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HANDY NUMBERS: FINGER COUNTING AND NUMERICAL COGNITION

Hosted by
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HANDY NUMBERS: FINGER COUNTING AND NUMERICAL COGNITION

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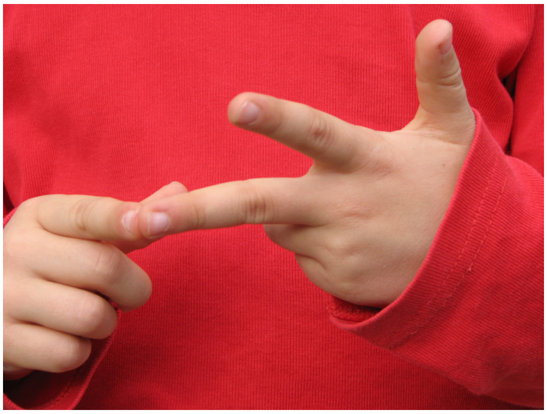

We are born with a “number sense” - the ability to respond to numerosity, which we share with other vertebrates. This inherited numerosity representation is approximate and follows the Weber-Fechner law that governs sensory perception. As educated adults we can also use culturally developed abstract symbol systems to represent exact numerosities – in particular number words and Arabic numbers. This developmental stage is preceded by an apparently transient phase of finger counting and finger calculation. In fact, the use of fingers to represent number is ubiquitous across ages and cultures. Children use finger counting even if they are discouraged to do so, sometimes even before they are able to utter the number word sequence. Furthermore, finger counting strategies may also be used by adults diagnosed with dyscalculia to make up for a deficient or absent mental number representation. The advantages of finger counting are evident: Fingers are readily available and perceptually salient, finger-numerical representations support short term memory and they provide a transparent one-to-one relationship between to-be-counted objects and their representation. Obviously, however, these advantages only hold for small numbers. Fully transparent finger counting systems are limited to the number range between zero and ten. Larger numbers can only be represented in perceptually less salient or symbolic ways.

In recent years, a growing body of evidence has suggested that finger-based representations of number do not form an arbitrary and transient stage of cognitive development. Rather, they seem to provide a good example of embodied cognition. According to this influential viewpoint, all of our knowledge is represented together with the sensory and motor activity that was present during its acquisition. As a consequence, even a supposedly abstract cognitive ability such as numerical cognition reuses the neural substrate and inherits functional properties of more basic perceptual and/or motor processes. Consistent with this assumption, finger counting habits and numerical processing do interact even in educated adults, casting doubts on purely abstract accounts of mental number representations.

The objective of this Research Topic is to document embodiment signatures in number processing and calculation – a domain of cognition that was long considered to epitomize the abstract symbol manipulation approach to human cognition. To this end, we invite empirical contributions using different methodologies including behavioural, developmental, neuroscientific, educational, cross-cultural, and neuropsychological studies. Moreover, we also seek theoretical contributions, review articles, or opinion papers. Questions to be tackled may include, but are not restricted to the following: Is finger counting only a useful or even a necessary step towards the acquisition of symbolic number representations? What are the neural correlates of the finger-number relationship? Which features of finger counting influence adult number processing – both approximate and exact? How can finger counting systems be classified typologically and how do different finger counting systems influence numerical cognition across cultures and populations? Should finger counting and finger calculation be promoted or discouraged in maths education? How are disturbances of finger gnosis and numerical abilities linked? We hope that this Research Topic will bring together researchers from different backgrounds to fruitfully discuss a topic which has both scientific and every-day relevance.

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EDITORIAL
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Finger counting and numerical cognition

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Following a recent surge of interest in finger-based number knowledge, we invited empirical and conceptual contributions to assess the feasibility of a Research Topic on this issue. We received a considerable number of submissions, many of which were further improved by constructive and interactive peer-review and ultimately appeared as part of the Research Topic "Handy numbers: Finger counting and numerical cognition." We wish to thank all authors and reviewers, as well as the publisher's support team around Meghan Hodge, for their excellent work.

This enthusiastic response from the research community confirmed our expectation that the time is ripe to consider the domain of number knowledge from the theoretical perspective of embodied cognition. This domain is particularly challenging for an embodied perspective on human cognition because mental arithmetic was thought to consist of abstract and amodal symbol manipulation. By disregarding the acquisition, implementation, or retrieval context of such knowledge, numerical cognition provided an ideal example of abstract information processing (e.g., Groen and Parkman, 1972). Yet in recent years a flurry of reports documented just such sensory and motor contributions to numerical cognition, and the contributions gathered for the present research topic on "handy numbers" provide an up-to-date survey of this development.

The published contributions make clear that there is no agreement about the relevance of finger counting for numerical cognition. For example, finger associations might not be a necessary component of number knowledge acquisition (Crollen et al., 2011), they might merely reflect immature retrieval strategies (Kaufmann et al., 2011), and some aspects of finger-based number representation might actually hinder the initial learning process (Beller and Bender, 2011). Nevertheless, all empirical contributions to this research topic support a role of fingers in numerical cognition: Spatial–numerical associations, previously attributed to reading habits, may at least partly have their origin in finger counting routines (Fischer and Brugger, 2011; Riello and Rusconi, 2011). They are prevalent in finger counting systems of many cultures (Previtali et al., 2011; Domahs et al., 2012), affect a wide range of behaviors (Fischer and Brugger, 2011), depend on hand orientation (Previtali et al., 2011), and possibly on finger gnosia (Costa et al., 2011; Reeve and Humberstone, 2011). Furthermore, finger usage and finger-based number representations may vary considerably according to cultural influences (Bender and Beller, 2011; Domahs et al., 2012). Mental addition is selectively impaired by passive hand movements (Imbo et al., 2011) and shows sub-base five effects that can be attributed to hand-based representations (Klein et al., 2011). Addition also activates finger-related cortical structures (Krinzinger et al., 2011).

Findings such as these highlight the special status of finger representations in numerical cognition (Di Luca and Pesenti, 2011) and require a conceptual rethinking. This can begin by aligning educational and neuroscientific perspectives (Moeller et al., 2011) or by contextualizing them within the embodied cognition framework (Fischer and Brugger, 2011).

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Explicating numerical information: when and how fingers support (or hinder) number comprehension and handling

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INTRODUCTION

Numbers are of enormous significance for modern society. They form the basis of currency and economic systems, of measurement and calculation, of engineering and the natural sciences, and, as a matter of course, lie at the heart of mathematics. Therefore, teaching mathematical skills plays an important role in preschool and school education. However, before children are able to perform their first symbolic algorithms such as multi-digit addition and multiplication they must have mastered two representational number systems: a verbal system (e.g., English number words) and a notational system (e.g., Arabic digits).

The main competence that children have to acquire with these systems is to represent and handle the numerical information *internally* (Zhang and Norman, 1995). Using one's fingers for numerical tasks may indicate that parts of the internal processes still require external support and are not mastered adequately, but it would be erroneous to infer that finger strategies are not worthy of support. On the contrary: we argue that one's fingers, applied properly, provide a natural, and readily available toolkit for modeling numerical information and reflecting on numerical concepts (cf. Fuson and Secada, 1986; Carpenter et al., 1999; Wright et al., 2002; Guha, 2006; Andres et al., 2008). This position is exemplified for the acquisition of the verbal number system and for verbal processes involved in counting and calculating. Following Zhang and Norman's (1995) representational analysis of notational systems, we analyze which features of the verbal system can be accessed externally, which have to be represented internally, and how this may be supported – or hindered – by finger counting strategies.

LEARNING THE VERBAL NUMBER SYSTEM

Number words refer to the (theoretically) infinite set of natural numbers, the positive integers. This set defines a ratio dimension, providing *category* (or nominal) information for judging whether or not two numbers are equal, *magnitude* (or ordinal) information for judging whether a number is smaller or greater than another, and *interval* as well as *ratio* information for assessing differences between and proportions of numbers.

Number words are distributed representations in that they make available some of this information externally – ready to be picked up by auditory or visual processes – while other information needs to be retrieved from memory and is thus available only internally (Zhang and Norman, 1995). In the case of number words, category information on whether a word is equal to or different from another can be perceived externally, whereas magnitude, interval, and ratio information cannot and therefore must be learned in order to be available. This is difficult not only because number is an abstract concept (Wiese, 2003), but also because three different kinds of numerical relations are involved (for a micro-genetic single case study of how the first number words are acquired, see Palmer and Baroody, 2011). One's own fingers support essential learning processes: in the beginning, they help to differentiate numerals by relating different phonological patterns to different finger patterns; later on, they help in the acquisition of numerical information as the fingers provide a ratio dimension of at least 10 units.

Number words constitute a numerical system with distinct properties such as dimensionality and regularity (Bender and Beller, 2011). While *one-dimensional* systems use a separate lexeme for each number, *two-dimensional* systems use lexemes only for the primary counting sequence and for the powers of the base. English, for example, contains a decimal system with nine primary numerals ("one" to "nine") and numerals for the powers of base 10 ("ten," "hundred," "thousand," etc.). From these, all other numerals are composed according to the addition and multiplication principle (with some exceptions in regularity). When hearing a number word, recurring phonological patterns provide us with externally perceivable *category* information on the dimensional structure of the system, but again, the *numerical* information is not externally available and has to be learned (e.g., that "two hundred and two" is $2 \times 100 + 2$). Likewise, finger counting systems can differ in dimensionality: in a one-dimensional system such as our 10-finger sequence each finger is counted separately. The Indian merchant system (Ifrah, 1985) is two-dimensional with base 5: the primary sequence (from one to five) is counted on one hand, the multiples of the base (5, 10, 15, 20, and 25) on the other (for this and other examples see Bender and Beller, submitted). Finger systems like this indicate that a new counting cycle has to start when the base is reached, and hence can support the distinction between base and power. Ensuring this supporting function, however, presupposes a structural match between the finger and the verbal system in terms of dimensionality, base, and regularity; mismatches in these regards slow down the learning process (Fuson and Kwon, 1991; Miller et al., 1995). Such mismatches are generated by irregular number words (like "twelve" instead of *ten-and-two) and digit inversion (like "fourteen" instead of *ten-and-four) as in verbal English, or when the finger counting system uses a (sub-) base different from the verbal system (cf. Domahs et al., 2010; Klein et al., 2011).

The verbal number system, once acquired, is not only used to refer to cardinal numbers, but also for counting and calculating. The next section discusses how these processes might be supported or hindered by finger counting systems.

LEARNING TO COUNT AND CALCULATE

Counting is typically performed with recourse to the verbal number sequence. The acquisition of the counting routine takes children several years, but eventually enables them to start counting from any number, proceed forward and backward easily, and extract its numerical meaning (Fuson, 1988; Wynn, 1992; Wiese, 2003). Five principles need to be learned (Gelman and Gallistel, 1978): (a) To each object, one number word is assigned (*one-to-one principle*); (b) the order of the objects is irrelevant; (c) the order of the number words is fixed; (d) the numeral for the last object represents the cardinality of the set; and (e) all sorts of objects can be counted in the same way. This learning process can be affected by finger activities in different ways: fingers are external tokens that can themselves be counted. Different from words, which fade away and must be memorized, fingers are permanently visible for perceptual processes and provide magnitude, interval, and ratio information. Typically, fingers are used in a stable order (Wiese, 2003; Lindemann et al., 2011), yet this yields a trade-off: it facilitates access to the number words in their correct order (principle c), but – as fingers tend to be paired with the same numerals – may conceal that neither the order nor the kind of objects to be counted are relevant (principles b and e). Finally, fingers can be used for book-keeping and thus for taking some load off from memory. This book-keeping, as well as implementation of the one-to-one principle, is supported more strongly, when children are allowed to gesture (Alibali and DiRusso, 1999), whereas *passive* hand movements tend to disrupt counting strategies, even in adults (Imbo et al., 2011).

Relieving memory is even more important when it comes to calculation. Mathematical algorithms like those for multi-digit addition and multiplication are taught in the first school years. They are communicated verbally, but operate on the Arabic digits. Several of their sub-processes involve language (Dehaene, 1992), for example, single digit calculations based on the addition and multiplication tables. Some of these are known to be supported by finger activities when children are not yet able to retrieve the results directly from memory. The first finger strategy typically used for addition problems like 3 + 5 is the "sum" strategy: hold three fingers up, hold five additional fingers up, and then count them all. Later on, children use their fingers adaptively and discover various shortcuts like *count from the first addend* (for 3 + 5: "four, five, six, seven, eight") or *count from the largest addend* ("six, seven, eight"; Siegler and Jenkins, 1989).

For the numbers 1–10, a decimal system encompasses 55 basic additions and multiplications each; the highest sum is 20, the highest multiple 100. Our classic finger system with 10 as limiting number provides for only 25 additions and 15 multiplications. In order to fully cover the basic operations, the limiting number needs to be extended (for respective strategies see Guha, 2006; Bender and Beller, submitted).

Furthermore, finger counting systems are unsuitable for depicting *negative* numbers, which may result from subtraction (e.g., 3–7). After all, as concrete tokens, fingers are either present (positive) or absent (zero), but not negative.

CONCLUSION

The acquisition of the verbal number sequence is an essential part of learning to count and an important prerequisite for mathematical education, often accompanied by finger counting strategies. Although finger counting competencies are not indispensable for the development of numerical abilities (Crollen et al., submitted), finger-training was shown to increase children's numerical performance, for instance, in quantification tasks (Gracia-Bafalluy and Noël, 2008). It is thus not surprising that imprints of finger counting systems can be found in children's early number representations (Domahs et al., 2008), and even in adults' finger-digit mappings on a computer keyboard (Di Luca et al., 2006).

Based on our analysis, however, we identified some factors that might also hinder the initial learning process: structural mismatches (e.g., in base and dimensionality) between the verbal and the finger counting sequence, the limited extent of finger counting, and too strong an association between the number words and specific objects (the fingers). While some of these problems are inherent in finger counting in general, others might be reduced by choosing an appropriate system carefully (e.g., a two-dimensional finger counting system for a two-dimensional verbal system). Such efforts appear to be worthwhile, as the prototypical finger counting systems come with at least one crucial advantage: they provide a visible and easy to manipulate set of "objects," which helps to model and to internalize all the numerical information that is not externally represented in the arbitrary symbols of number words and digits.

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Fingers as a tool for counting – naturally fixed or culturally flexible?

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INTRODUCTION

Like number words and written numerals, fingers can be used to represent numbers. In fact, due to their ubiquitous availability, agility, and discrete quantity, they are considered the most natural tool for counting, which renders them attractive for theories of embodied (numerical) cognition (Andres et al., 2008; Di Luca and Pesenti, 2011). As they are so closely linked to the human body, finger counting sequences may appear to be universal, but both their composition (Bender and Beller, in preparation) and their existence (Butterworth et al., 2011; Crollen et al., 2011) depend on culture. In this paper we will argue that it is crucial for any (embodied) theory of numerical cognition to take this cultural variability into account. To substantiate this claim, we depict some of the cultural variability in finger counting, followed by a brief representational analysis, from which directions for future research will be derived.

CULTURAL VARIABILITY IN FINGER COUNTING

Even regarding the simple use of fingers for counting from 1 to 10, a great deal of variability can be observed in how precisely this is done: (a) The palm can be turned toward oneself or toward others, (b) fingers can be extended or bent, (c) counting may begin with the left or right hand, and with thumb, index, or little finger, and (d) the switch between hands may be based on anatomical symmetry or spatial continuation (Menninger, 1969; Lindemann et al., 2011).

Beyond these variations in procedural detail, however, more fundamental differences arise in terms of which parts of a hand people count with and to what other body parts they extend counting (for a non-exhaustive sample see **Figure 1**). In "Western" systems like A, fingers are extended serially. German Sign Language DGS B uses the dominant hand for counting 1 through 5, while the other hand indicates sub-base 5 (Iversen et al., 2006). Indian merchants from Maharashtra C are reported to employ a proper base 5, the multiples of which are counted on the second hand (Ifrah, 1985). East African Bantu languages D switch between hands to obtain two approximately equal addends (Schmidl, 1915). And body counting systems of Highland New Guinea such as the Oksapmin counting system E make use of additional parts like the wrist, elbow, shoulder, and head (Saxe, 1981). Instead of entire fingers, some systems employ finger segments, the edges between segments as in F, or the space between fingers. Finally, the Roman system G illustrates a completely different type, as it represents numbers not by accumulating tokens, but by their distinct combinations. For instance, nine different gestures consisting of the little, ring, and middle finger of the left hand denote the units 1 through 9, whereas other finger sets denote the tens, hundreds, and thousands (Williams and Williams, 1995).

PROPERTIES OF FINGER COUNTING SYSTEMS

Like verbal counting sequences (Bender and Beller, 2011) and numeral notations (Zhang and Norman, 1995; Chrisomalis, 2004; Widom and Schlimm, in press), each finger counting sequence constitutes a numeration system with specific properties:

(1) *Dimensionality*: One-dimensional (1D) systems link number symbols to numbers by one-to-one correspondence; 1 × 1D systems compose number symbols from a base and power dimension; and (1 × 1) × 1D systems additionally use a sub-base. This taxonomy, designed to categorize notational systems, can also be applied to finger counting systems: A, D, E, and F all constitute 1D systems, C and G constitute 1 × 1D systems, and B constitutes a (1 × 1) × 1D system.

(2) *Dimensional representation*: Basic numbers are represented either by quantity (cumulative) or shape (ciphered). In **Figure 1**, all but the last system are cumulative, as the number is represented by the corresponding amount of tokens. Power terms are represented in an integrated, parsed, or positional manner. Representation is integrated when the same symbol(s) denotes multiplier and power simultaneously (as in Greek κ = 20), and parsed when multiplier and power are denoted by different symbols (as in "two hundred"). Positional representation is realized, for instance, in Arabic digits. Accordingly, B is parsed, and C and G are (partly) positional.

(3) *Base size*: In verbal numeration systems, the most frequently used base is 10, followed by 20 and 5 (Comrie, 2005). This prevalence has been repeatedly linked to the anatomy of the human body. Yet, even if the hand is the most important model for structuring numeral systems, this need not give rise to uniformly structured numeral systems. Our survey (Bender and Beller, in preparation) also attests to (sub-)bases 4, 6, 8, and 12 in extant systems – and to various different reasons for these bases (e.g., counting the space between fingers yields base 4, while adding the wrist to the full hand yields base 6).

(4) *Extent*: The extent of a numeration system is defined by its limiting number L (Greenberg, 1978), which is the largest number expression regularly composed or the farthest point reached in indexing. Due to the limited number of fingers, finger counting has often been assumed to be restricted to $L = 10$, and this has also been regarded as one of its most severe disadvantages. However, as demonstrated in **Figure 1**, extending counting beyond 10 is possible, either by enlarging the number of tokens or by

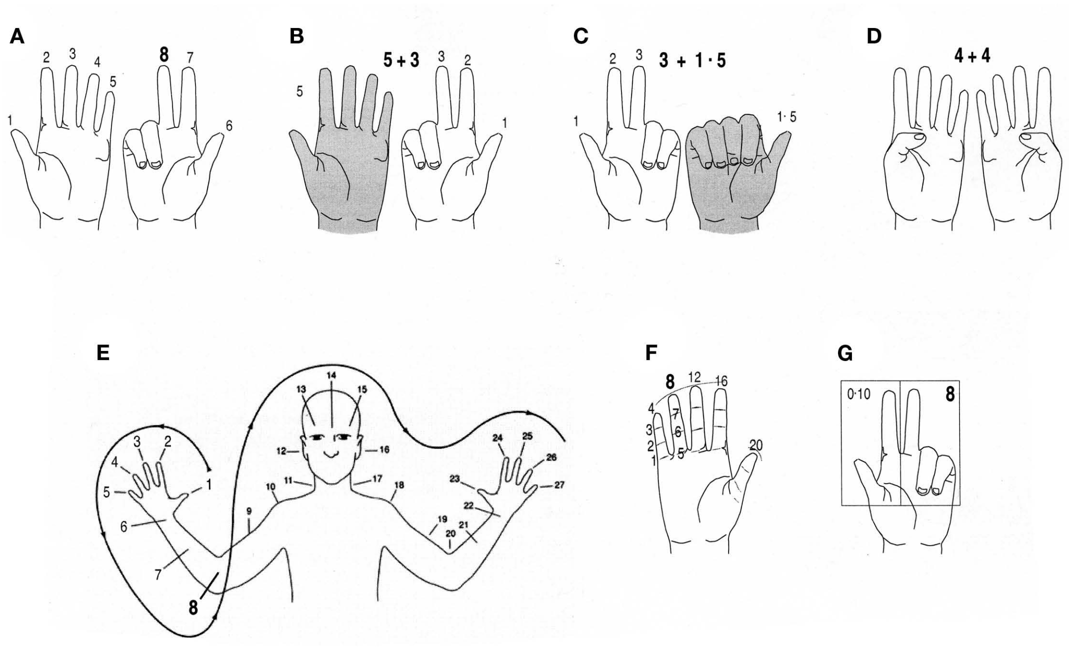

FIGURE 1 | Variability in finger counting systems, illustrated for number eight signs [(E) downloaded from Marmasse et al., 2000].

transforming a 1D system into 1 × 1D. The limiting numbers thus reached are 27 (in E), 30 C, 40 F, and 10,000 G.

It is evident that finger counting systems differ considerably with respect to their system properties. But how (if at all) do these differences affect the cognitive representation and processing of numbers?

COGNITIVE IMPLICATIONS

Embarrassingly little is known about the cognitive ramifications of cultural differences in finger counting. Most studies on finger counting conducted so far have restricted themselves to the type of 10 finger systems depicted in **Figure 1A** and its manifold variants. The most notable exception is recent work that scrutinizes possible effects of sub-base 5 inherent in DGS, as well as other 10 finger systems (Iversen et al., 2006; Domahs et al., 2010, 2011; Klein et al., 2011). The findings reveal that the specific structure of these systems has distinct consequences for cognitive processing in number comparison and parity judgment tasks, and affects both the SNARC and the MARC effects. More generally, finger counting habits modulate the markedness of numerical representations like the mental number line (overview in Andres et al., 2008; Fischer and Brugger, 2011).

