compared would require two hands instead of one if it were produced as a finger counting posture (Domahs et al., 2010; Domahs, Klein et al., 2012; Morrissey et al., 2016) and longer calculation times for addition problems when the sum of the unit digits exceeded five, that is, again, when it could not be represented with only one hand (Klein et al., 2011). Findings such as mental calculations missing the correct result by five (i.e., a full hand) above chance level (Domahs et al., 2008), on the other hand, indicate that the hands' symbolic representations interfered, too.

Fingers are symbolic representations of specific numbers

Just as words and digits (be they Arabic, Hebrew, Chinese or any other language or numerals), finger configurations can code magnitudes in a symbolic way. As described before, in cultures with one-to-one mappings of fingers to numbers in finger counting, these symbols coincide with analogue magnitude with the only difference that finger symbols usually have a consistent finger configuration, while it should not make any difference for analogue finger magnitudes. Evidence for such a distinction of finger counting and montring (i.e., canonical) postures as symbols and arbitrary (i.e., non-canonical) finger postures as analogue magnitudes is given by the results of Study 2 of the present thesis, where only canonical, but not non-canonical finger postures primed the corresponding number. Furthermore, in Study 4 canonical finger configurations were processed more easily than non-canonical finger configurations. Di Luca, Lefèvre, and Pesenti (2010) reported that canonical postures activated a place coding representation (as do also Arabic numerals) and non-canonical postures activated a summation coding representation (as do also dot patterns). The difference between symbolic and analogue magnitudes of finger postures becomes even more obvious in finger counting systems which do not exhibit a one-to-one correspondence for all numbers. For example in Chinese finger counting, two outstretched fingers can signify "2", "6", or "8", depending on whether it is the index and middle finger, the thumb and pinkie, or the thumb and index finger, respectively. That is, here it does not help to count the number of involved fingers to learn about the symbolically represented number.

Neuroscientific evidence (cf. Introduction) indicates that finger counting experience is reflected in the motor cortex' involvement in number cognition. Especially Sato et al.'s (2007) and Tschentscher et al.'s (2012) studies suggest that finger counting habits in the form of the preferred starting hand profoundly shape the way in which the brain represents numbers: the preferred starting hand in finger counting determined which hemisphere's motor cortex was more active in processing numbers up to five versus above five, that is, numbers that are represented with the starting hand only versus larger numbers that are represented with both hands. Just as the verbal code is subserved by left-hemispheric perisylvian language areas and the visual code is subserved by the left and right inferior ventral occipito-temporal areas (Dehaene & Cohen, 1995, 1998), I propose that the "new" motor code is subserved by the motor cortex.[31] Importantly, each of those codes is only of symbolic nature and does not per se carry semantic meaning. Numerical meaning is finally grounded in each representation's association with the analogue code rooted in the left and right inferior parietal areas (Dehaene & Cohen, 1995, 1998; Walsh, 2003).

Fingers directly link between the symbolic code and general magnitudes

Taking a closer look at the act of finger counting, besides numerical aspects, also spatial as well as temporal aspects become apparent: with a one-to-one correspondence of fingers to numbers, not only numerosity is perfectly reproduced. More fingers also take up more space and sequentially stretching the fingers out lets more fingers take up more time, too. Thereby, the three traditional dimensions of the generalized magnitude system are already directly coupled with finger counting. A fourth dimension, described above, in the form of sensorimotor activation naturally also corresponds directly with the amount of involved fingers (other "new" dimensions like pitch or luminance, however, do not present themselves as naturally within the fingers).

Finger counting has been proposed to provide the "missing tool to apprehend numbers in the physical world" (Andres, Di Luca et al., 2008, p. 642). Moreover, Coolidge and Overmann (2012), who argue that the ability to understand numbers is a cognitive base for symbolic thinking, agree with Malafouris' (cf. also Malafouris, 2008, 2010) response in the same article that "finger counting, engraved marks, or clay tokens do more than simply *stand for* number: they *bring forth* the number" (Coolidge & Overmann, 2012, p. 217, p. 221). My explanation for those strong statements regarding finger counting lies in the described direct link between the symbolic code and general magnitudes. Figure 3 illustrates this link (lines M1-M4) within a new model of numerical knowledge representations.