However, possible effects of variations in dimensional representation, base size, or extent remain unresolved. For instance, previous research emphasized the importance of acquired number systems for exact numerosity (Wiese, 2003; Feigenson et al., 2004) and indicated that the range of accurate counting is determined by the availability of number words (Beller and Bender, 2008; Frank et al., 2008). This primacy of verbal representations is questioned by cases in which lacking number words are compensated by body tallying systems (cf. Bender and Beller, in preparation). Moreover, while availability of body parts clearly constrains finger counting systems, their plain amount is not the limiting factor. Rather, the range of counting critically depends on dimensional representation and base size.

Another factor known to affect performance in numerical tasks is dimensional representation (Zhang and Norman, 1995; Zhang and Wang, 2005): Findings from number comparison tasks indicate that numbers are represented in a distributed manner, which incorporates the external representation. The specific properties of this external representation determine how salient the different types of numerical information are. The full range of numerical information (nominal, ordinal, interval, and ratio information) is made immediately available in cumulative representations, whereas ciphered systems provide nominal information only and thus increase the cognitive load as they require retrieval of the missing information from memory. A comparison of respective finger counting systems might shed light on how deeply these differences affect cognitive processing.

The final issue considered here relates to consistency with other representational systems. Most people use more than one numeration system – typically a verbal system, a notational system, and a more or less conventionalized finger counting sequence. In English, for instance, none of these is structurally identical to any other: The verbal system is ciphered/parsed (and fraught with irregularities), the Arabic digits are ciphered/positional, and typical finger counting is 1D cumulative. Structural mismatches like these are assumed to impede learning in novices and impair processing even in advanced users (cf. Beller and Bender, 2011), but the range of implications arising from these differences is not yet fully explored.

CONCLUSION

Embodied theories of numerical cognition are grounded in the hybrid position of fingers as naturally available tools and as crucial components in cognitive development. However, the numerical meaning attached to fingers is also culturally encoded, and in strikingly diverse ways. Taking this diversity into account more thoroughly is a prerequisite for promoting research in this field.

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A hand full of numbers: a role for offloading in arithmetics learning?

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Finger counting has been associated to arithmetic learning in children. We examined children with ($n = 14$) and without ($n = 84$) mathematics learning difficulties with ages between 8 and 11 years. Deficits in finger gnosia were found in association to mathematical difficulties. Finger gnosia was particularly relevant for the performance in word problems requiring active manipulation of small magnitudes in the range between 1 and 10. Moreover, the deficits in finger gnosia could not be attributed to a shortage in working memory capacity but rather to a specific inability to use fingers to transiently represent magnitudes, tagging to be counted objects, and reducing the cognitive load necessary to solve arithmetic problems. Since finger gnosia was more related to symbolic than to non-symbolic magnitude processing, finger-related representation of magnitude seems to be an important link for learning the mapping of analog onto discrete symbolic magnitudes.

Keywords: finger gnosia, mathematics difficulties, number sense, dyscalculia

INTRODUCTION

Finger counting is frequently used by children, and under some circumstances by adults too. This ability seems to be spontaneously learned, and practice varies widely across cultures (Domahs et al., 2010), with some cultures explicitly teaching this strategy (Guha, 2006). Finger counting is especially important in children beginning to learn arithmetics, being influenced by the socio-cultural background. Jordan et al. (2008) observed that while middle-class children resorted to this strategy from the first grade on and used it progressively less after the second grade, children of lower socio-economic strata began later to use fingers for counting and persisted to do so for a more extended period of time. Moreover, visual input and imitation play important roles in finger counting, as congenitally blind children engage less frequently in this practice, and use fingers in culturally non-canonical ways (Crollen et al., 2011a). Along with other less efficient strategies, finger counting is a classical resource employed by children with difficulties in learning arithmetics, which suggests difficulties with facts learning (Butterworth, 1999; Geary et al., 2000).

Usually, children start to count on fingers at the age of 3 years, typically persisting until the beginning of second grade (Lecointre et al., 2005). Alibali and DiRusso (1999) investigated the role of gesture on the development of counting abilities in 4-year-old children. Analysis of the error patterns committed in different counting conditions revealed that finger counting helps children to improve two aspects of one-to-one correspondence principle: keeping track of the counted objects and coordinating the number words with the objects. They proposed that finger counting serves as an offloading mechanism to reduce cognitive demands by physically instantiating some contents of working memory.

In a recent review, Raghubar et al. (2010) reported in detail the role of working memory in math achievement. A robust effect of verbal working memory on math performance has been consistently found in the literature, particularly regarding numeric stimuli (i.e., digit span and counting span). In contrast, concerning visuospatial working memory (i.e., Corsi Blocks) the picture has proved to be less consistent. General studies have shown that the central executive component plays a major role. Swanson (2004) has shown that effects of the slave systems in the multicomponential working memory model are attenuated when analyses include central executive measures. Hecht et al. (2001) observed that phonological decoding assessed by means of the phoneme deletion task is longitudinally predictive of mathematics achievement, but, performance on this task imposes demands on working memory resources. Direct implication of central executive mechanisms in math learning difficulties has been demonstrated several times (e.g., Bull and Scerif, 2001; van der Sluis et al., 2004, see review in Raghubar et al., 2010).

The signature of finger counting is observed also in the error patterns of children learning arithmetics. Domahs et al. (2008) observed that arithmetic errors committed by children beginning to learn fact retrieval frequently deviate from the correct result by multiples of five, suggesting that a sub-base five, probably related to the hand structure, plays an important role in calculation procedures. Later findings by Domahs et al. (2010) disclosed that the comparison of Arabic number symbols in adults is also influenced by a sub-base five system inherent in culturally bound finger counting habits. Besides, experimental studies with adults showed that number processing interacts in complex ways with egocentric, finger-based, and allocentric spatial representations, being modulated by finger counting habits (Fischer, 2008; Conson et al., 2009; Di Luca et al., 2010). Other results indicate that, both in a parity judgment (Sato et al., 2007) as well as in a counting task (Andres et al., 2007), motor evoked potentials for right hand muscles are modulated by number magnitude. These results are suggestive of a special role of embodied representations in the development of cognitive processes, finger representations being specific to the number and arithmetic domain.

Proficiency in finger counting relies at least to some degree upon the ability to locate, name, and discriminate individual fingers (i.e., finger gnosia). Accordingly, Gracia-Bafalluy and Noël (2008) showed that children with deficits in finger discrimination abilities also present a deficit in enumeration and counting tasks in comparison to children with above average finger discrimination abilities. A first longitudinal study by Fayol et al. (1998) found that a composite score encompassing finger gnosia and other somatosensory relatively complex abilities assessed at 5 years of age was able to predict math performance 1 year later ($r = 0.46$). These results were confirmed in a subsequent study for a period of 3 years of observation (Marinthe et al., 2001). However, these findings should be seen in perspective because math performance also correlated to more general developmental tests ($r = 0.44$).

Using more specific measures of finger gnosia, Noël (2005) also observed an association of finger recognition and discrimination at the beginning of first grade with mathematics performance 15 months later. In this study, both the specificity and relative predictive power of finger gnosia on math achievement were examined. Finger gnosia correlated with mathematics performance ($r = 0.48$), but not with reading achievement ($r = 0.11$). Performance on the WISC Coding task also correlated with math achievement, but to a lower degree ($r = -0.21$). Moreover, 46% of variance in second grade mathematics achievement was explained by beginning first grade measures of finger gnosia as well as second grade measures of handwriting and block design. This suggests that the association between finger gnosia and mathematics achievement is both strong and functionally specific. Similar results regarding the role of finger gnosia in number system knowledge and calculation skills were obtained by Penner-Wilger et al. (2007) in first grade children. A role for finger gnosia in learning arithmetics was also inferred from a training study conducted by Gracia-Bafalluy and Noël (2008). However, their experimental design was based on extreme performance groups, what renders the results subject to a regression to the mean interpretation (Fischer, 2010). These data suggest that finger counting related to gnosia abilities plays an important role in arithmetic learning in beginning formal schooling. One important aspect of this question is the investigation of the shared neurocognitive correlates of finger gnosia, number processing, and arithmetics.

The association between finger counting and mathematics performance has been traditionally interpreted in the context of the syndrome discovered by Gerstmann in 1924, and which carries his name (Gerstmann, 1940; see also Rusconi et al., 2010). In a series of case analyses, Gerstmann observed that patients with lesions in the region of the left angular gyrus presented disorders of right–left orientation, dysgraphia, acalculia, and finger agnosia. Gerstmann postulated a deficit in a more basic underlying function. As the internal correlations of the syndrome components are usually lower than their individual correlations with other neuropsychological deficits, the very existence of the syndrome has been subject to heated debate (Rusconi et al., 2010), and the identification of its underlying *Grundstörung* has eluded research efforts.

Interestingly, mathematical learning difficulties in some children are associated with the other three components of the Gerstmann syndrome (Kinsbourne and Warrington, 1963). However, as children with the so-called developmental Gerstmann syndrome usually exhibit more pronounced evidence of right hemisphere dysfunction, such as lower levels of finger gnosia performance with the left hand, this disorder is nowadays discussed under the rubric of "non-verbal learning disability" (henceforth NLD), and at least one prominent model attributes the underlying dysfunction to white matter damage (Rourke, 1989).

Two main hypotheses have been considered to explain the neural correlates of the relationship between finger gnosia/counting and arithmetic learning and its disorders from a developmental perspective, the localizationist and the functionalist views (Noël, 2005; Crollen et al., 2011b), to which a third hypothesis of redeployment of finger representations (Penner-Wilger and Anderson, 2008) or neuronal recycling (Dehaene and Cohen, 2007) must be added. According to the localizationist hypothesis, co-occurrence of deficits in finger gnosia and numerical and arithmetical disorders, such as observed in the Gerstmann syndrome, is merely accidental, reflecting topographic vicinity of unrelated functions. Recent evidence compatible with the localizationist hypothesis was obtained in adults by structural MRI, confirming that fibers connecting cortical areas related to the Gerstmann tetrad are densely packed beneath the angular gyrus (Rusconi et al., 2009). These authors were, however, unable to trace functional connections between those areas. From another point of view, the functionalist and redeployment hypotheses assume that finger representations are recruited or exaptated for counting because they are computationally suitable to implement number representations required for counting and arithmetic facts (Penner-Wilger and Anderson, 2008).

The only formal empirical test of the localizationist vs. functionalist hypotheses in developing individuals was conducted by Noël (2005). As predicted by the localizationist hypothesis, mathematical achievement was significantly correlated to other components of the Gerstmann constellation, besides finger gnosia: right–left orientation ($r = -0.34$), constructional abilities ($r = 0.44$), and handwriting ($r = 0.43$). The author planned to test the functionalist hypothesis by contrasting correlations between finger gnosia and performance in arithmetic tasks that are dependent on (i.e., addition) and independent of (i.e., magnitude comparison) finger counting. This latter test failed because number-related performance was explained by a single factor, and because finger gnosia correlated significantly to both kinds of numerical tests (all *r*s around 0.36–0.38). The negative results regarding a dissociation between number processes which are more or less independent of finger gnosia described by Noël (2005) may lay to a large extent on the methods used to investigate them. The sample size $n = 45$ examined in Noël (2005) is too small to reliably distinguish between the existence of one or two latent factors (MacCallum et al., 1999). Moreover, it is unrealistic to expect that the two factors describing two different aspects of number processing would be completely independent of each other. Considering the nature of these processes it is much more reasonable to expect that the factors would be at least moderately correlated. For these reasons, a selective impact of finger gnosia on specific numeric abilities remains elusive in this study. Hence, behavioral studies have established the importance of finger counting on arithmetic learning.

As already pointed out by Gerstmann (1940), brain regions responsible for finger gnosia and arithmetic abilities are neuroanatomic neighbors. A structural neuroimaging study corroborates the importance of both cortical and subcortical structures of the posterior right hemisphere in number processing and calculation. Rykhlevskaia et al. (2009) compared brain structural characteristics of children with dyscalculia to those of typically developing controls. Volumetric analyses revealed reductions of both cortical and gray matter around the inferior parietal sulcus and superior parietal lobule bilaterally. Fractional anisotropy was most altered in the right parietal lobe and tractographic analyses revealed that long range connections between the right fusiform gyrus and temporal–parietal regions via the inferior longitudinal fasciculus were compromised in children with dyscalculia.

fMRI studies have investigated the neural correlates of non-symbolic magnitude processing and finger representations (Kaufmann et al., 2008). When judging whether the number of fingers presented is smaller or larger than 5, adults show activation of the classical intraparietal areas related to non-symbolic magnitude processing while children also activated more anterior areas of the right intraparietal sulcus and post and precentral sulcus, which are related to hand functions. Moreover, in the same task, children with mathematical difficulties (MD) activate more the left intraparietal cortex, probably as a compensatory strategy (Kaufmann et al., 2009). Interestingly, a recent meta-analysis investigating the developmental fMRI studies of typical and atypical number processing revealed that (intra)parietal activations of dyscalculic children were more anterior than those displayed by controls, suggesting that those children strongly rely on finger-based number representations (Kaufmann et al., 2011). This suggests that neural impairments in mathematical learning disabilities are related to dysfunctions in a complex network of left and right hemispheric cortical and subcortical structures which typically connect finger counting, discrete magnitudes, and verbal and Arabic representations.

In the present study, the impact of finger gnosia on mathematical abilities was investigated in children with and without MD. In previous studies, an association between finger gnosia and mathematical abilities has been shown (Noël, 2005; Penner-Wilger et al., 2007). Moreover, according to Marinthe et al. (2001) finger gnosia predicted arithmetics achievement. Furthermore, Gracia-Bafalluy and Noël (2008) reported that finger gnosia training may improve arithmetics achievement. So firstly, it is reasonable to hypothesize that children with MD will present lower finger discrimination abilities in comparison to typically achieving children (TA). Additionally, since previous studies have found morphological and functional interhemispheric differences between TA and MD predominantly in the right hemisphere (Kaufmann et al., 2009; Rykhlevskaia et al., 2009), we may expect that difficulties in finger gnosia should be more pronounced in the (non-dominant) left hand. Secondly, finger discrimination deficits should not be related to more basic aspects of neurologic maturation, such as motor dexterity, and should not be explained by more general cognitive deficits such as working memory or intelligence alone. Thirdly, based on previous findings by Noël (2005), we expect a stronger impact of finger gnosia deficits on counting dependent procedures (i.e., arithmetic word problems) than on tasks tapping the approximate number system (ANS; i.e., magnitude comparison) or fact retrieval (i.e., multiplication facts). Finally, if the localizationist hypothesis is correct, then we should expect moderate to high correlations between finger gnosia and the other functions related to the Gerstmann syndrome constellation, such as right–left orientation and constructional abilities.

MATERIALS AND METHODS

PARTICIPANTS

The study was approved by the local research ethics committee (COEP–UFMG). Children participated only after informed consent was obtained in written form from parents, and orally from children. They were recruited in two distinct phases: in the screening phase, we selected public and private schools from Belo Horizonte and Mariana, Brazil, and used the arithmetics and spelling subtests of the Brazilian School Achievement Test (Teste do Desempenho Escolar, TDE; Stein, 1994). In this phase, testing was conducted in groups, on children from second to seventh grade. Children were then divided into a typical achievement (TA) group – no difficulties in the arithmetics and spelling subtests – and a MD – score inferior to 1 SD below the mean according to Brazilian norms in the arithmetics subtest.

Eighty-four typically achieving children (TA) and 14 children with MD took part in the individual neuropsychological testing phase. The two groups were matched regarding age and general intelligence. This sample was constituted by children with ages ranging from 8 to 11 years and normal intelligence (*z*-score between −1 and +1 in the Raven's Colored Progressive Matrices, see **Table 1**).

INSTRUMENTS

The following instruments were used in the neuropsychological assessment: Brazilian School Achievement Test (TDE; Stein, 1994), Raven's Colored Progressive Matrices, digit span (WISC), copy of Rey–Osterrieth Complex Figure, right–left orientation

Table 1 | Descriptive data of the individual assessment sample.

	TA		MD		x^2	df	*p*
N	84		14				
Sex (% female)	64.3		57.1		0.263	1	0.608
	Mean	**SD**	**Mean**	**SD**	***t***	**df**	***p***
Age (months)	122.02	13.13	122.14	12.84	−0.031	92	0.975
Raven (*z*-score)	0.18 (PR = 57)	0.49 (CI = 26–76)	0.09 (PR = 54)	0.67 (CI = 33–73)	0.576	96	0.566

TA, typically achieving children; MD, children with mathematics difficulties; PR, percentile rank; CI, confidence interval.

(Dellatolas et al., 1998), 9-hole peg test (Poole et al., 2005), handedness ascertainment (Lefèvre and Diament, 1982), non-symbolic magnitude comparison, symbolic magnitude comparison, finger localization test (Dellatolas et al., 1998), and tests for mathematical cognition (arithmetic word problems and basic arithmetic operations – addition, subtraction, and multiplication).

Brazilian school achievement test (TDE; Stein, 1994)

The TDE is the most widely used standardized test of school achievement with norms for the Brazilian population. It comprises three subtests: arithmetics, single-word spelling, and single-word reading. In the screening phase, we used the arithmetics and spelling subtests, which can be applied in groups. Norms are provided for school-aged children between the second and seventh grade. The arithmetics subtest is composed of three simple verbally presented word problems (i.e., which is the largest, 28 or 42?) and 45 written arithmetic calculations of increasing complexity (i.e., very easy: $4 - 1$; easy: $1230 + 150 + 1620$; intermediate: 823×96; hard: $3/4 + 2/8$). Specific norms for each school grade were used to characterize children's individual performance. The spelling subtest consists of dictation of 34 words of increasing syllabic complexity (i.e., *toca; balanço; cristalização*). Reliability coefficients (Cronbach α) of TDE subtests are 0.87 or higher. Children are instructed to work on the problems to the best of their capacity but without time limits.

Raven's colored progressive matrices

General intelligence was assessed with the age-appropriate Brazilian validated version of Raven's Colored Matrices (Angelini et al., 1999). Children with general intelligence below the 16th percentile (i.e., $g < -1$ SD) were not included in the sample.

Digit span

Verbal short-term memory was assessed with the Brazilian WISC-III Digits subtest (Figueiredo, 2002). Performance in the forward order was considered a measure of phonological short-term memory, and the backward order was used to assess verbal working memory.

Corsi blocks (forward and backward)

This test is a measure of the visuospatial component of working memory. It is constituted by a set of nine blocks which are tapped, in a certain sequence, by the examiner. The test starts with sequences of two blocks and can reach a maximum of nine blocks. We used the forward and backward Corsi span tasks according to Kessels et al. (2000). In the forward condition, the child is instructed to tap the blocks on the same order as the examiner, in the backward condition, in the inverse order. Span is determined by the longest sequence correctly repeated before two successive failures.

Rey–Osterrieth complex figure test (Strauss et al., 2006)

The copy of the Rey figure assesses visuospatial and visuoconstructional abilities. It is based on a complex black and white drawing that the child must copy as accurately as possible. Accuracy score was based on 18 elements of the figure. For each correctly copied element children scored up to two points when the element was perfectly reproduced (Lezak et al., 2004; Strauss et al., 2006).

Nine-hole peg test (9-HPT)

The 9-HPT is a timed test in which nine pegs should be inserted and removed from nine holes in the pegboard with each hand; dominant and non-dominant. The version used was based on Poole et al. (2005). The pegboard is placed horizontally in front of the child, so that the compartment that contains the pegs is on the side of the hand to be tested, while the compartment with the holes is on its contralateral side. Children must pick one peg at a time. The test is performed two times with each hand, two consecutive attempts with the dominant hand, followed immediately by two consecutive attempts with the non-dominant hand. The scores were calculated based on the mean time for each hand.

Handedness ascertainment

Lateral preference was investigated by means of tasks that examine the ocular, hand, and foot preference based on Lefèvre and Diament (1982). The child was instructed to look through a hole, to kick and to throw a ball, three times each. The result was given by the side the child had chosen more consistently.

Right–left orientation test

This test is based on Dellatolas et al. (1998). The test has 12 items of right and left body parts recognition. It is divided in three parts: the first part presents simple commands regarding the child's own body, the second consists of double commands – direct and crossed – toward the child's body. In the third part, pointing commands to single lateral body parts of an opposite-facing person were issued. Scores were attributed if the child correctly pointed to the nominated parts of the body; correct answers were coded with one and wrong answers with zero. Internal consistency was assessed with the Kuder-Richardson reliability coefficient, which was high (KR-20 = 0.80).

Finger localization task

This 24-item task also based on Dellatolas et al. (1998) was used to assess finger gnosia. It consists of three parts: (a) with the hand visible, localization of single fingers touched by the examiner with the pointed end of a pencil (two trials on each hand); (b) with the hand hidden from view, localization of single fingers touched by the examiner (four trials on each hand); (c) with the hand hidden from view, localization of pairs of fingers simultaneously touched by the examiner (six trials each hand). According to Dellatolas' et al. (1998) procedure, the participants were instructed to choose how they would rather respond: they could name the touched fingers, point to them on an outline drawing of the stimulated hand, or call out their numbers according to a figure in which fingers beginning with the thumb are numbered from 1 to 5. A correct answer was coded 1 and a wrong answer 0. A total score (ranging from 0 to 12) was calculated for each child. The internal consistency of this task is high (KR-20 = 0.79).

Simple reaction time

The computerized RT task is a visual detection task used to control for possible differences in basic processing speed, not related to numerical tasks. In this task the picture of a wolf (height 9.31 cm; length = 11.59 cm) was displayed in the center of a black screen for a maximum time of 3,000 ms. Participants were instructed to press the space bar on the keyboard as fast as possible whenever the wolf appeared. Each trial was terminated with the first key press. The task had 30 experimental trials, with an inter-trial interval varying between 2,000 and 8,000 ms.

Non-symbolic magnitude comparison task

In the non-symbolic magnitude comparison task, the participants were instructed to compare two simultaneously presented sets of dots, indicating which one contained the larger number. Black dots were presented on a white circle over a black background. On each trial, one of the two white circles contained 32 dots (reference numerosity) and the other one contained 20, 23, 26, 29, 35, 38, 41, or 44 dots. Each magnitude of dot sets was presented eight times. The task comprised 8 learning trials and 64 experimental trials. Perceptual variables were varied such that in half of the trials individual dot size was held constant, while in the other half the size of the area occupied by the dots was held constant (see exact procedure descriptions in Dehaene et al., 2005). Maximum stimulus presentation time was 4,000 ms, and inter-trial interval was 700 ms. Before each trial, a fixation point appeared on the screen – a cross, printed in white, with 30 mm in each line. If the child judged that the right circle presented more dots, a predefined key localized in the right side of the keyboard should be pressed with the right hand. On the contrary, if the child judged that the left circle contained more dots, then a predefined key on the left side had to be pressed with the left hand.

Symbolic magnitude comparison task

In the symbolic magnitude comparison task, Arabic digits from 1 to 9 were presented on the computer screen (height = 2.12 cm; length = 2.12 cm). The visual angle of the stimuli was 2.43° in both vertical and horizontal dimensions. Children were instructed to compare the stimuli with the reference number 5. Digits were presented in white on a black background. If the presented number was smaller than 5, the child had to press a predefined key on the left side of the keyboard with the left hand. If the stimulus was larger than 5, the key to be pressed was located at the right side and should be pressed with the right hand. The number 5 was never presented. Numerical distances between stimuli and the reference number (5) varied from 1 to 4, each numerical distance being presented the same number of times. Between trials a fixation point of the same size and color of the stimuli was presented on the screen. The task comprised 80 experimental trials. Maximum stimulus presentation time was 4,000 ms, and inter-trial interval was 700 ms.

Arithmetic word problems

Twelve arithmetical word problems were presented to the child on a sheet of paper while the examiner read them aloud simultaneously to avoid reading proficiency bias. There were six addition and six subtraction items, all of them with single-digit operands and results ranging from 2 to 9 (i.e., "*Annelise has* 9 *cents. She gives* 3 *to Pedro. How many cents does Annelise have now?*"). The child had to solve the problems mentally and write the answer down in Arabic format as quickly as possible, and the examiner registered the time taken for each item. Cronbach's α of this task was 0.83.

Basic arithmetic operations

This task consisted of addition (27 items), subtraction (27 items), and multiplication (28 items) operations for individual application, which were printed on separated sheets of paper. Children were instructed to answer as fast and as accurate as they could, time limit per block being 1 min. Arithmetic operations were organized in two levels of complexity and were presented to children in separated blocks: one consisted of simple arithmetic table facts and the other of more complex ones. Simple additions were defined as those operations with the results below 10 (i.e., $3 + 5$), while complex additions with the results between 11 and 17 (i.e., $9 + 5$). Tie problems (i.e., $4 + 4$) were not used for addition. Simple subtraction comprised problems in which the operands were below 10 (i.e., $9 - 6$), while for complex subtractions the first operand ranged from 11 to 17 (i.e., $16 - 9$). No negative results were included in the subtraction problems. Simple multiplication consisted of operations with results below 25 and with the number 5 as one of the operands (i.e., 2×7, 5×6), while for the complex multiplication the result of operands ranged from 24 to 72 (6×8). Tie problems were not used for multiplication. Reliability coefficients were high (Cronbach's $\alpha > 0.90$).

ANALYSES

Even though there was no statistical difference between groups regarding intelligence ($p = 0.530$), we decided to calculate the effect size of this difference ($d = 0.182$) and to include intelligence as a covariate in all further group comparisons. First, the differences between MD and TA groups regarding finger gnosia and other neuropsychological, cognitive, and numerical skills were investigated. Thereafter, the impact of finger gnosia on the differences between MD and TA groups in general cognitive functions (i.e., motor dexterity, right–left orientation) as well as numeric and arithmetic abilities (i.e., magnitude estimation, arithmetic word problems, simple and complex addition, subtraction, and multiplication problems) were examined. In a first set of ANCOVAS, group differences were calculated with intelligence as a covariate. In a second set of ANCOVAS, group differences were calculated again, but entering both intelligence and finger gnosia as covariates. Analyses in which finger gnosia reduced or even removed group differences were interpreted as indicative of a selective role of finger gnosia on specific cognitive functions. Finally, we examined the correlations of these variables. Finger discrimination was assessed separately for the left and the right hand. Only three children from the TA group and one MD were left-handed according to a lateralization test based on Lefèvre and Diament (1982). All analyses were duplicated excluding these children and the results did not differ so we did not exclude these individuals from statistical analyses. For this reason we considered finger gnosia for the left/right hand as an index of the non-dominant/dominant hand.

RESULTS

We investigated differences in cognitive and numerical abilities between children with typical arithmetical abilities and children with MD in the following neuropsychological variables: the copy of Rey–Osterrieth complex figure test, digit span, Corsi Blocks, 9-HPT, finger gnosia, right–left orientation, arithmetic word problems, addition, subtraction, and multiplication operations, as well as symbolic and non-symbolic magnitude comparison tasks.

RT data was trimmed, eliminating in two steps all responses more extreme than 3 SD from the individual means, as well as those RTs faster than 200 ms. Error data for the symbolic task was arcsine transformed to correct for skewness before entering statistical analysis. To analyze the non-symbolic task, we calculated for each children the *internal* Weber fraction (thereafter w), a measure previously used to estimate the acuity of the ANS (Piazza et al., 2004, 2010; Dehaene, 2007; Halberda et al., 2008; Izard and Dehaene, 2008; Mazzocco et al., 2011), based on the methods described by Piazza et al. (2004). One TA child refused to solve the subtraction task, and eight other TA children from early grades reported that they had not yet learned multiplication in school by the time of testing. Moreover, two TA and two MD did not complete the finger gnosia or the right–left orientation tasks, and nine TA did not complete the non-symbolic comparison task. Additionally, the r^2 of the fitting procedure to calculate the acuity of the ANS for three TA and for one MD children were less than $r^2 = 0.2$, so we did not consider the w for those children. Furthermore, 11 TA children did not complete the symbolic magnitude comparison task. **Table 2** describes the sample sizes, means and SD of the two groups, separately, for each measure.

A significant statistical difference between MD and TA was found for the finger gnosia task [F (1,81) = 9.04, MSE = 8.55; $p = 0.004$; $\eta^2 = 0.10$]. When each hand was analyzed separately, the effect was much more pronounced for the left hand [F

Table 2 | Descriptive data of the neuropsychological measures for each group.

Tasks	*N*		TA		MD	
	TA	MD	Mean	SD	Mean	SD
Rey's figure (copy)	84	14	27.33	6.43	27.96	4.77
Digits Wisc(forward)	84	14	5.44	1.03	4.93	0.48
Digits Wisc(backward)	84	14	3.21	0.91	2.79	0.43
Corsi blocks(forward)	84	14	4.85	1.03	5.00	1.04
Corsi blocks (backward)	84	14	4.17	0.97	4.36	1.01
9-HPT(dominant hand)*	72	12	20483.47	3174.69	20893.75	3773.14
9-HPT(non-dominant hand)*	72	12	21982.36	4511.07	22207.67	2499.94
Finger gnosia (right)	72	12	10.38	1.74	9.33	2.27
Finger gnosia (left)	72	12	10.71	1.56	8.83	2.59
Finger gnosia (both)	72	12	21.08	2.79	18.17	4.47
Right/left orientation	72	12	8.93	3.29	8.50	3.34
Arithmetics (TDE)	84	14	18.32	6.16	10.93	4.79
Arithmetics word problems	84	14	9.48	2.27	7.79	2.52
Addition	84	14	10.76	2.99	9.64	3.03
Subtraction	83	14	8.01	3.32	5.64	3.78
Multiplication	76	14	8.26	4.47	3.39	2.76
Symbolic task_errors	73	14	3.21	24.93	0.34	0.09
Symbolic task_RT*	73	14	939.89	250.36	951.73	271.57
Non-symbolic task_RT*	75	14	1262.98	351.81	1142.30	263.76
W	72	13	0.24	0.09	0.31	0.09

*TA, typically achieving children; MD, children with mathematics difficulties; 9-HPT, 9-hole peg test; RT, reaction time; W, Weber fraction; *time in milliseconds.*

(1,81) = 11.56, MSE = 2.91; $p = 0.001$; $\eta^2 = 0.125$] than for the right hand [F (1,81) = 3.02, MSE = 2.96; $p = 0.086$; $\eta^2 = 0.036$]. To investigate how finger gnosia is associated to other differences between TA and MD, two sets of ANCOVA models were calculated.

Statistical comparisons between groups revealed no significant differences between groups regarding the Rey–Osterrieth complex figure test, right–left orientation task, digit span (forward and backward), Corsi blocks (forward and backward), 9-HPT, simple reaction time task, symbolic and non-symbolic magnitude comparison tasks, and addition operations. In all of these comparisons, ANCOVA models including both intelligence and finger gnosia also remained non-significant (**Table 3**).

Significant differences between groups were found for the TDE, subtraction and multiplication operations, *w*, and arithmetic word problems. Importantly, after controlling for the impact of finger gnosia, all these comparisons remained significant, with the only exception of arithmetic word problems (**Table 3**).

Inspection of **Table 4** reveals that the finger gnosia score correlated moderately with arithmetics subtest of the TDE and word problems. Moreover, all arithmetic tasks correlated moderately or strongly with each other. However, *w* did not correlate with any other task rather than the arithmetics subtest of the TDE. Tasks tapping on core (the right–left orientation) as well as aggregated (visuospatial abilities, Rey–Osterrieth complex figure test) symptoms of the Gerstmann syndrome presented smaller correlations to finger gnosia compared to other tests that are not associated with the syndrome profile. Visuospatial working memory (Corsi Blocks) also presented significant correlations to the arithmetics subtest of the TDE as well as to the basic arithmetic operations and to the arithmetic word problems (range $r = 0.26$ to $r = 0.41$).

DISCUSSION

In the present study the impact of finger gnosia on mathematics achievement was examined in a sample of children with and without MD. Finger gnosia performance is substantially lower in MD than in typically achieving (TA) children. This difference could not be attributed to general deficits in cognitive or somatomotor development, since these groups did not differ regarding general intelligence, working memory, visuospatial abilities or motor dexterity. After removing the effect of finger gnosia, the differences between MD and TA in arithmetic word problems disappeared. However, these differences remained significant in measures of mathematics achievement, acuity of the ANS (i.e., *w*) as well as in written subtraction and multiplication. In the following, these results will be discussed in more detail.

GROUP DIFFERENCES IN FINGER GNOSIA

In line with previous studies investigating the association between finger gnosia and numeric and arithmetic competencies in typically achieving children (Fayol et al., 1998; Noël, 2005; Penner-Wilger et al., 2007), the present study showed for the first time the existence of a deficit in finger gnosia in children selected for MD in comparison to typically developing children. Our results corroborate and extend the previous findings that the ability to discriminate fingers is specifically associated with numeric and

Table 3 | Analysis of covariance of the neuropsychological tasks (ANCOVA).

Tasks	ANCOVA (Covariate: intelligence)				ANCOVA (Covariates: intelligence + gnosias)			
	F	**df**	***p***	**η^2**	***F***	**df**	***p***	**η^2**
Rey's figure (copy)	0.506	1;95	0.479	0.005	1.017	1;80	0.316	0.013
Digits Wisc(forward)	3.119	1;95	0.081	0.032	2.477	1;80	0.119	0.030
Digits Wisc(backward)	2.755	1;95	0.100	0.028	1.328	1;80	0.253	0.016
Corsi blocks (forward)	0.421	1;95	0.518	0.004	2.025	1;80	0.159	0.025
Corsi blocks (backward)	0.587	1;95	0.445	0.006	1.427	1;80	0.236	0.018
9-HPT(dominant hand)	0.051	1;81	0.822	0.001	0.053	1;80	0.818	0.001
9-HPT(non-dominant hand)	0.003	1;81	0.958	<0.001	0.079	1;80	0.779	0.001
Right/left orientation	0.067	1;81	0.796	0.001	0.001	1;80	0.970	<0.001
Arithmetics (TDE)	20.280	1;95	<0.001	0.176	11.801	1;80	0.001	0.129
Arit. word problems	6.496	1;95	0.012	0.064	1.467	1;80	0.229	0.018
Addition	1.385	1;95	0.242	0.014	1.213	1;80	0.274	0.015
Subtraction	5.655	1;94	0.019	0.057	4.831	1;80	0.031	0.057
Multiplication	15.422	1;87	<0.001	0.151	10.881	1;74	0.001	0.128
Simple reaction time	2.915	1;79	0.092	0.036	0.604	1;67	0.440	0.009
Symbolic task_errors	0.166	1;85	0.685	0.002	0.017	1;72	0.898	<0.001
Symbolic task_RT	<0.001	1;84	1.000	<0.001	<0.001	1;70	0.992	<0.001
Non-symbolic task_RT	0.881	1;86	0.351	0.010	1.731	1;73	0.192	0.023
W	5.890	1;82	0.017	0.067	4.723	1;70	0.033	0.063

Columns on the left show the set of ANCOVA models including only intelligence as a covariate. Columns on the right show those models including both intelligence and finger gnosia as covariates. TA, typically achieving children; MD, children with mathematics difficulties; 9-HPT, 9-hole peg test; RT, reaction time, W, Weber fraction.

Table 4 | Correlations between the neuropsychological measures.

Tasks	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1. Raven	1																				
2. Finger gnosia (R)	0.35**	1																			
3. Finger gnosia (L)	0.21	0.52**	1																		
4. Finger gnosia (B)	0.32**	0.87**	0.87**	1																	
5. Arith-metics (TDE)	0.44**	0.30**	0.37**	0.38**	1																
6. Arit. word prob.	0.43**	0.31**	0.39**	0.40**	0.68**	1															
7. Addition	0.39**	0.18	0.34**	0.30**	0.70**	0.56**	1														
8. Sub-traction	0.37**	0.25*	0.38**	0.36**	0.69**	0.45**	0.71**	1													
9. Multiplica-tion	0.37**	0.18	0.35**	0.30**	0.82**	0.49**	0.69**	0.73**	1												
10. *W*	−0.06	0.00	0.05	0.03	−0.28*	−0.10	−0.09	−0.17	−0.21	1											
11. Non-symbolic_RT	−0.05	−0.20	−0.16	−0.21	−0.27*	−0.12	−0.36**	−0.34**	−0.33**	−0.08	1										
12. Sym-bolic_errors	0.04	0.05	0.09	0.08	0.09	0.07	0.10	0.18	0.11	0.02	−0.09	1									
13. Sym-bolic_RT	−0.30**	−0.34**	−0.26*	−0.34**	−0.39**	−0.32**	−0.54**	−0.39**	−0.42**	−0.08	0.52**	0.25*	1								
14. Rey's figure (c)	0.51**	0.25*	0.22*	0.27*	0.40**	0.33**	0.36**	0.32**	0.35**	−0.04	0.06	0.10	−0.16	1							
15. Digits Wisc(fw)	0.09	0.10	0.13	0.13	0.16	0.16	0.20*	0.12	0.23*	0.01	−0.14	−0.04	−0.19	−0.11	1						
16. Digits Wisc(bw)	0.17	0.20	0.11	0.18	0.22*	0.19	0.11	0.16	0.19	−0.02	0.01	0.35**	−0.13	0.09	0.18	1					
17. Corsi blocks(fw)	0.23*	0.18	0.18	0.21	0.31**	0.28**	0.35**	0.27**	0.28**	0.04	−0.30**	−0.20	−0.49**	0.29**	0.16	0.04	1				
18. Corsi blocks(bw)	0.16	0.06	0.18	0.14	0.29**	0.31**	0.41**	0.26*	0.30**	−0.08	−0.26*	−0.03	−0.25*	0.23*	0.03	−0.02	0.28**	1			
19. R/L orientation	0.31**	0.15	0.13	0.16	0.40**	0.34**	0.38**	0.29**	0.47**	0.02	−0.39**	0.11	−0.54**	0.15	0.26*	0.15	0.18	0.18	1		
20. 9-HPT (dom.)	−0.34**	−0.24*	−0.20	−0.25*	−0.26*	−0.19	−0.29**	−0.23*	−0.24*	−0.02	0.02	0.02	0.16	−0.29**	0.00	0.03	−0.24*	−0.05	−0.31**	1	
21. 9-HPT (non-dom.)	−0.39**	−0.21	−0.14	−0.20	−0.32**	−0.23*	−0.33**	−0.30**	−0.35**	0.03	0.17	0.07	0.39**	−0.27*	−0.15	−0.11	−0.40**	−0.11	−0.41**	0.70**	1

***Correlation is significant at the 0.01 level (two-tailed); *correlation is significant at the 0.05 level (two-tailed). R, right; L, left; B, both; W, Weber fraction; RT, reaction time; C, copy; fw, forward; bw, backward; R/L, right/left; 9-HPT(dom), 9-hole peg test dominant hand; 9-HPT(non-dom), 9-hole peg test non-dominant hand.*

arithmetic abilities. Noël (2005) as well as Penner-Wilger et al. (2007) reported evidence that finger gnosia contributed independently to the prediction of numeric and arithmetic abilities in TA children. We found that finger gnosia discriminated between MD and TA even though general intelligence as well as verbal and non-verbal working memory were comparable across groups. Together, these studies suggest that finger gnosia contributes in a unique way to numeric and arithmetic abilities. Further evidence provided by Gracia-Bafalluy and Noël (2008) reinforces this conclusion. These authors have shown that children selected for their poor finger discrimination abilities performed worse in enumeration and counting tasks than children performing well in these number processing tasks. Altogether, these results are indicative that difficulties in MD children are not limited to basic magnitude representations but extend to finger representations. Finally, these results corroborate the view that the way finger discrimination determines numeric and arithmetic performance is related to working memory offloading (Alibali and DiRusso, 1999). As MD and TA children had comparable verbal and visuospatial working memory performance, MD may have failed to use finger representations to offload working memory and, for this reason, performed worse in arithmetic tasks intimately related to these capabilities. This topic will be discussed in the next section.

DISENTANGLING FINGER GNOSIA FROM MORE GENERAL GROUP DIFFERENCES

No differences in higher cognitive functions such as verbal and visuospatial working memory, visuoconstructional abilities, and general intelligence were found between MD and TA groups. In spite of the lack of differences between groups regarding these abilities, they all seem to have some peripheric relevance for the performance of arithmetical tasks, as can be seen in the small but significant correlations between them and arithmetic subtest of the TDE, arithmetic word problems, and basic arithmetic operations.

In summary, the deficit in finger discrimination observed in MD children does not seem to be related primarily to problems retaining and manipulating verbal or visuospatial information in a short-term buffer. Accordingly, if MD children may present difficulties offloading working memory (Alibali and DiRusso, 1999), these difficulties do not seem to be an outcome of capacity constraints or inability to apply the correct offloading strategy, since both MD and TA children showed comparable working memory capacity. Instead, the problems probably lay in accessing finger representations during calculation. Moreover, deficits in finger gnosia do not seem to be related to aspects of visuomotor transformations necessary for visuoconstructional abilities. This indicates that deficits in finger gnosia observed in MD children cannot be attributed to a generalized dysfunction of the left/right parietal lobes such as that observed for instance in Williams syndrome (Atkinson and Braddick, 2011) or in NLD more generally (Rourke, 1989). Finally, lack of difference in measures of general intelligence suggested that the deficit in finger gnosia is related to a very specific aspect of cognition and not to a general ability level. Therefore, one can be confident to explore a more specific link between finger gnosia and numeric and arithmetic abilities in the next section.

FINGER GNOSIA AND NUMBER PROCESSING

According to the functionalist hypothesis, finger gnosia should be related to some modalities of number processing and calculation but not to others. Finger gnosia should be relevant for tasks such as arithmetic word problems, which are frequently solved by beginning schoolers and MD children through finger counting. But finger gnosia should be less relevant for estimation or multiplication, which involve, respectively, magnitude estimation and fact retrieval (Noël, 2005). This prediction was corroborated by our empirical data.

Mathematical difficulties children presented higher *w* compared to TA children. These results are consistent with ongoing literature showing a deficit in the acuity of the ANS in dyscalculic children as well as in children with mathematical learning disability (Piazza et al., 2010; Mazzocco et al., 2011). Furthermore, the mean values of *w* found in this study ($TA = 0.23$ and $MD = 0.31$) were very similar to the ones reported by Piazza et al., 2010; controls $= 0.25$ and dyscalculics $= 0.34$). More importantly, a deficit in such basic number magnitude discrimination seemed to be independent from a deficit encountered in finger gnosia in the present study. After removing the impact of finger gnosia abilities, the MD deficit in *w* remained significant. Once more, these results suggest that finger gnosia provides a unique contribution to the deficits of MD children in numeric and arithmetic abilities. A controversial finding was the lack of group differences in the symbolic magnitude comparison task, which has also been reported in the literature regarding symbolic processing (one-digit magnitude comparison: Landerl et al., 2004; Mussolin et al., 2010).

In this study, MD performed worse than TA children in both multiplication and subtraction operation. After removing the impact of finger gnosia, these differences were not even attenuated. Despite the literature evidence concerning the relationship between finger gnosia and basic arithmetic operation (Ifrah, 2000; Crollen et al., 2011b), we did not find group differences specifically on the addition task. This might be due to the fact this task may have allowed for direct fact retrieval and be too simple for 10 or 11 years old children.

Noteworthy, after removing the effect of finger gnosia, the differences between MD and TA children observed in arithmetic word problems disappeared. Our results are in line with Butterworth's position, because they show that finger gnosia may serve as a mechanism to offload working memory demands, helping children to accurately represent quantities above the subitizing range, which in turn support arithmetic processing. According to Butterworth (1999), fingers a portable and always present tool used to link the abstract representation of numbers to concrete manipulations of quantities. As the capacity to perceive exact numerosities normally do not exceed four items, fingers are helpful to extend this limitation. Importantly, arithmetic word problems employed in the present study had solutions in the range between 2 and 9. The usefulness of finger representations in numeric and arithmetic tasks seem to be limited to the number range encompassed between 1 and 10. When calculation problems exceed this interval, such as in our subtraction operations, the role of finger representations seems to fade.