Fingers' multiple roles and the Model of Analogue and Symbolic Codes (MASC)

There is direct evidence that fingers are able to flexibly represent different contents and are thereby susceptible to different situational influences: Rinaldi, Di Luca et al. (2016) found that participants' preferred finger-to-number mapping depended on their finger counting habits while their preferred finger-to-day-of-the-week mapping depended on culturally determined reading direction. This is in line with the finding of the present thesis' Study 3 that participants' starting hand in finger counting differed depending on whether they counted numbers or syllables in a nursery rhyme with the latter exhibiting some more left-starters (all of the participants came from a culture with a left-to-right reading direction). These results support the notion that fingers symbolically represent numbers following individual finger counting experience, but that they can also represent any other magnitudes where other relevant (e.g., reading)

[31] In cultures that use hands to represent numbers (like most cultures) that is the hand motor cortex. In cultures with different counting styles as for example involving the feet (in the Americas, in Africa, and on Papua New Guinea; Bender & Beller, 2012), or the whole body (the Oksapmin; Bender & Beller, 2012), other parts of the motor cortex should be involved instead or additionally.

experience determines mapping rules. This illustrates that fingers can be mentally mapped flexibly to various numerical content. Previous literature as reviewed throughout the present thesis as well as the presented novel studies, however, suggest that the "default" mapping usually corresponds to finger counting

I propose a Model of Analogue and Symbolic Codes (MASC), which draws on Walsh's (2003) ATOM and Dehaene's (1992) TCM. The connection between the two models consists in the overlap between TCM's analogue code and ATOM's magnitudes: TCM's analogue magnitudes *are* the magnitudes from the generalized magnitude system. In other words, magnitudes are generally processed by an analogue magnitude code that follows the rules specified by ATOM – thereby, different magnitude representations (from within the analogue code) interact. Spatial associations like the mental number line then arise from interactions within the generalized magnitude system, that is, processing numerosities from the analogue code in the generalized way (i.e., with a common metric; Walsh, 2003).[32] The main proposition here is that within the MASC a distinction between an "analogue code" and magnitudes from a generalized magnitude system is not necessary. Henceforth, both terms refer to the same thing. The additional modifications to the merged model have been described above: sensorimotor activation is one of the magnitudes being processed by the generalized magnitude system, one-to-one mapped fingers are processed as analogue numerosities (and thereby also by the generalized magnitude system), and symbolic finger postures and finger-number associations form a fourth symbolic number code, rendering the hitherto triple-code model a quadruple-code model. The role of the symbolic codes is to enable exact representations of otherwise approximate magnitudes – to accomplish that they follow predefined rules like one-to-one mapping between numerosities and number symbols (e.g., items from the number word series) and usage of units to code durations, spatial extent etc. The connection between the analogue and symbolic codes is bi-directional (Dehaene, 1992): for example, for decisions regarding which of two number symbols refers to the larger quantity, the (motor, verbal, or visual) symbols are first translated into analogue magnitudes, because only there this semantic information is available. Furthermore, the different symbolic codes are connected with each other through association learning. Direct translations between symbolic codes do not per se require semantic knowledge (regarding the represented quantities). The underlying analogue magnitude representations are, however, usually automatically co-activated whenever number symbols are processed (Dehaene, 2011). The most important distinction within the MASC is that between *analogue* magnitudes (including all magnitudes of the generalized magnitude system) and *symbolic* codes which would not carry semantic information if it weren't for their connection to the "upper" analogue part. Figure 3 depicts the details of the MASC.

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[32] However, the mental number line in particular furthermore draws on inter-individually variable associations in that its orientation is culturally determined.