A final aspect of the result pattern obtained regards the specificity of the association between finger gnosia and numeric and arithmetic abilities. Previous studies have focused their attention on composite measures of these numeric and arithmetic abilities. Noël (2005) used a composite of comparison, Arabic digit comparison, subitizing, number writing, and addition as the dependent variable. Penner-Wilger et al. (2007) showed that finger gnosia was a predictor of number system knowledge, which was a summary variable consisting of digit recognition, counting, place value, and numeration. In the present study, the focus was more on the differential impact of finger gnosia on specific numeric and arithmetic tasks such as written subtraction and multiplication operations as well as word problems. Our results are, then, in accordance with the hypothesis that finger gnosia may play a role in certain arithmetic operations but not in others.

FINGER GNOSIA, MATHEMATICS DIFFICULTIES, AND THE GERSTMANN SYNDROME

Similarly to previous studies with neuropsychological patients (see review in Rusconi et al., 2010), the correlations between finger gnosia and other symptoms of the Gerstmann syndrome such as right–left orientation or aggregated visuospatial abilities were weak. In contrast, the correlation between finger gnosia and other numeric and arithmetic abilities tended to be higher. Together, these results are indicative that the deficits presented by MD children have another cause than a Gerstmann-like kind of disorder and are in accordance with previous findings (Rusconi et al., 2009).

Another source of evidence lending support to this conclusion is that finger gnosia deficits in MD children were more pronounced for the left hand than for the right hand. While the Gerstmann syndrome is typically associated with parietal lesions in the hemisphere dominant for language, more pronounced effects of finger gnosia were observed for the non-dominant left hand. Further evidence from neuropsychology as well as structural and functional imaging studies also supports the larger involvement of the non-dominant left hand in finger agnosia. A preponderance of left hand difficulties in sensorimotor and body perception in children with NLD (non-verbal learning disability) was observed by Rourke (summarized by Rourke, 1989). According to Rourke (1989, 1995), preponderant right hemisphere expression of symptoms in NLD may be explained by white matter subcortical dysfunctions, as observed in several genetic syndromes related to the disorder such as Turner and 22q11.2 deletion syndrome (Barnea-Goraly et al., 2003; Molko et al., 2004). Structural imaging techniques of cortical white matter have recently renewed interest in disconnection interpretations of several disorders, including learning disorders (Mitchell, 2011). Some results also point to interhemispheric asymmetries. Rykhlevskaia et al. (2009) observed that, besides gray matter alterations in relevant parietal cortical regions, underlying white matter fractional anisotropy and volume alterations on the posterior right hemisphere were also associated to developmental dyscalculia. Moreover, a hemispheric asymmetry related to magnitude processing in MD children, which indicated a malfunction of the right parietal cortex, has been observed by Kaufmann et al. (2009). In summary, neuropsychologic and imaging studies are suggestive about the existence of a functional link between right parietal functions, finger gnosia in the non-dominant hand, and numeric and arithmetic abilities.

PRACTICAL IMPLICATIONS

Specific deficits in finger gnosia observed in MD children are indicative that measures of finger gnosia may be useful in the early screening of MD (Noël, 2005). Research efforts are currently directed toward identifying cognitive/behavioral markers that could be easily employed by teachers in the identification of children at risk of developing MD (Mazzocco and Thompson, 2005; Geary et al., 2009; LeFevre et al., 2010). Evidence found in the present study advanced the discussion on the search after markers in two different ways. First, finger gnosia abilities differ substantially between MD and TA children. This suggests that finger gnosia can be used as a marker of MD. As reviewed by Beller and Bender (2011), finger abilities are not indispensable for the development of numerical competence, but they could increase children's numerical performance. Moreover, the absence of correlation between *w* and finger gnosia suggest that finger gnosia and acuity of the ANS could be dissociable. Therefore, finger gnosia seems to make an independent contribution to MD.

Research should focus on the relative predictive power of finger gnosia, adding measures of finger gnosia to the characterization of basic numeric abilities. Further studies should also investigate calculation strategies, specifically the use of overt finger representation. Finally, future studies investigating how finger discrimination training may be improved could be a valuable tool in the prevention and rehabilitation of MD (Gracia-Bafalluy and Noël, 2008). As it already occurs in some countries (Guha, 2006), finger discrimination training could be introduced explicitly in the preschool curriculum, thereby helping children to establish a functional bridge between magnitudes and their symbolic representations, facilitating calculation procedures.

In summary, deficits in finger gnosia are associated to MD in 8- to 11-years-old children. Finger gnosia seems to be particularly relevant for the performance in word problems requiring active manipulation of small magnitudes in the range between 1 and 10. Importantly, evidence relating finger gnosia to more complex calculations in a range of magnitudes over 10 was not found. Moreover, the deficits in finger gnosia could not be attributed to a shortage in working memory capacity but rather to a specific inability to use fingers to transiently represent magnitudes, tagging to be counted objects, and thereby reducing the cognitive load necessary to solve arithmetic problems. Since finger gnosia was more related to symbolic than to non-symbolic magnitude processing in our study, finger-related representation of magnitude seems to be an important link for learning the mapping of analog onto discrete symbolic magnitudes.

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Is finger-counting necessary for the development of arithmetic abilities?

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In the literature on numerical cognition, it is generally assumed that fingers play a functional role in the development of a mature counting system (Gelman and Gallistel, 1978; Fuson et al., 1982; Fuson, 1988; Butterworth, 1999a,b, 2005). Indeed, fingers have been assumed to contribute to: (1) giving an iconic representation of numbers (Fayol and Seron, 2005); (2) keeping track of the number words uttered while reciting the counting sequence (Fuson et al., 1982); (3) sustaining the induction of the one-to-one correspondence principle (Alibali and DiRusso, 1999) by helping children to coordinate the processes of tagging (i.e., attribution of a counting word to each item) and partitioning (i.e., isolating the items already counted from those which remained to be counted; Gelman and Gallistel, 1978); (4) sustaining the assimilation of the stable-order principle (i.e., numerical labels have to be enumerated in the same order across counting sequences) by supporting the emergence of a routine to link fingers to objects in a sequential, culture-specific stable order (Wiese, 2003a,b); (5) sustaining the comprehension of the cardinality principle (i.e., the last number word uttered while counting determines the total number of objects in a set) by leading children to always reach the same finger when counting to a specific number (Fayol and Seron, 2005); (6) prompting the understanding of the 10-base numerical system (as on our hands we represent numbers as a sum and/or a multiple of 10); and (7) sustaining the realization of basic arithmetic operations (Baroody, 1987; Fuson and Kwon, 1992; Geary, 1994; Ifrah, 2000).

In line with these assumptions, several studies have reported the existence of a close connection between finger representation and number processing (for a review, see Moeller et al., submitted). At a developmental level, for example, performance on finger discrimination tasks was shown to be a good predictor of arithmetic abilities (Fayol et al., 1998; Noël, 2005). Moreover, the specific sub-base-five structure of the finger-counting system (i.e., the representation of numbers larger than 5 always includes a full hand pattern) was shown to influence numerical processing in infants, hearing adults, and deaf signers (Iversen et al., 2006; Domahs et al., 2008, 2010). Finally, brain imaging studies suggested that the finger schema could rely on the same neuroanatomical substrate (i.e., parietal network) as the processing of numbers (Pesenti et al., 2000; Piazza et al., 2002; Pinel et al., 2004). Accordingly, some authors have suggested that fingers may be the "*missing tool*" (Andres et al., 2008) that sustains the assimilation of basic numerical abilities or the "*missing link*" (Fayol and Seron, 2005) that permits the connection between non-symbolic numerosities and symbolic arithmetic.

In this paper, we will not contest the empirical evidence showing that the use of fingers to represent numbers has a very important impact on numerical cognition. Rather, we will address the question of whether finger-counting is part of a necessary stage for the development of numerical cognition and whether its use is spontaneous in every human child.

If fingers constitute a first and obligatory step in numerical development, then one might expect that children first represent quantities with their fingers before being able to represent them with number words. Similarly, we might expect that during the first developmental stages, children would be more accurate to represent numerosities with their fingers than with number words. To our knowledge, no systematic longitudinal data have been reported on the developmental chronology of fingers use versus number word use. However, interesting transversal observations have been recently published by Nicoladis et al. (2010) who presented either hand shape or number words (from 1 to 10) to 2- to 5-year old children and asked them to put that number of toys in a box. No difference was seen between these two presentation modalities for 2- and 3-year olds who performed equally badly in the two conditions. Yet, for 4- and 5-year olds, performance was actually better with number words than with hand shapes. The authors also presented collections of toys to the children who were asked to say the corresponding number word or to show the correct number of fingers. Again, performance was better with words than with hand shapes. This result does therefore not support the idea that the symbolic numerical system is rooted in our bodily experience. However, it is possible that praxic difficulties contribute to explaining the poor performance obtained by the children in the second task, when required to show a finger configuration corresponding to the number of toys. However, this does not explain the weaker performance in the first task and it also indicates that the use of fingers does not precede the use of language.

Another interesting opportunity to examine whether the finger code facilitates the development of the concept of exact number is the study of homesigners (i.e., deaf children who do not have access to a model for signed language but who nevertheless develop their own gestures to communicate). In their study, Spaepen et al. (2011) examined the numerical abilities of adult deaf homesigners who use their fingers to communicate about numbers. For sets containing more than three items, the number of fingers used to indicate the number of objects in a set was close but most of the time not equal to the number of items to represent. Similarly, homesigners were not able to produce a set of the same number as another one. In some situations, they used their fingers to establish one-to-one correspondence and thus achieved greater accuracy than with pure approximation but they did not use this strategy in all conditions. For instance, they did not use it when asked to produce a set of the same number as a series of sequential events. Importantly, in all these tasks, homesigners performed more poorly than deaf individuals who had learned a sign language. So, despite the fact that homesigners used their fingers to communicate about numbers, they did not consistently and accurately represent the cardinality of sets containing more than three items. So, when fingers configurations used to represent numbers are not embedded in a counting routine, their iconic structure seems insufficient to allow the development of an exact representation of large numbers.

The second question we will address in this paper is whether finger use is spontaneous or whether it requires some modeling. In several contexts, including the resolution of basic additions and subtractions (Geary, 1994), we use fingers to keep track of our counting. We might thus wonder whether this is a spontaneous practice or whether we develop this strategy because we have seen others doing it. Recently, Crollen et al. (2011) compared the spontaneous use of fingers to count and to represent numerical quantities in blind and sighted children. Although these two groups of participants did not differ in terms of basic finger discrimination abilities, blind children used finger-counting strategies significantly less frequently than their sighted peers. Moreover, despite this difference in finger use, blind and sighted children achieved quite similar level of performance in several enumeration tasks. In fact, blind children had weaker performance than sighted controls only when the tasks were very heavy in terms of verbal working memory resources (counting two series in parallel or counting with concomitant articulatory suppression). These data therefore suggest that finger-counting is a useful tool to alleviate the working memory load but not a necessary tool for the emergence of good counting skills. Furthermore, when explicitly asked to count and show quantity with their fingers, the majority of blind children showed unconventional and unstable (changing from trial to trial) configurations of fingers, suggesting that they had used their fingers for the first time. Yet, in a simple addition task, both groups performed equally well. These data suggest that, without the opportunity to watch others using their fingers, many blind children did not spontaneously use their fingers to count or to show numbers. Yet, they were able to keep track of their counting in another manner and to learn basic arithmetic equally as well as sighted controls. These results thus indicate that finger use is not universal or spontaneous but requires some modeling.

In summary, fingers have been assumed to play a crucial role in the development of a mature counting system. However, in this paper, we have presented empirical evidence that constrains this hypothesis. First, in typically developing children, the use of fingers does not precede the use of language. Second, for hearing children, the iconicity of hand shape does not seem to be an advantage for representing numbers. Third, if not embedded in a counting routine, use of finger configuration to represent numbers is not sufficient to allow the development of an exact representation of large numbers. Fourth, models of finger-counting are culturally determined (see Bender and Beller, submitted) and use of fingers is rare when these models are not available (as in blind children). Finally, children who do not use their fingers to count and represent numbers do not show atypical or delayed numerical development. Accordingly, we argue that finger-counting is not a necessary step for numerical development. However, it is undoubtedly a very useful tool (Beller and Bender, 2011; Di Luca and Pesenti, submitted) that allows, among other things, the working memory load to be alleviated and thus perform better in complex numerical tasks. Thus, explicit teaching of this useful tool might be considered in kindergarten, especially in populations where natural access to the social transmission of this system is problematic (e.g., in blind populations).

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Finger numeral representations: more than just another symbolic code

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Representing numerosities with finger configurations offers children the opportunity to learn and internalize fundamental properties of natural numbers through sensory–motor interactions with the world. Recent findings show that even educated adults use their fingers as a visuo-motor support to process, represent, and communicate numerosities. Indeed, using fingers to represent numerosities prototypically has been shown to give the corresponding finger configurations a special status in long-term memory: these configurations are recognized and processed faster than other finger configurations, providing a direct access to number magnitude, what other finger configurations do less efficiently. This occurs for configurations stemming from finger counting (i.e., the way the fingers are raised to count for oneself; for example, thumb, index, and middle fingers for numerosity {*3*}) and from finger montring (i.e., the way fingers are raised to show numerosities to someone else; for example, index, middle, and ring fingers for numerosity {*3*}). However, finger numeral representation is not just another way of representing numerical magnitudes mentally. We argue that it also contributes to acquiring, building, and then accessing number semantics, and that, compared to other numerical representations, it provides an extra value by rooting number meaning in a culturally shared yet non-arbitrary and self-experienced sensory–motor representation.

ACQUIRING NUMERICAL KNOWLEDGE AND MATHEMATICAL CONCEPTS THANKS TO FINGERS

Children from many human cultures use finger-counting strategies to enumerate sets of objects and use their fingers when solving mathematical tasks. They "visually" represent numerosities by raising the same number of fingers as the number of items counted and, by doing this, they get a finger configuration preserving the cardinality of the set. Using finger counting is the first or second most frequent strategy observed in preschoolers during counting and arithmetical tasks (Fuson, 1982), importantly even when no explicit instructions to use their fingers have been given (Siegler and Shrager, 1984). Their use during basic arithmetical learning has been extensively studied (e.g., Fuson, 1988), and internal traces of these external strategies may still affect calculation in children even when finger counting is no longer overtly used. For example, children's typical split-5 errors in addition and subtraction (e.g., 12–5 = 2) may stem from an interiorized finger-counting strategy using a sub-base 5 represented with a full-opened hand (Domahs et al., 2008). Using the same finger configuration repeatedly to represent a given numerosity for oneself or to show it to others gives this configuration a special iconographic status and, as shown below, also a symbolic one. Likewise, the use of a stable, culturally determined – and probably partly constrained at the motor level – sequence of finger movements while counting allows children to remember the sequence of counted elements by establishing a *one-to-one correspondence* between the raised fingers and the objects, and to better understand and develop numerical concepts such as *cardinality* and *ordinality*, or the *first element* and *unique immediate successor–predecessor* principles. For these reasons, finger counting has been considered as a mediator between an inner rough number sense and a developed, symbolically represented, number concept (Fayol and Seron, 2005; Andres et al., 2008). It explains why tactile discrimination is strongly related to arithmetical competencies. As a matter of fact, the score obtained in finger discrimination tasks is the best predictor of arithmetical performance in 5- to 8-year old children (Fayol et al., 1998; Marinthe et al., 2001; Noël, 2005), and training in finger differentiation to increase finger gnosis can improves untrained mathematical skills (Gracia-Bafalluy and Noël, 2008).

This influence of fingers on the acquisition of numbers and numerical concepts is also indicated by several historical and linguistic facts. Indeed, "handling" numerosities not only improved human mathematical competencies (Butterworth, 1999), it probably gave rise to our positional base-10 numerical system rather than others (e.g., a base-12 one), which possess some arithmetical advantages (e.g., more divisors) and are thus more suitable for geometric calculus and algebra. This occurred not in a few limited cultural groups, but in many different cultures across human history. There are numerous archeological traces (e.g., artifacts such as reliefs and mosaics) of finger-counting strategies in ancient cultures (Boyer, 1968; Ifrah, 1981), and numerous references to finger counting or finger calculation in Greek and Roman manuscripts (Williams and Williams, 1995). Around two thirds of several hundred Native American tribes used base-5 or base-10 systems derived from finger counting (Eels, 1913; cited in Boyer, 1968), and several studies have described in detail how indigenous Papua New Guineans use their fingers and body parts while counting (Lancy, 1978; Saxe, 1982). An additional piece of evidence concerns the origin of number names themselves. In various languages, number names stem from an ancient embodied vocabulary referring to fingers (e.g., in English, *digit* means at the same time *number* and *finger*; *five* comes from a common root of *finger* and *fist*; Menninger, 1969), supporting the idea that counting originates from the use of fingers rather than from arbitrary quantitative words.

ACCESSING NUMBER SEMANTICS THROUGH FINGER NUMERAL REPRESENTATIONS DURING ADULTHOOD

Besides these developmental and cultural pieces of evidence, recent findings in adults show that finger counting shapes number processing and calculation throughout life, and that finger numeral representations do not disappear when symbolic numerical representations develop. On the contrary, their critical impact is still observed in educated adults.

Firstly, finger-counting strategies influence the way numerical information is projected onto physical space and induces compatibility effects, at least at the level of motor outputs. For example, personal finger-counting habits were found to actively interact with Arabic digit processing during a number-to-finger mapping task. When asked to identify Arabic digits by pressing a key with 1 of their 10 fingers, participants produced faster responses when the mapping between the Arabic digits and the fingers matched their own finger-counting habits than with other mappings (Di Luca et al., 2006). This is also evidenced in parity judgments by a specific increase in motor-evoked potentials for the right hand only when small numerosities are processed by adults who show a prototypical finger-counting sequence starting with the right hand (Sato et al., 2007). Personal finger-counting habits could even mediate the well-known association between space and numbers (i.e., small numbers being associated with the left space, and larger numbers with the right; Dehaene et al., 1993), as they seem to modulate the strength of this association (Fischer, 2008).

Next, finger numeral representations exert their influence even when no motor outputs are required. For example, just like children (Noël, 2005), adults name finger configurations faster when they conform to their own finger-counting habits than when they do not (Di Luca and Pesenti, 2008). This facilitation in the naming of canonical configurations is not a mere perceptual effect but truly reflects semantic access. Indeed, numeral finger configurations used as unconsciously presented primes influence comparative judgments of Arabic numeral targets: the participants respond faster to and make fewer errors with numerical than with non-numerical primes, and when the primes and targets are congruent (i.e., lead to the same response), but this priming effect generalizes to new, never-consciously seen, numerosities for canonical configurations only, not to non-canonical ones. Furthermore, mere visuo-perceptual differences are not the source of the better identification of and semantic access to canonical configurations. When participants have to decide whether a canonical configuration is present among a set of distractors expressing the same numerosity in a non-canonical way, the time to detect the presence of the target grows linearly with the number of distractors showing that canonical targets enjoy no perceptual saliency (i.e., no *pop-out* effect; Di Luca and Pesenti, 2010). Most interestingly, a recent study shows that canonical configurations are processed in the same way as other symbolic notations (Di Luca et al., 2010). When participants named Arabic and verbal numerals primed by canonical and non-canonical finger numeral configurations, canonical configurations primed target numbers to which they were close, whether they were smaller or larger than the target, with the extent of activation being inversely proportional to the distance between the prime and the target. This results in a *V*-shaped pattern of priming, supporting the idea that canonical configurations, although not supported by a written system, activate representations with the same properties as those activated by verbal or Arabic numerals (i.e., a place-coding representation; Roggeman et al., 2007).

Finally, finger numeral representations also have an impact on arithmetic. In a recent study (Badets et al., 2010), participants provided a verbal response to simple additions, which triggered the presentation of a correct or incorrect result displayed either as canonical configurations of fingers or as a series of rods. They answered more quickly with finger configurations than with rods, but only when the finger configurations showed the correct response. This supports the idea that, even in adults, simple arithmetic operations are still unconsciously underpinned by finger numeral representations.

EXTRA VALUE CODE?

Given these findings in children and adults, finger numeral representations (whether they come from finger counting, finger montring, or other personal ways of using fingers to represent numerosities) certainly 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. But is that all? Are finger numeral representations nothing but another way of representing numbers, mainly small ones, mentally? What, after all, makes them so special for numerical cognition?

We believe and argue that finger numeral representations are more than just another way of mentally representing numerosities. Firstly, they possess almost all the properties presented separately by the other representations (i.e., visual, verbal, and analog). Although they are optimal only for small numerosities and they are not linked to a written notation, they possess simultaneously iconic (i.e., features shared with the referent), symbolic (i.e., conventional meaning shared with other individuals), computational (i.e., used to support calculation procedures), and communicative (i.e., used to communicate numerosities through gestures with other individuals whatever their language) properties. Secondly, and most importantly, all these properties rely on perceptual and sensory–motor processes that provide a non-arbitrary link between the symbols (here, finger configurations) and reality (here, numerosity), and that can be spontaneously self-experienced by every human child and adult. In contrast, other representations only possess some of these properties and they cannot be inferred and acquired without external influence. Visual and verbal representations serve a communicative purpose because they are shared among individuals, but they possess no numerical meaning and very little can be inferred from them by the cognitive system as they stand for symbolic notations (respectively, verbal and Arabic numerals) composed of totally arbitrary symbols. For example, "6" and "six" can unambiguously be communicated and understood, but no numerical meaning can be inferred from either their physical traits, or their mental representation. An analog number line can easily represent continuous and large numerical quantities and their ratio, but it cannot easily serve the purpose of accurate communication. Moreover, except in very few people who explicitly develop a spatio-linear representation of numbers (Galton, 1880; Seron et al., 1992), there is no evidence of a spontaneously self-practiced linear medium underlying and guiding early numerical learning. Rather, early numerical competencies may simply rely on some perceptual object-tracking system (Simon, 1997; Uller et al., 1999; Mix et al., 2002), the association between numbers and space leading to a linear representation being constructed by exposure to cultural conventions (Dehaene, 1997; Simon, 1999), such as reading–writing direction. By contrast, the very act of using fingers to represent numerosities seems quite spontaneous – what is culturally determined is the sequence in which fingers are raised – and can guide early numerical learning. In other words, a number line is most probably the best conceptual representation induced by the cultural environment, whereas finger numeral representations are the best empirical representation, which can be deduced from personal sensory–motor experience.

CONCLUSION

Recent findings show that finger numeral representations possess many characteristics of the other numerical representations postulated in classical cognitive number architectures. Among others, they, like other symbolic notations, are shared by individuals of the same cultural group, they can be used to communicate numerosities and to calculate, they possess iconic properties preserving cardinality, and place-coding properties. Most importantly, they have specific sensory–motor properties preserving numerical properties and allowing mathematical principles to be inferred and experienced. Thus, they are not just a way of mentally representing (in the sense of "standing for") numerosities as other representations do; they represent and, at the same time, can help to build or, at least, improve the concept of number. We do not intend to claim that finger numeral representations replace all other representations, or that without finger-counting activities, human beings could not develop an accurate concept of number. But finger-counting/montring activities, especially if practiced at an early age, can contribute to a fast and deep understanding of number concepts, which has an impact during the entire cycle of life by providing the sensory–motor roots onto which the number concept grows.

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Multimodal semantic quantity representations: further evidence from Korean sign language

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Korean deaf signers performed a number comparison task on pairs of Arabic digits. In their response times profiles, the expected magnitude effect was systematically modified by properties of number signs in Korean sign language in a culture-specific way (not observed in hearing and deaf Germans or hearing Chinese). We conclude that finger-based quantity representations are automatically activated even in simple tasks with symbolic input although this may be irrelevant and even detrimental for task performance. These finger-based numerical representations are accessed in addition to another, more basic quantity system which is evidenced by the magnitude effect. In sum, these results are inconsistent with models assuming only one single amodal representation of numerical quantity.

Keywords: finger-counting, number comparison, magnitude effect, numerical size, Arabic digits, embodiment, hand posture orientation, motor imagery

INTRODUCTION

Numerical cognition can be conceived as a distributed cognitive function, meaning that it requires interactive processing of information gained from both internal and external representations (Zhang and Norman, 1995; Zhang and Wang, 2005). For instance, when we have to compare two numbers regarding their numerical magnitude, we not only need to process information from internal representations (e.g., knowledge about the magnitude of the numbers), but also information from external representations (e.g., visuo-spatial properties of the symbols). In the present paper we explore the possibility that internal (i.e., mental) quantity representations are multimodal such that innate analog representations are complemented by representations based on different cultural tools (e.g., number words, Arabic numbers, finger-counting habits) which may affect performance even in simple numerical tasks. In the following, we will first shortly summarize evidence for innate analog quantity representations. Afterward, evidence for effects of culturally developed representations on numerical tasks will be reviewed. Finally, we will outline the rationale of the present study.

INNATE ANALOG QUANTITY REPRESENTATION

There is widespread agreement that humans share a basic internal representation of numerical quantity with higher vertebrates (Feigenson et al., 2004; Beran, 2007; Cantlon and Brannon, 2007; Agrillo et al., 2011). Using this representation, animals as well as human infants are able to decide which of two sets of objects is the numerically larger one (i.e., contains more elements) in a magnitude comparison task. Usually, performance in this kind of task is affected by the ubiquitous magnitude effect, i.e., response times (RT) and error rates increase with the numerical size of the operands involved (Restle, 1970; Brysbaert, 2005; Verguts et al., 2005; Dehaene, 2007). It has been suggested that the magnitude effect can be traced back to the spiking characteristics of specific number-sensitive neurons in prefrontal and parietal cortices, which respond increasingly diffuse to increasing numerical magnitude (Nieder, 2005). A related psychological effect is the so-called distance effect, which describes the observation that discriminating between two numbers gets easier (reflected by decreasing RT and error rates) as the numerical distance between the numbers increases. Both the magnitude and the distance effect have become hallmark effects associated with quantity processing and are addressed by virtually every model of numerical cognition. Although found in humans as well as non-human animals, it has been shown that both the effects of numerical magnitude and numerical distance decrease with education (Pica et al., 2004; Halberda and Feigenson, 2008). Decreasing magnitude and distance effects during the course of education have been attributed to an increasing degree of precision of the internal magnitude representation.

CULTURAL TOOLS OF QUANTITY REPRESENTATION

Improving precision of the human analog quantity representation during development is accompanied by the acquisition and use of culturally bequeathed number notations such as number words, Arabic digits, and finger-counting gestures (Pica et al., 2004; Halberda and Feigenson, 2008). How does the use of culturally developed number systems influence the innate analog quantity representation? The exact nature of this interaction is still under debate. Three different scenarios seem possible: first, the internal analog quantity representation, which is often described by the metaphor of a mental number line (Dehaene and Cohen, 1995; Dehaene, 2003), may be influenced by external representations such that it increases its acuity (Verguts and Fias, 2004; Dehaene, 2007) and/or adopts the base-10 structure of the Arabic number system (Nuerk et al., 2001, 2004a; Nuerk and Willmes, 2005; Verguts and De Moor, 2005; Moeller et al., 2011). Second, the inherited analog quantity representation may be replaced by a symbolic quantity representation. One proposal of this type assumes that the internal quantity representation is abstract and similar to the place-value system of the Arabic number system and most number word systems (McCloskey and Macaruso, 1995). Unfortunately, this model is silent about the nature of the transition from analog to symbolic representation and about the fate of the innate analog quantity representation.

Note that both accounts of semantic quantity representation mentioned so far (i.e., the analog mental number line and the abstract place-value system) assume that there is only one amodal representation of quantity employed across all types of stimuli and tasks (e.g., Libertus et al., 2007; Santens et al., 2009). With respect to the first account by Dehaene and Cohen (1995) it is true that the Triple-Code model proposes three different representational codes. However, only one of these three codes (i.e., the analog magnitude code) reflects a semantic representation of quantity. Input from the other two codes (i.e., visual Arabic or verbal) needs to be transcoded to the analog magnitude code to access quantity information. Even more evident is this central amodal quantity representation in the model by McCloskey (1992). The so-called Abstract Code model (McCloskey, 1992; McCloskey and Macaruso, 1995) proposes that its subsystems (comprehension, calculation, and response production) communicate through a single abstract semantic quantity code. The comprehension subsystem transforms different numerical inputs into the abstract code on which calculation and response generation subsequently operate. Access to this abstract code is necessarily required before any other numerical process is possible. In particular, the calculation subsystem operates only on this code. Finally, the production subsystem transcodes the abstract code into Arabic, written, or spoken verbal number formats again as required by the task at hand. Taken together both the Triple-Code model and the Abstract Code model assume a single amodal representation of quantity. In line with this, the dominant view in numerical cognition research claims that "robust evidence demonstrates that with or without language, number is represented abstractly – independently of perceptual features, dimensions, modality, and notation [as] in fact, this is the very definition of *number*." (italics added, Cantlon et al., 2009, p. 332; see also Cohen Kadosh and Walsh, 2009 and invited commentaries for a comprehensive discussion of this point).

Nevertheless, this view is in contrast to a third type of models which assert that there is a multitude of semantic number representations, including internal analog and symbolic quantity representations, which are used depending on the type of stimuli and task at hand (Campbell and Clark, 1992; Campbell, 1994; Cohen Kadosh and Walsh, 2009). Typically, these models are rather vague, both in terms of developmental aspects and in specifying the exact interactions of the different internal representations assumed for a given task (although attempts have been made to address both issues, e.g., Cohen Kadosh and Walsh, 2009; Kucian and Kaufmann, 2009). Nevertheless, they seem easily ready to integrate finger-based quantity representations. Such finger-based representations have been assumed to play an important role at least for small quantities (Di Luca and Pesenti, 2011).

The behavioral impact of symbolic representations in numerical tasks has been described repeatedly. For instance, the base-10 structure of the Arabic number system and most number word systems (i.e., the most frequently used symbolic representations) is reflected in several numerical effects:

(i) The carry effect in mental addition: the influence of a carry operation on task performance is probably one of the most robust findings in multi-digit addition. Arithmetic problems requiring a carry operation, because the sum of the units is equal or larger than 10 (e.g., $47 + 18 = 65$; unit sum $7 + 8 = 15$), are usually associated with decreased performance (mirrored by larger RT and error rates) than addition problems not requiring a carry (e.g., $52 + 13 = 65$; Ashcraft and Stazyk, 1981; Fürst and Hitch, 2000; Deschuyteneer et al., 2005; Kong et al., 2005; Imbo et al., 2007; Klein et al., 2010a,b).

(ii) The decade consistency effect in multiplication: multiplication errors are influenced by positional consistency, where consistency means that the error and the correct result share the same digit at the same place-value position (Campbell, 1994; Verguts and Fias, 2005a,b). For instance, the error $7 \times 3 = 28$ will be more likely than the error $7 \times 3 = 14$, because 28 and the correct result 21 share the same decade digit. Verguts and Fias (2005a,b) termed this finding neighborhood consistency: consistent neighbors share their decade digit with each other. Neighborhood consistency provides an alternative way to explain multiplication effects that were previously not associated with multi-digit structures, namely problem size-, five-, and tie-effects (see Verguts and Fias, 2005a,b, for details). The theoretically postulated consistency effect was demonstrated by Domahs et al. (2006) in a reanalysis of multiplication production data reported by Campbell (1997). Multiplication problems with many consistent neighbors tended to be less error-prone, but whenever an error occurred, it was more likely to be a consistent neighbor than an inconsistent one (see also Campbell et al., 2011). The consistency effect was replicated by Domahs et al. (2007) in an ERP study using a verification paradigm. Obviously, consistency effects cannot exist for single-digit numbers. Thus, these effects show that multiplication fact retrieval performance cannot be fully understood without taking into account structural properties of the symbolic format of input, output, and/or internal representation (i.e., multi-digit Arabic numbers or number words).

(iii) The unit-decade compatibility effect describes an aspect of multi-digit number magnitude processing performance in a magnitude comparison task. The effect is driven by the place-value structure of to-be-compared numbers. A number pair is termed unit-decade compatible whenever separate decade and unit digit comparisons lead to the same decision (as for the pair 42_57, 4 < 5, and 2 < 7) and incompatible when unit and decade comparisons lead to different decisions (47_62; 4 < 6, but 7 > 2). Since its discovery by Nuerk et al. (2001), several studies in children and adults have shown that incompatible number pairs are processed slower and with more errors than compatible pairs (Nuerk et al., 2002, 2004b, 2005).

In sum, in all the examples mentioned, behavioral traces have been observed which suggest that numerical representations are not perfectly smooth, but that there are decade breaks in the quantity representation. However, in all these cases, the base-10 structure was part of the external, i.e., stimulus representation (Arabic digits or number words) and potentially also of the putative internal quantity representation (which could be an abstract base-10 system as proposed by McCloskey and Macaruso, 1995), such that it is impossible to disentangle external from internal representational effects.

THE PRESENT STUDY

The present study aimed at investigating whether there is only one single amodal (analog or symbolic) internal quantity representation or rather several different, interacting internal quantity representations (Campbell and Clark, 1992; Campbell, 1994; Cohen Kadosh and Walsh, 2009). To address this question, we made use of peculiarities of culturally developed number representations (i.e., canonical finger-counting patterns) which are not part of the external stimulus representation employed in the task (Arabic numbers). It is important to note that finger-counting was not required in the current task neither for processing the stimuli nor for providing the response. With regard to finger-counting habits two things are important to the present study. First, canonical numeral finger configurations are shown to have a special status compared to non-canonical ones (Di Luca and Pesenti, 2008). Second, canonical configurations are highly diverse across cultures (Bender and Beller, 2011).

The present investigation is based on an approach successfully adopted by Domahs et al. (2010). In a number comparison task employing Arabic digits as input format, the authors found the magnitude effect (reflecting the analog quantity representation) to be modified by the number of Arabic digits, i.e., number pairs with different number of digits (8_10 and 9_11) were responded to faster than pairs with the same number of digits. Crucially, the magnitude effect was also modified by the number of hands involved in number signs, such that Arabic numbers associated with two-handed number signs yielded relatively long RTs. While the number of Arabic digits effect can in principle be related to properties of both external and internal representations, the number of hands effect can only be driven by internal representations as it is no feature of the input format (Arabic digits). Furthermore, the fact that the number of hands effect was only present in those cultural groups using two-handed number signs (hearing Germans and deaf German signers) but not in hearing Chinese, who use one-handed number signs in the relevant number range from 6 to 9 (see **Figure 2**), further supported the interpretation that hand-based internal number representations were activated, even though they were irrelevant and even detrimental to the task. Given that the analysis indicated specific slowing associated with two-handed number signs, Domahs et al. (2010) argued for an interpretation in terms of motor imagery involved to represent quantity in addition to some other (probably analog) quantity representation.

In the current study, we examined users of a different finger-counting system – Korean sign language (KSL). KSL involves some interesting properties which are neither part of the finger-counting systems previously investigated nor included in the Arabic digit system (see **Figure 1**):

a) Similar to other finger-counting systems in which only one hand is used to represent numbers larger than 5, there is a break between transparent and symbolic quantity representation. This means that only representations of small numbers allow for a one-to-one correspondence between the fingers raised and the objects to be counted. However, in contrast to most of these systems, the transparency limit does not appear between 5 and 6 (see **Figure 2** for the example of Chinese), but already between 4 and 5 in KSL number signs. Domahs et al. (2010) suggested that number comparison crossing this transparency limit may lead to a small but significant relative RT increase. Thus, we hypothesize that it may be more demanding to compare a pair of numbers, in which one number is represented transparently and one symbolically (i.e., 3_5 or 4_6 in KSL) than a pair of numbers where both items are either transparently or symbolically signed (i.e., all remaining number pairs).
b) In KSL numbers are signed with different hand orientations, i.e., the observer sees either the palm or the back of the hand. We hypothesized that the comparison of number pairs, where both numbers are signed in a different orientation (e.g., 4_6 or 18_20), may lead to prolonged RT as compared to the comparison of pairs with same hand orientation (e.g., 2_4 or 7_9).
c) Finally, some signs in KSL (11, 15, and 16) require a sequential movement of the same hand. This may lead to a relative RT increase for all comparisons between pairs which contain such a number.

In sum, using a simple number comparison task with pairs of Arabic digits, we expected to find (i) the standard magnitude effect, associated with the internal analog quantity representation. In line with findings reported by Domahs et al. (2010) we also expected (ii) a number of digits effect such that number pairs in which one number was represented by a single Arabic digit and the other by two Arabic digits (i.e., 8_10 and 9_11) should be responded to significantly faster than to be expected on the basis of their magnitude. This could be interpreted as an

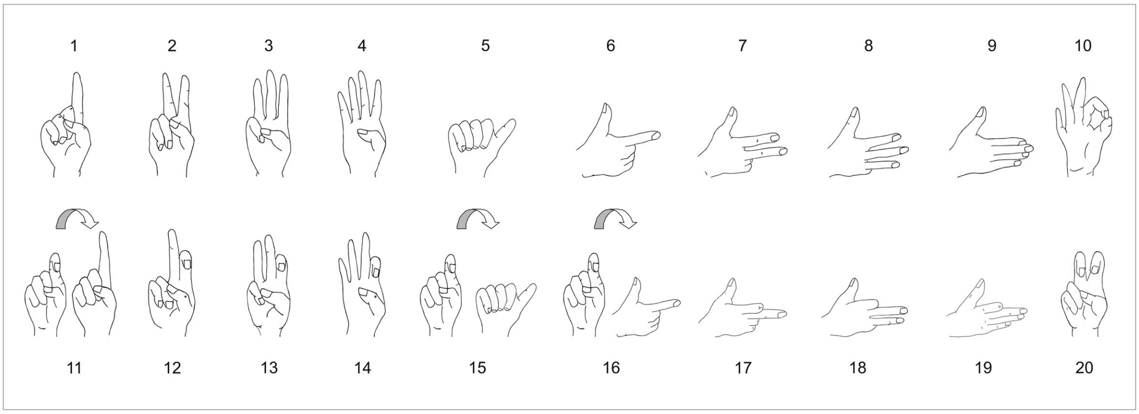

FIGURE 1 | Finger-counting system in Korean Sign Language from the viewer's perspective. Note that numbers 11, 15, and 16 are signed in a sequential movement of the same hand.

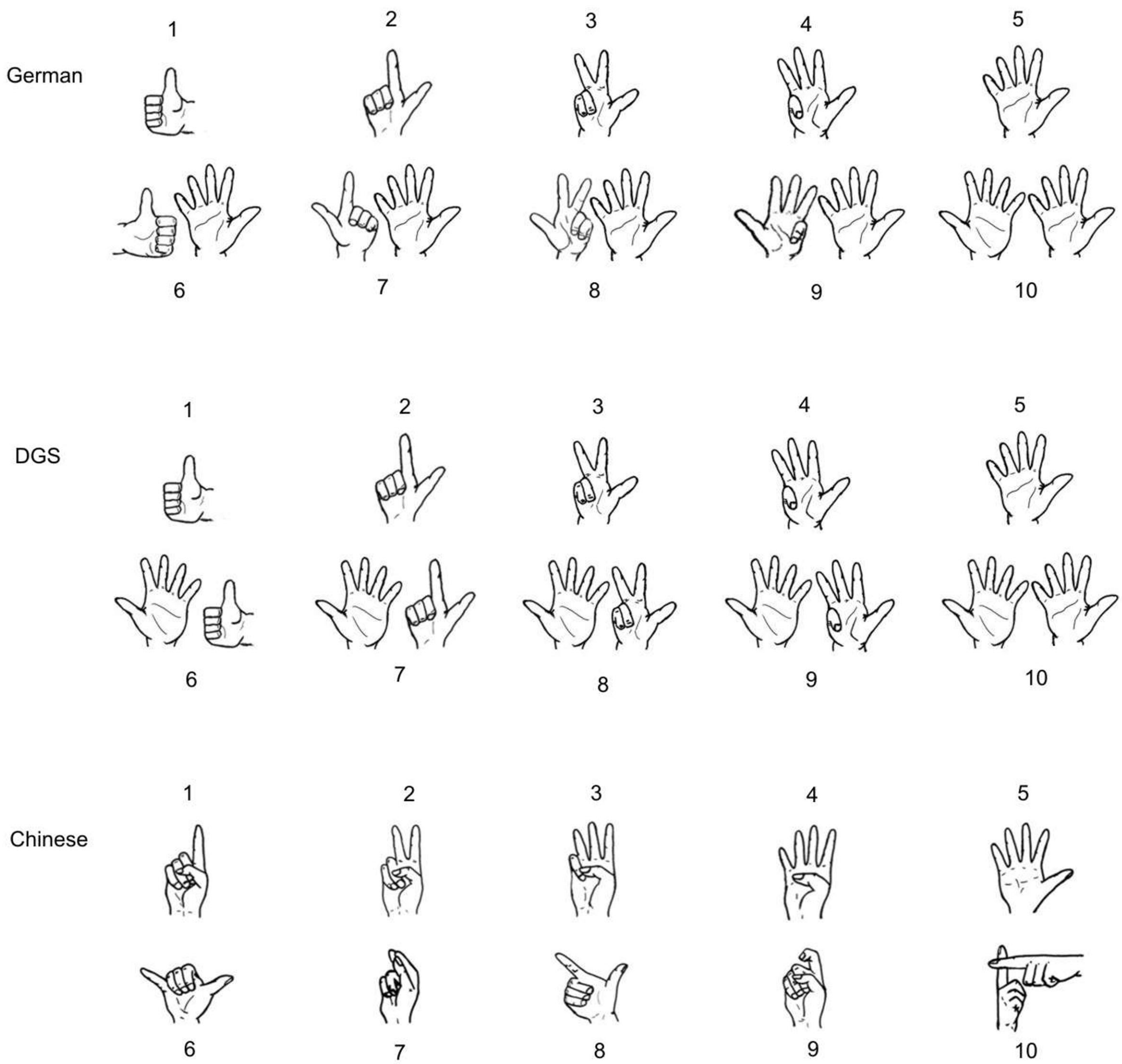

FIGURE 2 | Finger-counting systems in German, German Sign Language (DGS), and Chinese (Domahs et al., 2010). Reprinted with permission.

effect of the external stimulus representation. Crucially, we also expected to find (iii) influences of characteristic properties of the KSL number sign system (transparency limit effect, hand orientation effect, or sequential movement effect), which are not predicted by models assuming an amodal semantic quantity representation. Therefore, if such effects were observed in a culture-specific way, they would witness the multimodal nature of internal quantity representations.

MATERIALS AND METHODS

PARTICIPANTS

Twenty-five Korean deaf signers, enrolled as undergraduate students at the Korea Nazarene University, Cheonan, took part in the experiment. Data sets of two participants had to be excluded from analyses due to failure in data recording. Mean age of the remaining 23 (11 females) participants was 22.1 years (SD = 1.6). On average, they have received 14.4 (1.1) years of formal education. All were right-handed according to their own disclosure, had normal or corrected-to normal vision and reported no mathematical deficits. All participants used KSL as their primary language although mean age of acquisition of KSL was relatively late (mean = 9.0, SD = 4.4). Nevertheless, participants' counting habits were evaluated prior to the experiment confirming that all used the KGS finger-counting system depicted in **Figure 1**. All participants gave their informed consent to take part in the study.

STIMULI

The same stimulus set was used as described by Domahs et al. (2010). All number pairs with a distance of 2 within the number range from 1 to 20 were shown in both orders (i.e., 1_3 to 18_20 and 3_1 to 20_18, respectively). Stimuli were presented in central position as Arabic digits in black Arial 60 pt font against a white background. Both numbers were presented in the same line separated by seven blanks.