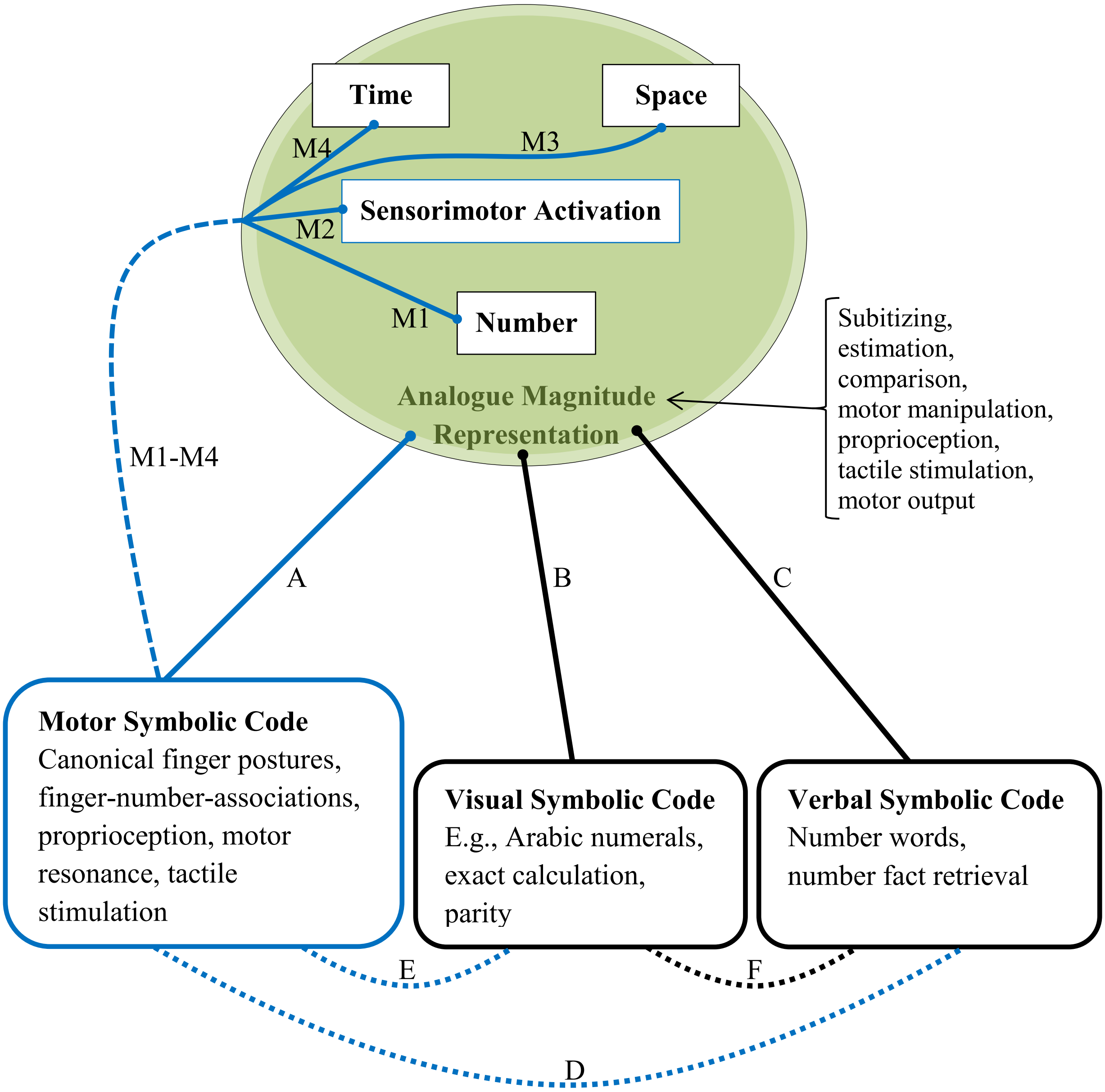

Figure 3. The *Model of Analogue and Symbolic Codes*. The model combines Walsh's (2003) ATOM with Dehaene's (1992) TCM by ascribing TCM's analogue code the properties of ATOM's generalized magnitude system. Sensorimotor activation is included as one additional dimension of the generalized magnitude system and fingers and finger postures are added as another symbolic code, rendering the hitherto triple-code model a quadruple-code model. Note that lines M1-M4 are each actually part of line A. Black lines indicate "original" connections, blue lines indicate "new" connections. See text for further explanations.

The four studies within the MASC

In Experiment 2 of Study 1[33] participants produced finger postures according to visually presented Arabic numerals. In principle this merely required the translation from the visual code into a motor code (line E in Figure 3). However, the relatively high amount of split-one errors, that is, errors that deviated from the correct target posture by 1 indicates that numbers were translated into analogue (and therefore approximate) motor activation (M2 in Figure 3). The likewise relatively high amount of split-five errors speaks for the direct path (line E) which cares more about symbolic resemblance than analogue numerical contiguity. Besides manually reproducing the Arabic numeral in the "exact" task, participants produced the next smaller or bigger numerosity in the "smaller" and "bigger" task, respectively. Especially in the "bigger" task, the choice of the starting hand was affected by the mathematical operation involved. The higher prevalence of a right starting hand in this task can be explained by an interaction of magnitude representations and spatial-numerical associations, which are either culturally determined (e.g., Dehaene, 1992; Fischer et al., 2010; Shaki et al., 2009; Shaki & Fischer, 2008) or even innate (e.g., de Hevia, Addabbo et al., 2017; de Hevia, Veggiotti et al., 2017; Rugani et al., 2015). Following this line of reasoning, the large magnitude inherent in the instruction to produce always "one more" activated the associated right side. Alternatively or additionally, the mathematical operation was mentally performed by a step to the right on the mental number line, which was then transferred into the outside world and thereby influenced the selection of the starting hand of the finger posture.