PROCEDURE

Instructions were given in written Korean (Hangul) and, additionally, in KSL. Participants were instructed to answer as fast and accurately as possible. Half of the participants started with the instruction to indicate the smaller number by a corresponding button press while the other half was instructed to indicate the larger number. Response keys were the "S" key and the "L" key on a standard keyboard. After the first half of the experiment, response assignments were reversed. For each response assignment, each number pair was presented five times per order (i.e., five times 4_6 and five times 6_4). Thus, the presentation of 36 number pairs × 5 repetitions × 2 response assignments led to a total of 360 experimental trials separated in five blocks per response assignment, each block including all 36 number pairs in randomized order. Each response assignment was preceded by an additional training block of all 36 number pairs. Training results were not included in the analyses.

Each trial started with a blank screen (500 ms), followed by the presentation of a fixation cross in central position (200 ms) and another blank screen (200 ms). Then, the number pair was presented until one of the response buttons was pressed or the time limit of 2000 ms was reached. Trials were initiated in a self-paced manner, i.e., participants pressed the space-bar on the keyboard to proceed to the next trial.

ANALYSES

There was no speed–accuracy trade-off as indicated by a non-reliable negative correlation between mean RT and error rate ($r = -0.14$, $p = 0.54$). Incorrect responses or RT falling outside the interval of ±2.5 SD from the individual mean were excluded from the analyses. This resulted in a loss of 7.5% of data points.

The influence of the structure of different external and hypothesized internal representations on symbolic number processing was assessed by a linear mixed-effects regression analysis on mean RT per number pair. The following measures of external and internal representations were entered: first, a variable coding the presence or absence of a different number of Arabic digits (coded as −1 for pairs 8_10 and 9_11 and +1 for other pairs) was included to represent characteristics of the Arabic stimulus format. Second, numerical magnitude [i.e., the natural logarithm (ln) of the mean of each number pair] and parity (coded as +1 for odd and −1 for even pairs) were used as predictors reflecting basic semantic number representations. Finally, the following predictors were included, representing potential hand-based internal representations: transparency limit (coded +1 for pairs where one number is represented transparently and one number symbolically in KSL, i.e., 3_5 and 4_6, and coded −1 for other pairs), hand orientation (coded +1 for pairs with different hand orientation in KSL, i.e., 4_6, 5_7, 8_10, 9_11, 14_16, 15_17, 18_20, and −1 for other pairs), and movement sequence (coded +1 for pairs where at least one number is signed in a one-handed movement sequence in KSL, i.e., 9_11, 11_13, 13_15, 14_16, 15_17, 16_18, and −1 for other pairs). The contribution of these variables to the goodness of fit of the model was evaluated within the linear-mixed-effects model (lme) framework, using the lme4 package (Bates, 2007) in the R system for statistical computing (R Development Core Team, 2006). Both participants and number pairs were treated as random factors.

Moreover, intergroup differences comparing our present data of deaf Korean signers with data from participant groups (hearing Germans, deaf German signers, and hearing Chinese participants) previously reported by Domahs et al. (2010) were evaluated using one-way ANOVAs.

Finally, a stepwise discriminant analysis was conducted over mean RTs for all number pairs (1_3 to 18_20) to investigate how well the four groups of participants could be differentiated. Using the leave-one-out procedure as a cross-validation method to prevent underestimation of error classification probabilities, the best discriminating number pairs were used to classify individual RT-profiles into one of the four cultural groups.

RESULTS

VARIABLES INFLUENCING SYMBOLIC NUMBER COMPARISON IN KSL PARTICIPANTS

The resulting final model of the linear mixed-effects regression analysis is presented in **Table 1**. Individual participants varied substantially, as did individual number pairs, which was confirmed by log-likelihood tests for both random effects. As can be seen in **Table 1**, the differing number of Arabic digits, numerical magnitude as well as hand orientation turned out as significant predictors ($t > 2$), while all other effects (parity, transparency limit, and movement sequence failed to explain significant amounts of additional variance. Specifically, the comparison of two Arabic numbers became relatively slower with increasing numerical magnitude and when KSL hand orientation differed for the to-be-compared numbers, whereas RT became relatively faster when a one-digit Arabic number had to-be-compared with a two-digit Arabic number (see **Figure 3**).

CROSS-CULTURAL COMPARISONS

With respect to global mean RT and RT increase (slope of a logarithmic fitting curve), KSL participants did not differ significantly from hearing Germans, deaf German signers, and hearing Chinese participants as reported by Domahs et al. (2010): mean RT was 566 ms (SD = 79 ms) for Korean deaf signers, 617 ms (104 ms) for hearing Germans, 594 ms (99 ms) for German deaf signers, and 569 ms (80 ms) for hearing Chinese participants [$F(3, 95) = 1.69$, $p = 0.17$]. Mean slope was 0.081 (SD = 0.044) for Korean deaf signers, 0.085 (0.034) for hearing Germans, 0.085 (0.026) for German deaf signers, and 0.094 (0.025) for hearing Chinese participants [$F(3, 95) < 1$].

However, these globally similar RT patterns were modulated differentially by local effects, as evidenced by different patterns of residuals from individual logarithmic fittings (see **Figure 4**; fitting procedure described in detail in Domahs et al., 2010). These local effects seem to be culture-specific. Interestingly, different hand orientation, a variable significantly contributing to the variance explained by the mixed-effects regression model on mean RTs per number pair and KSL participant (see above), did not improve regression models for hearing Germans, deaf German signers, or hearing Chinese. Note that this is the expected result in case this variable indeed reflects specific properties of KSL finger-counting (not present in the other systems) rather than some artifact (which may also be existent in the other cultural groups).

Finally, in a stepwise linear discriminant analysis a two-dimensional discriminant function space allowed for the significant differentiation of the four groups of participants (see **Table 2**; **Figure 5**). The variables selected for inclusion in the discriminant function space were mean RTs for the four number pairs 10_12, 8_10, 6_8, and 11_13. Using these four best discriminating number pairs, it was possible to classify a total of 57.6% of all cases correctly into one of the four cultural groups (using the leave-one-out procedure as a cross-validation procedure to prevent underestimation of error classification probabilities). Performance was best for deaf Korean signers (91.3% correctly classified) and Chinese participants (74.1% correctly classified), while RT-profiles of both German groups of participants lead to a large degree of overlap between the latter two groups (see **Table 2**).

Table 1 | Regression coefficients with associated SE and *t*-values from the analysis of mean RTs from Korean deaf signers.

Random effects	**Variance**		
Participants	6377.7		
Number pairs	209.0		
Residual	1584.4		
Fixed effects	**Estimate**	**SE**	***t*-value**
Intercept	**452.1**	**22.8**	**19.8**
Different number of Arabic digits	**33.4**	**7.4**	**4.5**
Magnitude	**43.0**	**7.3**	**5.9**
Parity	−0.9	4.1	−0.2
Transparency limit	1.2	7.0	0.2
Hand orientation	**10.3**	**4.8**	**2.1**
Movement sequence	6.3	7.2	0.9

Significant predictors are highlighted in bold face. For a detailed explanation of predictors, see Section "Materials and Methods."

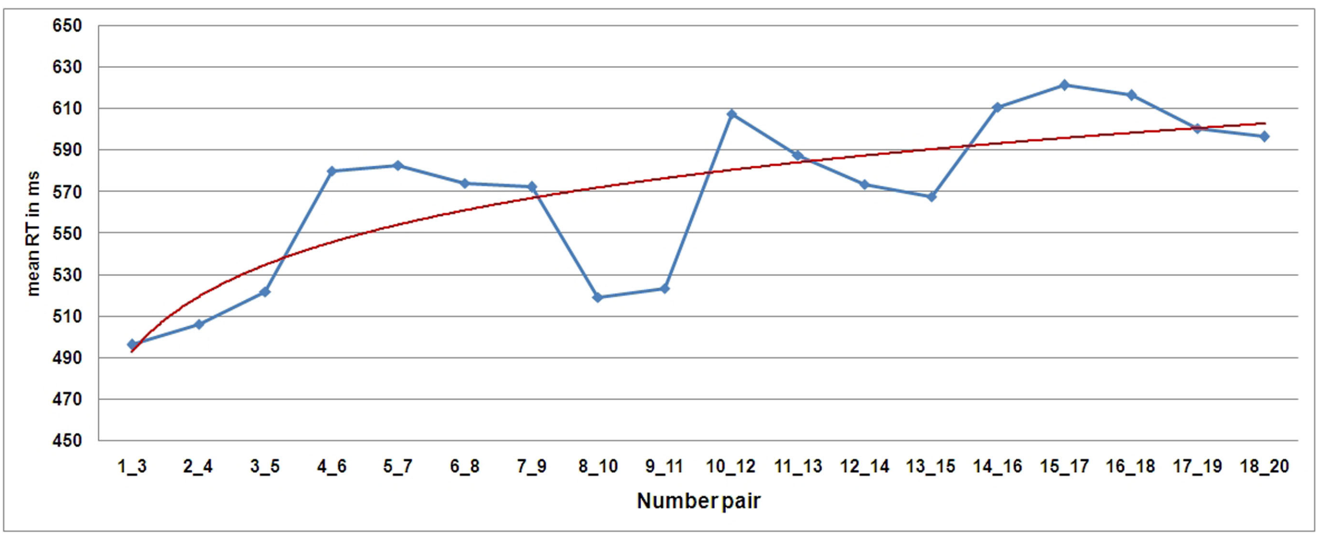

FIGURE 3 | Mean reaction times per number pair (blue line) and logarithmic fitting (red line) of KSL participants ($n = 23$). For a description of the fitting procedure see Domahs et al. (2010).

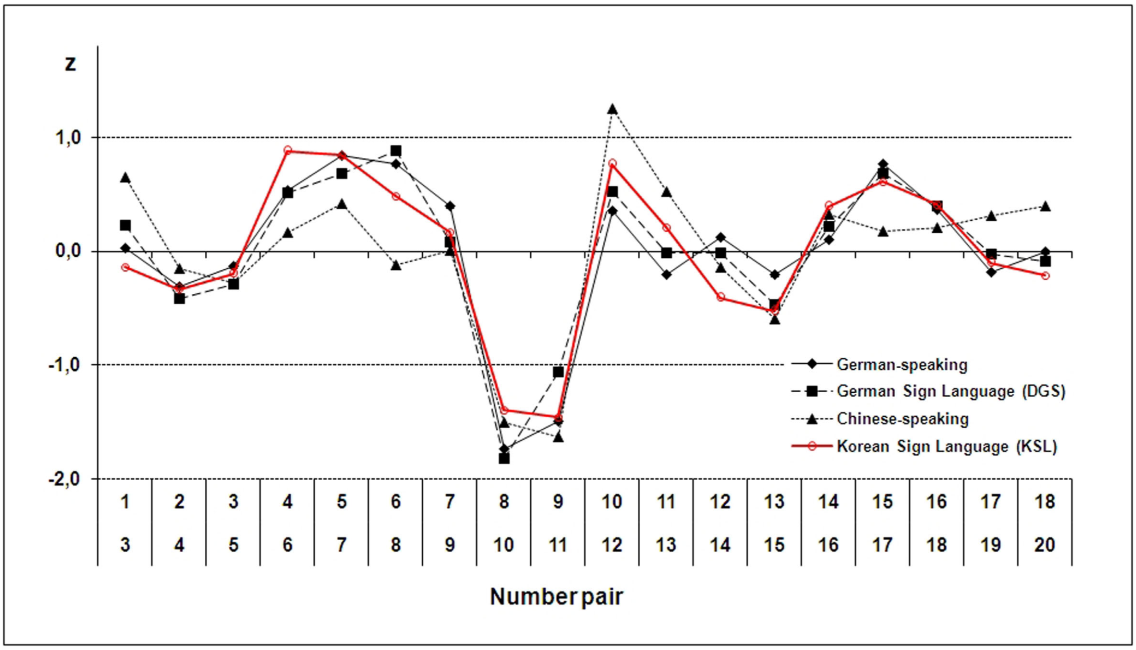

FIGURE 4 | Standardized residuals for Korean deaf signers (red line) and three different participant groups performing the same task. Details on hearing German, deaf German, and hearing Chinese participants and the standardization procedure are reported by Domahs et al. (2010).

Table 2 | Classification of cases based on the stepwise linear discriminant function analysis using a leaving-one-out cross-validation procedure (see also Figure 5).

Actual group	Predicted group			
	hearing German	**DGS**	**Chinese**	**KSL**
Hearing German (24)	**8 (33.0)**	12 (50.0)	3 (12.5)	1 (4.2)
DGS (25)	10 (40.0)	**8 (32.0)**	7 (28.0)	0 (0.0)
Chinese (27)	3 (11.1)	2 (7.4)	**20 (74.1)**	2 (7.4)
KSL (23)	0 (0.0)	1 (4.3)	1 (4.3)	**21 (91.3)**

Indicated are number of cases (% cases).

We can only speculate why these four number pairs are able to discriminate between the four cultural groups. For instance, the residuals for number pair 6_8 diverge between both German groups on the one hand and Korean as well as Chinese participants on the other – possibly because for Germans 6 and 8 require two-handed finger patterns while for Korean signers both numbers are represented in the same orientation and both Asian groups can represent the individual numbers of these pairs on one hand, respectively. With respect to number pair 8_10 all four groups showed a strong effect of different number of Arabic digits, resulting in large negative residuals. However, this effect seems to be somewhat less pronounced for Chinese and Korean participants, but possibly for different reasons: for Chinese, the number sign for 10 is motorically complex, requiring a coordinated movement of both hands. For Korean signers, the signs representing 8 and 10 have different hand orientation, also causing some additional representational costs. As can be seen in the latter example, the interpretation of residuals may become particularly difficult, if different effects interfere.

DISCUSSION

In a simple number comparison task performed by educated adult participants, we replicated the standard numerical magnitude effect, probably reflecting properties of the analog quantity representation. In line with previous findings (Domahs et al., 2010), we also observed a number of Arabic digits effect, i.e., a relative RT advantage for those number pairs comparing a single-digit and a two-digit number (8_10 and 9_11). Obviously, this effect reflects properties of the external stimulus representation (Arabic digits) on mental number processing. Both the magnitude effect and the number of digits effect have already been described for other groups of participants and do not seem to be culture-specific (e.g., Domahs et al., 2010). This is not unexpected as it is plausible to assume that both the internal analog magnitude representation and the processing of externally presented Arabic digits should in general not be modulated by culture. Crucially, we also found evidence for an influence of the specific properties of the finger-counting system used by deaf Korean signers reflecting culture-specific differences in number processing. In particular, the coding based on KSL hand orientation was a significant predictor of performance for KSL participants. Importantly, this indication of culture-specificity was further corroborated by the fact that the predictor hand orientation did not explain any additional variance when included in regression models for the other three groups (hearing and deaf Germans, hearing Chinese).

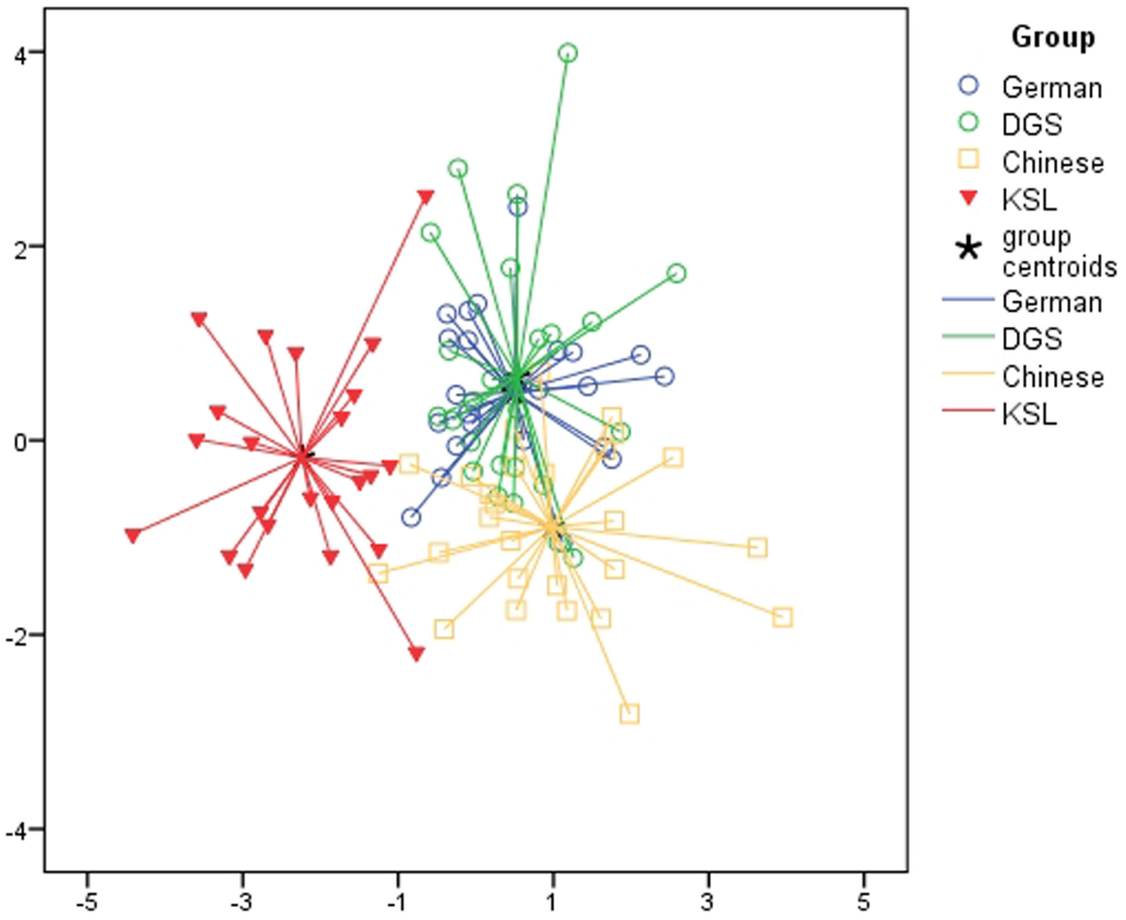

FIGURE 5 | Combined groups plot of the results from a stepwise linear discriminant analysis on mean RT per number pair and participant (see also Table 2) using the first two dimensions of the discriminant functions space. Note that hearing Germans and deaf German signers, who have the least discriminable RT-profiles in a magnitude comparison task with Arabic digits, also have very similar finger-counting systems (see **Figure 2**).

We used a simple number comparison task. This task does not involve any overt finger-counting. Furthermore, Arabic digits were used as input, which do not show characteristic properties of KSL finger-counting. Nevertheless, using the RT-profiles we were able to discriminate between cultural groups with different finger-counting habits (deaf Korean signers vs. hearing Chinese vs. German signers and hearing Germans), but failed to discriminate between groups with similar finger-counting systems (hearing Germans vs. deaf German signers).

Taken together, these results are inconsistent with theoretical approaches assuming only one single amodal semantic representation of number magnitude. Although models of this type might in principle be adapted to account for hand-based effects in numerical cognition, at present it seems unclear, how characteristic properties of finger-counting habits could be integrated in an analog quantity representation (Dehaene and Cohen, 1995; Dehaene, 2003) or an abstract base-10 based quantity representation as proposed by McCloskey and Macaruso (1995). Approaches which assume multimodal semantic representations (Campbell and Clark, 1992; Campbell, 1994; Cohen Kadosh and Walsh, 2009), on the other hand, could easily integrate a hand-based representation of quantity, although typically, this has not been included yet (e.g., Campbell and Epp, 2004). However, at present these models are grossly underspecified. It still remains to be explored which representation has to be activated in which task and to which extend. However, recent evidence suggests that finger-based representations are not only used in simple number processing but also in calculation – in children (Domahs et al., 2008) or in cases of persisting dyscalculia (Kaufmann et al., 2011) as well as in healthy adult participants (Klein et al., 2011). Thus, models of numerical cognition should incorporate the option that finger-based representations are accessed – at least concomitantly – in simple number processing and calculation tasks even if the input is in a different format and finger-based representations are not the dominant input modality for the task at hand. This has previously been suggested by Di Luca and Pesenti (2011) who proposed to consider finger-numeral representations as a fourth type of representation in the Triple-Code model originally proposed by Dehaene and Cohen (1995).

It should be noted that we do not claim that all of the systematic variance can be explained by finger-based numerical representations. Rather, it seems likely that other internal representations may be involved as well. These may include number word systems, representations based on calculation machines (e.g., abacus), regular dot patterns as found on dice, and others. However, finger-counting habits seem to be an important predictor in our data as they can predict locus (i.e., affected number pairs) and direction (RT increase or decrease) of the residuals in a culture-specific way (i.e., corresponding to the respective finger-counting habits). The fact that we observed a relative RT *increase* for number pairs associated with different hand orientations further supports the motor generation hypothesis proposed by Domahs et al. (2010): motor imagery for motorically more complex number signs (e.g., two-handed signs in German and DGS or reorientation of hand posture in KSL signs) leads to increased cognitive processing costs even for abstract symbolic input (Arabic digits). In contrast, we did not find evidence for the assumption that a break between transparent and symbolic finger-counting patterns affects behavior in the same task. This seems to be in line with the assumption that – at least during acquisition – number gestures are not analyzed according to their transparency (Nicoladis et al., 2011). Moreover, one could speculate whether motorical effects (like hand orientation) have more behavioral impact than purely semantic effects (like transparency limit). Yet, at the present state, a detailed account of what kind of motor complexity should affect performance to which extent is still lacking. Thus, further research is needed to disentangle why the motorical effect of hand orientation was significant in the current data while another motorical effect, i.e., the effect of movement sequence, was not.

In sum, our results support the assumption that educated adults activate some kind of internal finger-or hand-based numerical representation even in a simple task with purely symbolic input. This representation seems to be evoked automatically, even though it can have detrimental effects on the task to be solved. Consequently, our results corroborate the idea of embodied numerosity representations and are inconsistent with amodal models of quantity representation.

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When digits help digits: spatial–numerical associations point to finger counting as prime example of embodied cognition

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Spatial–numerical associations (SNAs) are prevalent yet their origin is poorly understood. We first consider the possible prime role of reading habits in shaping SNAs and list three observations that argue against a prominent influence of this role: (1) directional reading habits for numbers may conflict with those for non-numerical symbols, (2) short-term experimental manipulations can overrule the impact of decades of reading experience, (3) SNAs predate the acquisition of reading. As a promising alternative, we discuss behavioral, neuroscientific, and neuropsychological evidence in support of finger counting as the most likely initial determinant of SNAs. Implications of this "manumerical cognition" stance for the distinction between grounded, embodied, and situated cognition are discussed.

Keywords: embodied cognition, finger counting, numerical cognition

SPACE AND NUMBERS ARE ABUNDANTLY ASSOCIATED

We all use space when dealing with quantities, both in real-life situations and in our minds. Examples include the sorting of objects into physical piles when counting them, or organizing tallies into spatially separate groups. Documenting this pervasive use of mental space, well over 100 experiments have now studied our tendency to associate small numbers (1 or 2) with left hemispace and larger numbers (8 or 9) with right hemispace, usually in parity or magnitude classification tasks (Wood et al., 2008). But spatial–numerical associations (SNAs) influence our entire behavioral repertoire, from response selection to response force, from movement initiation speed to subsequent attention allocation (Hubbard et al., 2005; Fischer, 2011). Spatial activities including drawing and gesturing help both children and mathematicians to solve numerical problems (Nunez, 2006; Goldin-Meadow et al., 2009; Lubin et al., 2010). Finally, we also think of even numbers as more "right" than odd numbers (Nuerk et al., 2004) and of addition as rightward movement and subtraction as leftward movement (McCrink et al., 2007; Pinhas and Fischer, 2008; Knops et al., 2009). Here we refer to all such relationships collectively as SNAs.

Despite the remarkable prevalence of SNAs there is currently no consensus as to how they originate. This omission hampers our understanding of numerical cognition and is incompatible with the prevalent theoretical framing of cognition as an abstract and amodal process (Barsalou, 2008). We address this omission by first reviewing the notion, prominent in current theoretical arguments, of SNAs as emerging from reading habits. Then we describe recent behavioral and neuroscientific evidence in support of an alternative origin of SNAs, namely finger counting habits. We argue that reading-related biases are only a minor contributor to SNAs, and that finger counting is an important universal factor that shapes the spatial nature of numerical representations and processing. Despite being the most conspicuous element of embodiment in the domain of numerical cognition, finger counting remains a relatively neglected issue (**Figure 1**). Therefore we sketch out theoretical implications of finger counting for grounded, embodied, and situated cognition more generally in a final section. We conclude that the study of "manumerical cognition," the role of fingers in our comprehension of numbers, holds great promise for grasping the embodied nature of thought.

RE-EVALUATING THE ROLE OF READING

Early studies of SNAs in Western countries proposed that a directional left-to-right scanning habit is initially acquired with reading and subsequently "spills over" into the numerical domain, thus causing horizontal SNAs (Dehaene et al., 1993; Berch et al., 1999). But at least four arguments suggest that reading habits themselves cannot fully account for the multitude of SNAs and are unlikely to be their ultimate cause.

First, even within a given culture, the notion of a well-defined one-way reading direction is an oversimplification. For instance, Hebrew readers, who read text right-to-left still read embedded numbers left-to-right. Accordingly, the absence of horizontal SNAs was demonstrated in a Hebrew population – presumably because word and number reading habits cancel each other (Shaki et al., 2009). Consistent with this observation, SNAs do obtain in Hebrew readers when the spatial associations of numbers are made

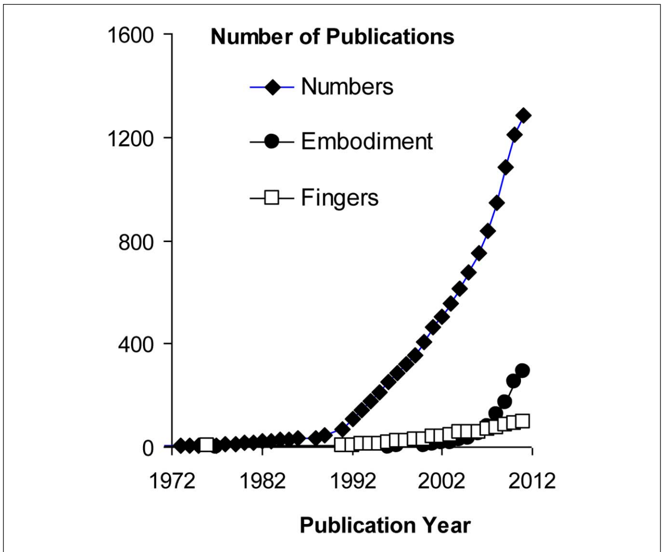

FIGURE 1 | Cumulative number of publications found in Web of Knowledge on July 2, 2011, using as search terms (a) TS = ("embodied cognition") or TS = ("embodied process*"); (b) TS = ("finger count*"); (c) TS = ("num* cognition" or "num* process*").

FIGURE 2 | Change in SNAs of Hebrew and English participants reading cooking recipes with different number magnitudes at the beginning and end of each line. Change was measured per regression slopes calculated from number classification speed in the parity task before vs. after reading. In both languages only the incongruent SNA (large number at sentence start) induced a change. Arrows above text excerpts indicate reading direction. Adapted from Fischer et al. (2010).

consistent with the general reading direction (Fischer et al., 2010; **Figure 2**), or when the association is assessed orthogonally to the conflict-inducing dimensions, i.e., by using vertical response keys (Shaki and Fischer, 2011). In Chinese–English bilingual readers the presentation format of numbers (Chinese or Arabic symbols) determines their mapping along the vertical or horizontal dimension (Hung et al., 2008), again indicating the presence of multiple SNAs. In both cases it is not reading direction *per se*, but their spatial consistency, or their contextual association, which shapes SNAs.

Secondly, the assumption that years of exposure to a reading culture gradually shape a person's SNAs runs against more recent observations. Russian–Hebrew bilinguals modify their SNA after reading a few minutes of Cyrillic or Hebrew text (Shaki and Fischer, 2008); in fact, merely reading a single Cyrillic or Hebrew word changes their SNA from 1 s to the next (Fischer et al., 2009). Even during reading, SNAs depend on the positioning of digits within a text (Fischer et al., 2010, **Figure 2**), clearly indicating that effects of reading are much more short-lived and fragile than originally thought. Directional reading habits provide, at best, only a small contribution to the overall SNAs.

Developmental data provide a third argument against a role of reading as the origin of SNAs. For example, 4.5-year-old children already explore objects more efficiently when they are numbered in left-to-right ascending order (Opfer and Furlong, 2011; see also Tversky et al., 1991). These observations establish the small-left association as a default in Western cultures that needs to be explained. The developmental time-line of SNAs is more fully discussed in a recent review by Göbel et al. (2011).

Finally, SNAs can emerge in the complete absence of reading. Gulledge (2006) compared students against rhesus monkeys in a magnitude classification task. Participants moved a mouse cursor to indicate the numerically larger of two dot patterns, and response latencies showed a horizontal SNA for both groups. In another animal study, newborn domestic chicks learned the positions of 10 pecking holes arranged in a radial array (extending from near to far). When later tested with the array rotated 90°, i.e., in a horizontal extension, they spontaneously translated the formerly radially ascending sequence into a left-to-right, but not a right-to-left ascending sequence (Rugani et al., 2010). Spatial exploration biases have been made responsible for this asymmetric organization of number space in the avian brain (Rugani et al., 2011). Together, these animal studies indicate that directional scanning habits in a linguistic context are not needed to explain the emergence of systematic SNAs.

FINGERS LEND A HAND TO DIGITS

Given the limited legs of the reading hypothesis, we propose that SNAs might instead originate from a different directional habit that exhibits both universality and cross-cultural variability: Finger counting. Across the world, most children initially acquire number concepts through finger counting, by either spontaneous practice, observing their parents, or direct tutoring. Finger counting has a long cultural tradition (Göbel et al., 2011) and is surprisingly prevalent today, both as an overt behavior and as a cognitive representation. A girl born without forearms and hands used her phantom fingers to solve arithmetic problems (Poeck, 1964). While this behavior could have been learned from observing other people, a scaffolding function of innate components of both a finger schema and basic calculation routines cannot be excluded. This hypothesis receives tentative support from the fact that newborns already imitate finger postures (Nagy et al., 2005). Interestingly, they prefer to do so with their left hand, which, in turn, links in with findings from an ongoing internet-based study (please visit www.counting.cognitive-psychology.eu/) which showed that adults in English-speaking countries also prefer to start counting on the fingers of their left hand (Lindemann et al., 2011). Thus, they associate small numbers with left space, and might have done so as children. It is not clear why this pattern is less biased in some Mid-European and Mediterranean cultures but the preference clearly reverses in Middle Eastern cultures, where there are more right-starters. Importantly, left-starters as a group have stronger and more consistent SNAs than right-starters (Fischer, 2008), possibly due to congruency between their individual SNAs and the population stereotype that is expressed on rulers, graphs, etc. This makes finger counting a prime candidate for the origin of directional SNAs and their cross-cultural variation. Given this potential of finger counting as a foundation of SNAs, we now review the empirical evidence for an involvement of fingers in numerical cognition, including behavioral, and neuroscientific studies.

BEHAVIORAL EVIDENCE

Recent research has established links between hand movements and number processing, such as congruency effects between number magnitude and grasp aperture (reviewed in Andres et al., 2008; Badets and Pesenti, 2010). But several observations show that the SNA can be traced to the finger level: Finger responses are faster when the mapping of number stimuli onto fingers agrees with the direction of finger counting (Di Luca et al., 2006). Seeing canonical finger counting postures differs from seeing arbitrary finger postures: Di Luca and Pesenti (2008), Di Luca et al. (2010) documented faster naming of numerosities indicated by canonical postures, and ruled out differential familiarity or saliency as confounds. Di Luca et al. (2010) found that canonical postures selectively prime one target number whereas arbitrary finger postures prime all numbers-up to and including the target. We will return to this important observation of a modulation of grounded number representations by embodied number associations. Finally, addition is faster when canonical finger postures appear after naming the result, thus providing evidence for arithmetic outcome anticipation in terms of finger associations (Badets et al., 2010).

Early studies reporting a negative relationship of finger counting with intelligence did not control for individual differences in the ability to differentiate between the single fingers (Sauls and Beeson, 1976). In fact, this faculty of finger gnosis predicts future numerical skills (Fayol et al., 1998; Noël, 2005). Children between 7 and 9 years no longer use fingers overtly during mental calculation but make a disproportionate number of split-5 errors (deviating by 5 from the correct solution), suggesting they forgot to "keep their hand in mind" (Domahs et al., 2008). In adults, classifying the digit pairs 4–6 and 5–7 by magnitude is slower in Germans (who count up to 5 on one hand) than in Chinese (who count up to 9 on one hand), suggesting that it takes longer to compare bimanually than unimanually represented numbers (Domahs et al., 2010), presumably because the latter do not require interhemispheric communication.

Some studies that investigated finger-number associations as a function of hand posture (palm down, i.e., right thumb is left of pinkie vs. palm up, i.e., right thumb is right of pinkie) seem to weaken the case for exclusively finger-based SNAs. Brozzoli et al. (2008) found that, after seeing a small number, participants responded faster to tactile stimuli on either the thumb or the pinkie, whichever was the leftmost finger in space (see also Behrmann and Moscovitch, 1994). Likewise, in a finger-number size compatibility task the speed advantage of the index over ring finger was inverted when hand posture was changed (Leuthard et al., 2005, see also Riello and Rusconi, this issue). Similar space-based rather than hand-based finger-number associations resulted from another hand posture manipulation, arm crossing. When participants tapped their fingers repeatedly in random order, while simultaneously naming the numbers from 1 to30 in a random sequence, they named smaller random numbers when the new tap occurred to the left of the previous one *in space*, regardless of whether their hands were straight or crossed (Plaisier and Smets, 2011). Both hand posture manipulations (pronation/supination and midline crossing) seem to show dominance of external over hand-based space in the mapping of numbers. However, on second consideration, these findings do not diminish the impact of finger-number associations, but only show how flexible the reference frames are that allow an optimal orientation in physical as well as in number space and that guarantee rapid adjustments to a given situation. Detailed processing models that combine somatotopic and external referencing of fingers and hands, respectively (Haggard et al., 2006) are currently missing. They will have to consider that the cortical representation of hands and fingers are overlapping to a large extent, but once required by situational demands can function surprisingly independently (Heed et al., 2011).

NEUROSCIENTIFIC EVIDENCE

Tang et al. (2006) showed that numerical tasks activate motor cortex in Chinese but not Western adults. This was taken to reflect arithmetic learning with an abacus in Asian cultures, indicating their embodied representation of number facts. Kaufmann et al. (2008) showed that children's (but not adults') brain activity during magnitude judgments reflected finger-based processing strategies. Two TMS studies showed increased corticospinal excitability specifically for the hand muscles during numerical judgments (Andres et al., 2007; Sato et al., 2007). Also, when TMS is applied to the angular gyrus (Rusconi et al., 2005) it disrupts both access to the finger schema and number magnitude processing. Evidence for a functional overlap of number and finger representations is often claimed from Gerstmann syndrome (Gerstmann, 1940), where acalculia is accompanied by finger agnosia. Although this interpretation is now unlikely (Rusconi et al., 2010), co-morbidities involving writing and left–right discrimination put the association between fingers and numbers in the larger context of symbolic action in space. The spatial–postural invariance noted by Brozzoli et al. (2008) and Plaisier and Smets (2011) may make digits as body parts ideal candidates to deal with digits as points in number space. Finally, Tschentscher et al. (2010) recently compared activation in primary hand motor cortex in adults who start finger counting on either their left or their right hand. The authors found that passively looking at small numbers or number words activated right motor cortex in left-starters but not in right-starters. This work extends the influential demonstration of a somatotopic activation of motor cortex by the reading of action verbs (Pulvermüller,

2005) to the reading of numerical concepts. Together, this behavioral, neuropsychological, and neuroscientific evidence supports the idea of a close link between number and finger knowledge.

GROUNDED, EMBODIED AND SITUATED MAGNITUDE PROCESSING

The brain has developed together with the rest of the body as a way to regulate perception and bodily actions in a situation- and task-appropriate manner. This insight has recently regained attention as "embodied cognition," often also as "grounded" or "situated cognition." We propose a hierarchical relationship between these terms before discussing implications of this view for the origin of SNAs (**Figure 3**).

The most fundamental aspect of cognitive representations is their *grounding* which reflects universal properties of the world. One example is the large numbers-up and small numbers-down association that comes from accumulating objects into piles and that subsequently pervades our metaphorical use of language (Lakoff and Nunez, 2000). On top of this environment-based conceptual grounding, the sensorimotor constraints of our bodies shape *embodied* knowledge representations, as in grasp aperture modulation during object interactions or finger counting (De Cruz, 2008). Finally, range- and context-dependence of SNAs (Dehaene et al., 1993; Bächtold et al., 1998) reflect the flexibility of *situated* number concepts. This theoretical stance is orthogonal to other theoretical views such as the extended mind hypothesis (Clark, 2008) or the more general theory of magnitude representation (Bueti and Walsh, 2009). It makes several predictions about mathematical practice that can inform our search for the origins of SNAs and the nature of human thought.

First, the hierarchical priority of *grounding* over embodiment implies that summation coding should be more robust than place coding of numerosities, i.e., larger numerosities should experientially encompass smaller numerosities, unless a cognitively higher level of processing intervenes. This prediction is in line with empirical findings, summarized above, on place vs. summation coding as a function of canonical vs. arbitrary finger postures (Di Luca et al., 2010). By the same rationale, vertical SNAs should be more robust and harder to abolish than horizontal SNAs (Fischer, 2011; Shaki and Fischer, 2011).

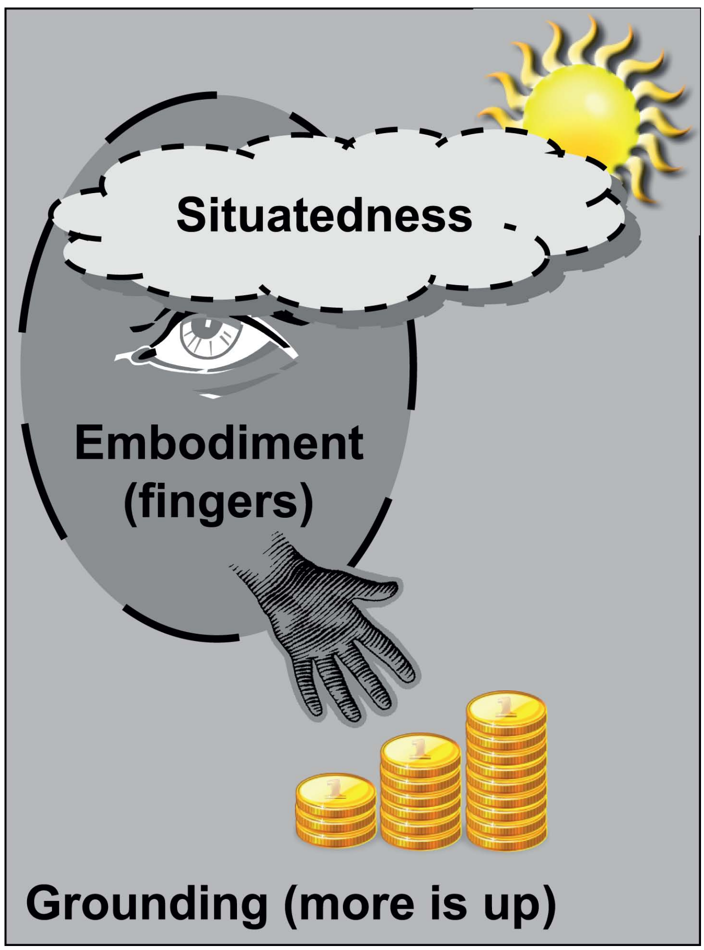

FIGURE 3 | Illustration of the hierarchical relationship of grounded, embodied, and situated cognition in the numerical domain.

Second, an *embodied* stance on numerical cognition predicts that different body postures, and their effects on spatial reference frames, should influence SNAs. Supporting this prediction, healthy adults generate smaller random numbers while turning their head left and larger random numbers while turning their head right (Loetscher et al., 2008). Also, both horizontal and vertical eye positions reliably predict the magnitude of a number emitted "at random" (Loetscher et al., 2010). Crossing one's hands over lateralized response keys can eliminate SNAs (Wood et al., 2006). Furthermore, the embodiment nature of number processing predicts that sensory–motor idiosyncrasies should impact on SNAs. There is clinical evidence that this is in fact the case. Patients with right-hemisphere lesions, who fail to attend to the left side of their body and who neglect left hemispace, err toward large numbers when asked to bisect number intervals (Zorzi et al., 2002). The error in explicit number interval bisection is not correlated, however, with rightward displacements in the bisection of real lines (Doricchi et al., 2005), nor does left-sided neglect manifest itself as small number bias in random generation (Loetscher and Brugger, 2009). This indicates that, while hemispatial neglect affects orientation along a number line, the laws that govern attention in physical and number space are not identical.

A third set of predictions comes from the view of *situated* magnitude processing. Thus, SNAs should be differentially affected by task-dependent hemispheric deployment. Evidence for such flexibility comes from dual-task paradigms, where left-hemisphere verbal memory load abolished SNAs in parity decisions but not in magnitude comparisons, whereas the opposite interference pattern occurred for right-hemisphere visual–spatial load (van Dijck et al., 2009). Hemispheric activation paradigms can also bias healthy subjects' preference for small or large numbers during digit randomization (Loetscher and Brugger, 2007), and individual preferences for left- vs. right-hemisphere mediated tasks bias number choices toward higher or lower magnitudes (Bachmann et al., 2010). Finally, handedness, one of the most conspicuous signs of hemispheric specialization, does not influence SNAs *per se* (Dehaene et al., 1993). However, considering that in most cases "more is better" (rather than worse), interactions between emotional valence and hemispace (Casasanto, 2009) are to be expected. Thus, we recently found regular SNAs as long as small numbers denoted undesirable and large numbers desirable events, but as soon as emotional connotations were reversed, no SNAs were observed (in preparation).

MANUMERICAL COGNITION: THE SCIENCE OF DACTYLONOMY

Our brief review illustrates the bewildering number of potential sources of the association between number and space. We believe that this reflects the human capacity to quickly learn to associate any symbol or abstract relation with a spatial position or relationship (Bächtold et al., 2000; Gattis, 2002). Thus, SNAs are the expression of some general cognitive rule that reflects the "placement" of an image in space (the spatialization of ideas) and the relative (in) compatibility that emerges from using lateral effectors to respond to these ideas. Studies with children and amputees are likely to further advance our understanding of this intriguing phenomenon. The embodied cognition approach is a most suitable framework for further progress along this path, and the study of "manumerical cognition" (Fischer, 2008) holds great promise for our understanding of the embodied nature of thought.

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Passive hand movements disrupt adults' counting strategies

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In the present study, we experimentally tested the role of hand motor circuits in simple-arithmetic strategies. Educated adults solved simple additions (e.g., 8 + 3) or simple subtractions (e.g., 11 – 3) while they were required to retrieve the answer from long-term memory (e.g., knowing that 8 + 3 = 11), to transform the problem by making an intermediate step (e.g., 8 + 3 = 8 + 2 + 1 = 10 + 1 = 11) or to count one-by-one (e.g., 8 + 3 = 8…9…10…11). During the process of solving the arithmetic problems, the experimenter did or did not move the participants' hand on a four-point matrix. The results show that passive hand movements disrupted the counting strategy while leaving the other strategies unaffected. This pattern of results is in agreement with a procedural account, showing that the involvement of hand motor circuits in adults' mathematical abilities is reminiscent of finger counting during childhood.