In Experiment 1 of Study 2 auditorily perceived number words had to be compared with a (standard) reference number, which on a task-relevant level addressed the path from the verbal code to the analogue code (line C in Figure 3), because comparing the magnitudes behind the number symbols requires an analogue number representation. During the comparison task participants simultaneously produced finger counting postures which acted as motor primes and influenced reaction times: reaction times were shorter when the number that was indicated by the finger posture and the target number were "on the same side" of the reference number. The congruency effect arose (either) from direct pre-activation of the congruent number words (and thereby facilitating its processing) and/or from response priming, that is, pre-activation of the response which would be given if the number activated by the finger posture were compared with the reference number. With only canonical finger postures as primes, it is not possible to distinguish an effect of the posture's proprioceptive analogue magnitude from an effect of the posture as a number symbol. Therefore, fingers as analogue numerosities would have accomplished number word priming via line C and response priming within the magnitude system; fingers as number symbols would have accomplished number word priming via line D and response priming via line A (cf. Figure 3).

Experiment 2 of Study 2 was quite similar on the surface: symbolic (here: visual Arabic) target numbers had to be compared with a reference number (here: a flexible number; line B in Figure 3). Introducing both canonical and non-canonical finger

[33] Experiment 1 of Study 1 is skipped because it consists of a description of counting and montring behaviour without experimental manipulation.

postures as motor primes allowed investigating both the influence of symbolic and analogue motor codes because only canonical postures can be symbolic, while the non-canonical postures encompass analogue magnitudes only. Both are capable of eliciting sensorimotor activation within the generalized magnitude system. Results showed that the congruency effect only appeared for canonical but not non-canonical finger postures: symbolic primes, instead of approximate analogue primes, were required to prime number concepts in this setup (via line E in number symbol priming or line A in response priming). However, it is conceivable that the reduced range of target numbers prevented a congruency effect also for non-canonical postures, because their approximate nature co-activated a broader range of numbers. This explanation is endorsed by Di Luca and Pesenti's (2008) finding of congruency effects not only for canonical but also (albeit weaker) for non-canonical (visually presented) finger posture primes.

In Study 3 participants named Arabic numerals whose visual presentation was triggered by sequential finger movements. The task-relevant path followed line F of Figure 3: visual Arabic numerals had to be translated into number words to be spoken aloud. Finger movements co-activated the associated numerical knowledge, opening the path along lines E and/or D in Figure 3 – the congruency effect reflects facilitated detection of the corresponding Arabic numerals (line E in Figure 3) and/or pre-activation of the corresponding number word (line D in Figure 3). Interestingly, this task did not require any analogue magnitude information. The observed congruency effect is therefore probably a consequence of overlearned symbol associations.

In Experiment 1 of Study 4 participants named the number of tactually stimulated fingers. The set of stimulated fingers corresponded to either canonical or non-canonical finger configurations. This task could be accomplished by estimating and naming analogue, tactually conveyed numerosities or the amount of (tactile) sensory activation (both line C in Figure 3) or by naming the tactually perceived motor symbol (line D in Figure 3). In general, performance was better for canonical than for non-canonical finger configurations. This suggests that naming the analogue magnitude (i.e., line C) was more difficult than the (asemantic) translation between symbolic codes (i.e., line D) or a compound of both (i.e., line C and D only for canonical configurations).

In Experiment 2 of Study 4 multiple stimulations occurred in quick succession on single fingers. The task was to indicate the number of stimulations quickly and accurately by pressing one of three buttons on a button box. Thus, the task required comprehension of analogue, tactually conveyed numerosities. Responses in this task are not as easily classifiable, because the perceived numerosity (which possibly involved sub-vocal counting, i.e., the translation of a sequentially presented numerosity into number words: line C in Figure 3) had to be translated into the assigned spatial position of the response buttons, involving computations of the spatial dimension within the generalized magnitude system, possibly using the culturally determined mental number line, which had to be mentally reversed by half of the participants. However, the relevant congruency effect arose from learned, exact finger-number associations (i.e., an instance of the motor symbolic code) which probably primed the associated number concept (line A in Figure 3) or (asemantically) affected the result of the sub-vocal count (line D in Figure 3).

The MASC and the present results within the hierarchy of groundedness, embodiedness, and situatedness

The MASC with its different levels is well-suited to address groundedness, embodiedness, and situatedness. The upper level comprising the generalized magnitude system contains "real" magnitudes that as such exist in the physical world: time, space, number, neural activity, and other dimensions exist inside or outside our bodies, (assumedly) independent from people interpreting them as magnitudes. Their nevertheless inherent magnitudes, when eventually interpreted by people, share a common metric in mental processing. Thereby, "more is up" (Fischer & Brugger, 2011; Lakoff & Núñez, 2000), longer lines last longer (Casasanto & Boroditsky, 2008), bigger numbers co-activate grip opening (Andres et al., 2004; Namdar et al., 2014), short durations should be associated with weak force, and so on. It is this common metric and these automatic co-activations that constitute the grounded level of cognition.

Embodiment can be viewed as a description of how (arbitrary) symbols (e.g., number symbols from the QCM) become meaningful. Meaningful number symbols, that is, *embodied numbers*, need to be learned to be associated to numerosity (or other magnitudes), as opposed to grounded numbers' inherent magnitudes. However, when acquired, their association is stable, that is, the amount of three arbitrary items is always associated with a specific number word ("drei" in German), the Arabic numeral "3", and a specific finger posture (thumb, index, and middle finger for most Germans; see also Study 1). By linking into the other dimensions of the generalized magnitude system, these symbols will also be associated with a rather short duration, a rather weak force, and combined with culturally determined knowledge a spatial position a bit more to the left (considering a number range from 1 to 10 for most Western cultures), as well as probably a rather low pitch and a rather weak luminance and so forth. Thus, the embodied level relates to the grounding of (culturally determined) symbols.[34]

The specialty of situated cognition is its flexibility. It makes use of all the stable embodied and grounded associations, but by (explicitly) stressing or (implicitly) supporting the one or other association, this one becomes more influential. However, also less stable numerical associations like small numbers on the right side and large numbers on the left side of a clock face can exert the same influence on number processing, but only attentively with explicit instruction (Bächtold et al., 1998). Embodied and grounded associations do not need attention for exerting influence, like when moving the head to the left, or unknowingly leaning to the left automatically activates the left side of the analogue mental number line and thereby gives preference to the generation of smaller numbers (Eerland et al., 2011; Loetscher et al., 2008).

Broadly speaking, according to the MASC grounded cognition originates from the generalized magnitude system, embodied (numerical) cognition originates from learned associations between the three symbolic codes and the analogue code in the QCM (lines A, B, C in Figure 3) due to sensorimotor experience (Krause, 2014), and situated cognition is everything that moves along more than one line (or along one line

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[34] Note that the MNL and resulting spatial-numerical associations therefore also count as *embodied* because their orientation is to a certain degree arbitrary (e.g., culturally determined) and their positions in space have been (more or less willingly) associated with magnitude information.

in more than one direction) within Figure 3. That is, groundedness and embodiedness are default associations, where grounded associations should be shared by everyone and embodied associations should be shared only by everyone with the same specific learning experience. Situatedness, on the other hand, describes the weight bias of different (possibly grounded, embodied, or any other) associations in specific situations. Note that lines D, E, and F in Figure 3 are asemantic, purely associatively linked symbol translations, nicely demonstrating the symbol grounding problem (cf. Harnad, 1990; Searle, 1980).[35] Symbol grounding, that is, embodiment only comes into play as soon as any analogue representation chimes in (through lines A, B, or C[36], or M1-M4 in Figure 3; note that the information transmitted via line A fully encompasses the information transmitted via M1-M4 if we assume that the analogue code is equivalent with the generalized magnitude system – they were retained for reasons of clarity).

Referring to the previous paragraph describing the studies of the present thesis as lines within the MASC, all relevant results can be classified as situated effects, because they relied on interference effects stemming from the motor code or from sensorimotor activation from the generalized magnitude system (i.e., more than one line, or one line in more than one direction, in Figure 3; cf. section "The four studies within the MASC").

Finger gnosis in the MASC

Finger gnosis has repeatedly been shown to be connected with numerical abilities (Fayol et al., 1998; Gracia-Bafalluy & Noël, 2008; Kohn et al., 2015; Newman, 2016; Noël, 2005; Poltz et al., 2015; Wasner et al., 2016) and has been taken as one basis for pre-numerical trainings and the prevention of math difficulties (esp. Gracia-Bafalluy & Noël, 2008). Locating finger gnosis within the MASC might give some indication of how it functions as a precursor of mathematical skills. As described in the Introduction, finger gnosis is the ability to discriminate the own fingers from each other. This can, for example, be measured by lightly touching or mechanically stimulating the tip of one or two fingers and letting the participant name the stimulated finger(s) or point to (figures of) the stimulated finger(s) with the other hand (e.g., Benton, 1955; Gracia-Bafalluy & Noël, 2008; Noël, 2005). Thus, it does not measure the ability to know the amount of stimulated fingers or any other prothetic dimension. Consequently, finger gnosis does not tap into the analogue field of numerosity or the general magnitude of sensory activation. Finger gnosis regards finger identity only and hence links to the symbolic motor code instead: it should therefore be important for the ability to quickly understand and distinguish different finger configurations as well as finger-number pairs, that is, symbolic numbers in the motor code.

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[35] However, number symbols usually have been acquired through association with analogue magnitudes (i.e., they are embodied), which will therefore assumedly always be co-activated during symbol perception (Dehaene, 2011). That is, as long as the inferior parietal cortex – the locus of analogue magnitude knowledge (Walsh, 2003; Dehaene & Cohen, 1995, 1998) – is operational and communicating with the loci of the symbolic codes (cf. Dehaene & Cohen, 1995, 1998), even mere symbol translations will not be asemantic, because analogue magnitude knowledge will be automatically co-activated.

[36] An automatic activation along lines A, B, and C probably represents Barsalou's (1999) "simulators" within his theory of perceptual symbol systems (see Introduction).

In other words, finger gnosis is probably not directly connected with a general understanding of and ability with numerosities, but with the ability to code numbers as symbols. Via the motor code, however, finger gnosis does indirectly link to the generalized magnitude system, because it facilitates an understanding of spatial, temporal, sensorimotor, and also numerical magnitudes (lines M1-M4 in Figure 3).

In sum, consequently following this theory, finger gnosis is a precursor of numerical abilities, which is fully mediated by the motor code of the QCM. Only the motor code directly and specifically links to (the traditional and further) dimensions of the generalized magnitude system, that is, training finger gnosis can only influence numerical abilities by affecting the symbolic motor code first, which in turn affects actual (semantic) numerical knowledge. This hypothesis is still pending empirical evidence. However, a recent study by Fischer et al. (2017) endorses this general explanation: the authors addressed manual fine motor skills, that is, a competency which, arguably like finger gnosis, is "a necessary prerequisite for the sensorimotor experience of numbers through finger counting" (Fischer et al., 2017, p. 7). The study investigated the relationship between manual fine motor skills and conceptual counting knowledge. Results indeed showed a significant positive correlation between the two and furthermore, importantly, that this relationship was fully mediated by procedural counting skills. Procedural counting skills were defined as the ability to execute the counting procedure correctly (one-to-one correspondence of items and number words) and to come to the correct counting result. Conceptual counting skills were defined as the understanding of the purpose of the counting procedure, that is, to know the cardinality, abstraction, and order-irrelevance principles (cf. Gelman & Gallistel, 1978). Fischer et al. (2017, p. 7) reasoned that the "development [of finger-based representations] is influenced by FMS [fine motor skills] through the multi-sensory experience of finger counting". Although the authors did not assess actual finger counting behaviour, their interpretation is in line with the MASC: manual fine motor skills contribute to (semantic) numerical knowledge because they facilitate the acquisition of motor symbols.

Predictions of the MASC

On the basis of the hypothesised model, following its conjectured inner mechanisms of action, predictions can be made regarding the interplay of its components. The first prediction directly follows from the previous section. If finger gnosis and manual fine motor skills can affect semantic numerical knowledge merely via the symbolic motor code, effective trainings of finger gnosis and manual fine motor skills should consequently always also affect the symbolic motor code. That is, after such trainings which improve numerical competencies, children should for example be quicker and more accurate in producing and recognizing finger counting postures.

Another prediction follows from the dissociation of finger postures as approximate magnitudes and exact symbols. Imagine a patient with lesions to the inferior parietal cortex which has been proposed to be the locus of analogue magnitude processing (Dehaene & Cohen, 1995, 1998; Walsh, 2003). This patient should not be able to process physically grounded magnitudes. Nevertheless, he or she should still be able to directly translate between the different symbolic codes. That is, if shown three bananas he or she should not be able to immediately tell how many bananas there are, neither spontaneously show that number with the fingers. However, if shown the Arabic numeral "3" or if verbally told "three", he or she should be able to produce the finger counting (or montring) posture – if these symbols had been learned prior to the lesion – even without grasping its numerical meaning.[37]

Vice versa, another patient with lesions to the motor cortex should not be able to promptly understand motor symbols. While for healthy subjects canonical, but not non-canonical finger postures prime number comprehension (Study 2) and they are faster and more accurate in naming canonical than non-canonical finger configurations (Study 4; Di Luca & Pesenti, 2008), our imaginary patient should exhibit no such priming effects and no difference in naming the two types of configurations. In the naming task he or she would have to count all items (i.e., fingers) analogously and not benefit from their symbolic status.

Note that the model does not predict impairments in numerical concepts after systematic prevention of finger counting. It would only predict that the motor code would not become a deeply rooted part of numerical cognition. However, the same would be true for the visual code if children were prevented from calculating with Arabic (or similar) visual number symbols. They can still be able to acquire mature number concepts – some parts of the acquisition process might just be a little more difficult. The claim that numerical skills are affected (but not fully mediated) by the motor symbolic code is endorsed by many studies that report mostly weak, but significant relationships between skills that support the motor symbolic code (i.e., manual fine motor skills and finger gnosis) and different numerical competencies (Dinehart & Manfra, 2013; Fayol et al., 1998; Fischer et al., 2017; Gracia-Bafalluy & Noël, 2008; Kohn et al., 2015; Luo et al., 2007; Newman, 2016; Noël, 2005; Poltz et al., 2015; Thevenot et al., 2014; Wasner et al., 2016). The MASC's explanation of this relationship lies in the motor code's direct connection to time, space, number, and sensorimotor activation (cf. Figure 3, lines M1-M4). Therefore the model predicts that proficient finger counters (with consistent finger counting postures) more easily grasp the relation between physical magnitudes and symbolic codes. Thus, referring to this model, I boldly postulate that systematically teaching consistent finger counting postures as (another) symbolic form of representation in early mathematical education improves children's conceptual numerical understanding, because especially through (again: consistent!) finger counting postures and finger-to-number mappings they can learn that symbols are directly associated with non-symbolic meaning.

Conclusions

The present thesis tested the embodied cognition hypothesis that bodily experience during concept acquisition stays a fundamental part of these concepts' mental representations throughout life. The four novel studies strongly suggest that finger counting experience profoundly shapes mental representations of numerical concepts and that finger counting and montring postures have evolved into motor symbols for numbers. These motor symbols do not only constitute a coequal code with

[37] Note that in healthy subjects, the analogue numerical meaning is nevertheless usually co-activated, as indicated by split-one errors (i.e., approximation errors) in the "exact" task of Study 1 which otherwise only required translations from the visual into the motor symbolic code.

Dehaene's (1992) TCM’s two symbolic codes (effectively rendering the model a quadruple-code model), but even something richer in that they additionally directly link to physically grounded magnitudes. Following these lines of thinking I arrived at the conclusion that Walsh's (2003) ATOM and Dehaene's (1992) TCM should not be referred to as two distinct theories, but that they belong into one merged model, where all magnitude information is generally processed by (formerly TCM’s) analogue code with the common metric proposed by ATOM: TCM’s (or rather, QCM’s) analogue magnitudes *are* the magnitudes from the generalized magnitude system. Furthermore, the novel studies suggest that finger postures incorporate characteristics of both symbolic and analogue nature in the form of motor symbols and sensorimotor activation, respectively, and that motor symbols interact both with other symbolic codes and with analogue magnitude representations. Not only does the “TCM part” gain a motor code, also the “ATOM part” gains sensorimotor activation as a magnitude dimension.

In conclusion, the novel findings presented within the present thesis extend our knowledge about bodily rooted knowledge representation in general and about finger-based number representations in particular. The findings indicate a special role of finger counting experience in mental number representations and they stress the importance of bodily interactions with physical magnitudes for a fundamental grasp of numerical concepts.

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