Keywords: mental arithmetic, mathematic, finger counting, hand movement, embodied cognition, strategy, retrieval, counting

INTRODUCTION

During development, children all go through a stage in which they count on their fingers to solve simple-arithmetic problems like 8 + 5 and 7 – 4. They use their fingers to represent numerosities before they acquire symbolic representations of numbers (such as number words and Arabic digits). It is thus no surprise that finger gnosia or "finger sense" (i.e., the ability to mentally represent one's fingers) plays an important role in the development of numerical abilities. Indeed, Noël (2005) showed that finger gnosia tested at the beginning of grade 1 predicted numerical abilities (tested by tasks such as digit comparison and subitizing) and mathematical abilities (tested by an addition task) in grade 2; whereas it did not predict reading abilities (see also Fayol et al., 1998). Similarly, Penner-Wilger et al. (2007) showed that children able to use their fingers as representational tools performed better in mathematics. Training children's finger differentiation even increases finger gnosia and improves numerical performance (Gracia-Bafalluy and Noël, 2008, but see Fischer, 2010).

Generally, adults no longer use their fingers to solve arithmetic tasks, and the correlation between finger use and math accuracy decreases across development (Jordan et al., 2008). One may therefore suppose that the link between finger gnosia and numerical or mathematical abilities is absent in adults. However, there is evidence that indicates that this might not be true.

In a seminal electromyographic (EMG) experiment, Andres et al. (2004) showed that adults' grip closure was initiated faster in response to small digits, while grip opening was initiated faster in response to large digits (see also Andres et al., 2008). In a similar vein, it has been shown that adults' precision grip was initiated faster in response to small numbers, while power grip was initiated faster in response to large numbers (Lindemann et al., 2007; Moretto and di Pellegrino, 2008). Finally, using transcranial magnetic stimulation (TMS), Sato et al. (2007) observed increased corticospinal excitability of adults' hand muscles during a parity judgment task. Taken together, all these studies show that adults still exhibit a neural link between fingers and numbers.

The neuro-cognitive relationship between fingers and adults' *mathematical* abilities remains debated, though. Rusconi et al. (2005) showed that repetitive TMS on adults' left angular gyrus interfered with finger gnosia and explicit magnitude processing but did *not* affect the network of stored arithmetic facts. Andres et al. (2007), in contrast, showed that TMS affected the corticospinal excitability of adults' hand muscles during a dot counting task. It thus seems that the relationship between hands and mathematical abilities is functionally differentiated, with a connection between hands and counting dots but not between hands and retrieving arithmetic facts.

With the present study, we wanted to pursue the role of hand motor circuits in adults' mathematical abilities. More specifically, we wanted to test if the functional relationship between hand movements and mathematical abilities depends on the arithmetical strategy used. In the domain of simple arithmetic, three main strategies can be distinguished: (a) direct memory retrieval, for example knowing that 8 + 3 = 11, (b) transformation or using intermediate steps, for example first retrieving 8 + 2 = 10 and then 10 + 1 = 11, and (c) one-by-one counting, for example 8 + 3 = 8…9…10…11. The question now is: to what extent do hand movements play a role in these different strategies? According to the *representational account*, the configuration of our fingers is used to mentally represent and process numbers (Di Luca et al., 2006; Fischer, 2008). Because we need to access numerical information irrespective of the applied strategy, this theory predicts a functional relationship between hand movements and all three strategies. According to the *procedural account*, in contrast, the involvement of hand motor circuits in adults' mathematical abilities is reminiscent of finger counting during childhood, a universal behavior observed in several different cultures (Butterworth, 1999). Hence, this theory predicts that adults will mainly use their fingers to support one-by-one counting strategies and will not use their fingers to retrieve answers from long-term memory.

In order to distinguish between both theories, we conducted an experiment in which adults solved simple-arithmetic problems applying one of the three strategies described above. While solving these problems, the experimenter did or did not move the participants' hand on a four-point matrix. We chose for this passive hand movement task so as not to load attentional or executive resources, which have been shown to play a role in simple-arithmetic problem solving (Hecht, 2002; Seyler et al., 2003; Imbo and Vandierendonck, 2007a,b,c)[1]. The *representational* account predicts that the passive hand movements will affect *all* strategies whereas the *procedural* account predicts that mainly the *counting* strategy will be affected.

MATERIALS AND METHODS

PARTICIPANTS

Twenty participants took part in the present experiment, 10 solving subtraction problems and 10 solving addition problems. They were all first year psychology students at Ghent University and participated for course requirements and credits. The two participant groups did not differ from each other in age, calculator use (rated on a scale from 1 "never" to 5 "always"), math experience (i.e., the number of mathematics lessons per week during the last year of secondary school), or arithmetic skill (tested with the French Kit; French et al., 1963; see **Table 1**).

PROCEDURE

Each participant was tested individually in a quiet room for approximately 1 h. The choice/no-choice method, designed by Siegler and Lemaire (1997), was used to independently assess strategy selection and strategy efficiency. This entails that the participants solved the simple-arithmetic problems under four conditions: first the choice condition, in which they were allowed to choose strategies, and then three no-choice conditions, in which they had to solve all problems with the same specified strategy. The order of the no-choice conditions was randomized across participants. Data obtained in no-choice conditions are unbiased because they are not susceptible to selection effects (e.g., if a certain strategy is only used on easier problems, this strategy may look more efficient than it actually is). In the choice condition, 5 practice problems and 32 experimental problems were presented. The no-choice conditions comprised the 32 experimental problems. Each condition was further divided into two blocks: one without passive hand movements and one with passive hand movements. For half of the participants, each condition started with hand movements whereas for the other half of the participants each condition started without hand movements.

[1]Although passive hand movements may put a load on visuo-spatial working memory, it is very unlikely that this will influence our results. Indeed, although adults do rely on visuo-spatial working-memory resources to solve *complex*-arithmetic problems (Trbovich and LeFevre, 2003; Imbo and LeFevre, 2010), they do *not* rely on visuo-spatial working-memory resources to solve *simple*-arithmetic problems (Seitz and Schumann-Hengsteler, 2000; see also DeStefano and LeFevre, 2004, for review). Further, even if a visuo-spatial load would affect people's simple-arithmetic performance, it would do so on both transformation and counting, and not only on counting, as was observed.

Table 1 | Participant information for the addition group (*N* = 10) and the subtraction group (*N* = 10).

	Addition	Subtraction	Difference
Females:males	8:2	8:2	
Age (in years)	18.4	18.8	$t(18) = 1.1$
Calculator use questionnaire	3.3	3.3	$t(18) < 1$
Arithmetic skill (French Kit score)	34.3	35.9	$t(18) < 1$
Math experience (number of arithmetic lessons)	4.5	4.7	$t(18) < 1$

SIMPLE-ARITHMETIC TASK

The addition problems consisted of two one-digit numbers. Problems involving 0 or 1 as an operand or answer (e.g., 5 + 0) and tie problems (e.g., 3 + 3) were excluded. All problems crossed 10 (e.g., 3 + 8). Since commuted pairs (e.g., 9 + 4 and 4 + 9) were considered as two different problems, this resulted in 32 addition problems (ranging from 2 + 9 to 9 + 8). The 32 subtraction problems were the reverse of the addition problems. A trial started with the presentation of a fixation point for 500 ms. Then the arithmetic problem was presented horizontally in the center of the screen, with the operation sign at the fixation point. The problem remained on the screen until the participant responded. Timing began when the stimulus appeared and ended when the response triggered the sound-activated relay. To enable this sound-activated relay, participants wore a microphone that was activated when they spoke their answer. This microphone was connected to a software clock accurate to 1 ms. On each trial, feedback was presented to the participants: a green "Correct" when their answer was correct and a red "Incorrect" when it was not. Immediately after solving each problem, participants in the choice condition were presented four strategies on the screen: retrieval, counting, transformation, and other. These four choices had been extensively explained by the experimenter:

1. Retrieval: you solve the problem by remembering or knowing the answer directly from memory. For example, you know that 8 + 3 = 11 because 11 "pops into your head."
2. Counting: you solve the problem by counting one-by-one to get the answer. For example, 8 + 3 = 8…9…10…11.
3. Transformation: you solve the problem by making an intermediate step to 10. For example, 8 + 3 = 8 + 2 + 1 = 10 + 1 = 11.
4. Other: you solve the problem by a strategy unlisted here, or you do not know what strategy you used to solve the problem. For example, guessing.

After each problem, participants were asked to verbally report which of these strategies they had used. In the no-choice conditions, participants were asked to use one particular strategy to solve all problems. In no-choice/retrieval, they were asked to retrieve the answer. More specifically, they had to say the answer that first popped into their head. In no-choice/transformation, they were asked to transform the problem by making an intermediate step to 10. In no-choice/counting, finally, they had to count one-by-one (subvocally) until they reached the correct total. After having solved the problem, participants also had to answer yes or no to indicate whether they had succeeded in using the required strategy. The answer of the participant, the strategy information, and the validity of the trial were recorded on-line by the experimenter. All invalid trials (e.g., failures of the voice-activated relay) were discarded and returned at the end of the block, which minimized data loss due to unwanted failures.

PASSIVE HAND MOVEMENTS

In the block with passive hand movements, participants were told to stretch their index finger while keeping their wrist and arm muscles relaxed so that the experimenter could move hand and arm. The experimenter moved the non-dominant hand and arm of the participant on a four-point matrix in such a way that the participant's index finger sequentially tapped the numbers 1, 7, 9, and 3 (i.e., clockwise) on a numerical keyboard. There was about one tap per second.

RESULTS

Failures of the sound-activated relay spoiled 6.7% of the trials. Since all these invalid trials returned at the end of the block, most of them were recovered from data loss, which reduced the trials lost due to failures of the sound-activated relay to 1.1%. All incorrect trials (2.7%), all choice trials on which participants reported having used another strategy (0.4%), and all no-choice trials on which participants failed to use the required strategy (10.5%) were deleted. All data were analyzed on the basis of the multivariate general linear model, and all reported results were considered to be significant if $p < 0.05$, unless stated otherwise.

STRATEGY EFFICIENCY

Only the RTs uncontaminated by strategy choices (i.e., no-choice RTs) will be considered, since only these RTs provide clear data concerning strategy efficiency. A 2 × 2 × 3 ANOVA was conducted on correct RTs with Operation (addition or subtraction) as between-subjects factor and Movement (with or without passive hand movements) and Strategy (retrieval, transformation, counting) as within-subjects factors (see **Table 2**). The main effects of Operation and Movement were significant. Participants were faster on addition (1.8 s) than on subtraction (2.7 s), $F(1,18) = 13.20$, MSe = 1925240, $\eta_p^2 = 0.42$ and faster without than with passive hand movements (2.1 vs. 2.4 s), $F(1,18) = 12.60$, MSe = 130460, $\eta_p^2 = 0.41$. The main effect of Strategy was significant as well, $F(2,17) = 69.89$, MSe = 838067, $\eta_p^2 = 0.80$. Retrieval (1.0 s) was faster than transformation (1.6 s), $F(1,18) = 35.55$ and transformation was faster than counting (4.1 s), $F(1,18) = 147.25$.

Strategy interacted with Operation, $F(2,17) = 4.44$, MSe = 838067, $\eta_p^2 = 0.21$. The difference between addition and subtraction was larger when counting (1.9 s) than when transforming (0.6 s), $F(2,17) = 8.73$, and slightly larger when transforming than when retrieving (0.2 s), $F(1,18) = 3.99$ ($p = 0.06$). As predicted, Strategy also interacted with Movement, $F(2,17) = 7.00$, MSe = 115034, $\eta_p^2 = 0.29$. As can be seen in **Figure 1**, participants slowed down when their hands were passively moved in the counting condition, $F(1,18) = 12.08$, but not in the retrieval or transformation conditions (each $F < 1$). The Operation × Movement and Operation × Movement × Strategy interactions were not significant (both $ps > 0.20$).

STRATEGY SELECTION

In order to test whether passive hand movements affected people's strategy choices, a 2 × 2 ANOVA was conducted on percentages use of each strategy (in the choice condition), with Operation (addition or subtraction) as between-subjects factor and Movement (with or without passive hand movements) as within-subjects factor (see **Table 3**). The main effects of Operation and Movement did not reach significance for any of the strategies (highest $F = 1.1$, each $p > 0.30$). The Operation × Movement interaction was significant for neither strategy (highest $F = 1.5$, each $p > 0.23$). The absence of dual-task effects on adults' strategy choices is in agreement with

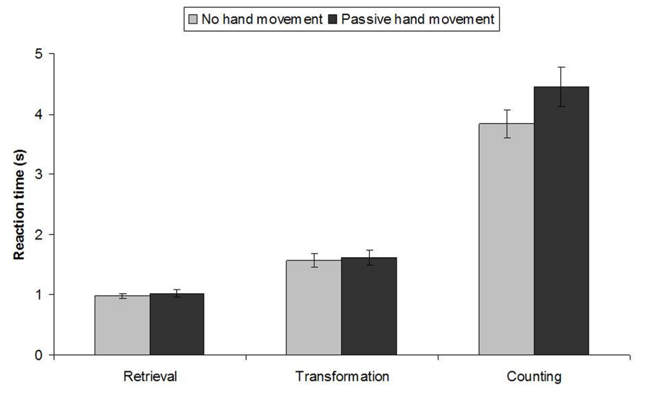

FIGURE 1 | Reaction times (in seconds) as a function of Strategy and Movement. Error bars denote standard errors.

Table 2 | Reaction times (in seconds) as a function of Operation, Movement, and Strategy.

	No hand movement	Passive hand movement
ADDITION		
Retrieval	0.8 (0.1)	0.9 (0.1)
Transformation	1.2 (0.2)	1.3 (0.2)
Counting	3.1 (0.3)	3.4 (0.5)
SUBTRACTION		
Retrieval	1.1 (0.1)	1.1 (0.1)
Transformation	1.9 (0.2)	1.9 (0.2)
Counting	4.7 (0.3)	5.5 (0.5)

Standard errors are shown in parentheses.

Table 3 | Strategy choices (%) as a function of Operation, Movement, and Strategy.

	No hand movement	Passive hand movement
ADDITION		
Retrieval	62.5 (8.4)	64.1 (6.8)
Transformation	36.2 (8.4)	33.8 (6.6)
Counting	1.3 (1.0)	2.0 (0.7)
SUBTRACTION		
Retrieval	57.5 (8.4)	65.2 (8.4)
Transformation	40.9 (8.4)	34.4 (6.6)
Counting	1.7 (1.0)	0.3 (0.7)

Standard errors are shown in parentheses.

earlier studies showing that choosing among simple-arithmetic strategies does not load on working-memory resources (Hecht, 2002; Imbo and Vandierendonck, 2007a,b).

DISCUSSION

Adults solved simple-arithmetic problems applying three different strategies: retrieval, transformation, and counting. While they solved these problems, the experimenter did or did not move their hand. The question was to which extent these passive hand movements would affect the different strategies. According to the representational account, all strategies would be affected, whereas according to the procedural account, mainly the counting strategy would be affected. The results clearly supported the latter account, since adults counted slower during passive hand movement, while their retrieval and transformation efficiencies stayed unaffected.

ALTERNATIVE EXPLANATIONS

Can the selective effect of hand movements on counting be explained by characteristics of the counting strategy, such as (a) its slowness, (b) its difficulty, or (c) its subvocalization? In following, we disprove these three alternative explanations.

First, we tested whether the movement effects on the counting strategy could be due to the fact that counting takes much more time than retrieval and transformation. The same $2 \times 2 \times 3$ ANOVA with Operation (addition or subtraction) as between-subjects factor and Movement (with or without passive hand movements) and Strategy (retrieval, transformation, counting) as within-subjects factors was conducted on the on *z*-scores of the correct RTs. That is, we subtracted each participant's mean RT (averaged over conditions) from his/her observed RT and divided this by each participant's SD. These *z*-scores correct for the latency differences between strategies and between operations, as proven by the insignificant main effect of Strategy ($F = 1.1$), the insignificant main effect of Operation ($F < 1$), and the insignificant interaction between Strategy and Operation ($F < 1$). The main effect of Movement and the Movement × Strategy interaction were still significant though, $F(1,18) = 9.70$ and $F(2,17) = 3.62$. Planned comparisons showed significant effects of movement on counting, $F(1,18) = 16.21$, but not on retrieval or transformation (each $p > 0.25$). Hence, the observed effect cannot be due to the fact that counting takes more time than retrieval and transformation.

Second, we tested whether the movement effects on the counting strategy could be due to the fact that counting is more difficult than retrieval and transformation. Problems get more difficult when problem size increases (Ashcraft, 1992; Zbrodoff, 1995). Hence, if the passive hand movements simply interfered with problem difficulty, we would expect a Size × Load interaction. This was tested by means of a $2 \times 2 \times 2 \times 3$ ANOVA on correct RTs with Operation (addition or subtraction) as between-subjects factor and Size (small or large), Movement (with or without passive hand movements) and Strategy (retrieval, transformation, counting) as within-subjects factors. Problems were coded as small when the sum (for additions) or the subtrahend (for subtractions) was smaller or equal to 13 (= the median) and coded as large otherwise. The Load × Size and Load × Size × Strategy were not significant (each $F < 1$), indicating that load effects were equally large for small problems (237 ms) as for large problems (214 ms). Hence, the observed load effects cannot be attributed to cognitive interference caused by problem difficulty.

Finally, one could argue that load effects were found for counting only because counting relies on subvocalization. Indeed, subvocalization requires the movement of speech muscles, which in their turn evolved from manual gestures (Gentilucci and Corballis, 2006; Gentilucci and Volta, 2008). However, previous studies also showed that subvocalization is not only applied in counting strategies but also in transformation strategies (Imbo and Vandierendonck, 2007a,b). Hence, if the load effects would be driven by mouth movements rather than by hand movements, we should have found load effects in the transformation strategy. However, the effect of passive hand movements on transformation was not significant, indicating that the load effects cannot be attributed to subvocalization processes.

THEORETICAL INTERPRETATION

Hand motor circuits are thus involved in one-by-one counting but not in other simple-arithmetic strategies. This result extends the – previously observed – neural link between hands and numbers (Sato et al., 2007) by giving it a functional interpretation. In the domain of mathematical abilities, the link between hands and numbers seems to depend on the procedure that is applied: hand movements are irrelevant for retrieval and retrieval-like strategies (such as transformation) but relevant for counting. This observation also solves the discrepancy between two earlier TMS studies, one observing a link between hands and counting dots (Andres et al., 2007) and another one observing no link between hands and retrieving arithmetic facts (Rusconi et al., 2005).

The fact that hand motor circuits are involved in counting is in agreement with the premotor theory of counting (Andres et al., 2007). According to this theory, counting in adults consists in building a motor plan for moving fingers sequentially without actually executing these movements. Adults' finger and number sense are thus still related because of the functional role fingers play in numeracy development (Butterworth, 1999). Indeed, children use their fingers to point to objects when counting, to represent cardinality (e.g., raising fingers to show how old they are), and to keep track of the counting steps when solving arithmetic problems. When learning arithmetic facts, at the other hand, children do not use their fingers.

Finger gnosia and computational abilities are also supported by neighboring brain regions in the posterior parietal lobe (Dehaene et al., 2003). Retrieval and transformation strategies, in contrast, would not rely on motor plans but on a verbal number code. This verbal number code is located in the angular gyrus of the left hemisphere (Dehaene and Cohen, 1995), distant from the brain areas supporting the representation of fingers and magnitudes. Our results suggest that adults' counting strategies do not only (re-)use the same neural substrates that serve finger counting, they also inherit the *functional* properties of these basic motor processes. Indeed, according to embodied cognition theories (Barsalou, 2008; Domahs et al., 2010), mathematical knowledge is represented together with the sensory and motor activity that was present during its acquisition. The motor function of counting thus extends to adulthood.

In conclusion, our data show that developmental processes that were thought to be transient (e.g., finger calculation) still affect adults' mathematical performance. Finger and hand movements are thus not just an arbitrary and transient stage of cognitive development, they still exert their effects in educated adults. It would be interesting to test the effect of passive hand movements in groups that show a more frequent use of counting strategies, such as children and mathematically disabled persons. We predict that the disturbing effect of passive hand movements will even be greater in these groups. It would also be interesting to test the effect of active rather than passive hand movements. Indeed, passive hand movements mostly affect proprioception, which is just one component of the hand motor circuit. We predict that the disturbing effect of active hand movements will even be greater than the effect of passive hand movements.

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Finger usage and arithmetic in adults with math difficulties: evidence from a case report

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INTRODUCTION

The role of finger usage upon learning arithmetic has received increasing interest from various disciplines. In this opinion paper, we would like to emphasize that finger usage in calculation is not a unitary phenomenon. Rather, we propose two different types of finger usage: First, in many countries and independent of the number system in use, typically developing children use fingers as important transitory (and intuitive) tools to represent small quantities (Butterworth, 1999; Bender and Beller, 2011). According to Di Luca and Pesenti (2011), finger counting habits are needed to build, acquire, and access mental number representations, the building blocks for semantic number knowledge. Second, developmentally inappropriate finger usage of children with math difficulties (MD) reflects their persistent need to apply back-up strategies to compensate for deficient or lacking number representations (e.g., Brissaud, 1992; Kaufmann, 2002; Wright et al., 2002). Here, we will focus on the second type of finger usage (i.e., persistent finger usage in individuals with MD) and we argue that (a) finger usage in arithmetic is not restricted to children; and (b) finger-based calculation strategies utilized by adults with MD reflect immature calculation strategies that are comparable to those displayed by affected children.

I. FINGER USAGE IN ADULTS: A CASE REPORT

In contrast to the extensive literature on children's finger usage, respective studies of adults are lacking. In the following, we will present data of a bright young adult (RM) who experiences severe difficulties with arithmetic. RM is a psychology undergraduate student at the end of her second year. RM's intelligence, reading, and spelling skills as well as her working memory resources are average (short form of the Wechsler Adult Intelligence Scale full-scale IQ 108; Wide Range Achievement Test (WRAT3) reading and spelling standard scores (SS) 119 and 101, respectively; digit and spatial span forward/backward scaled scores 12 and 10, respectively). RM's arithmetic skills, however, are weak (WRAT3 arithmetic SS 80).

RM's performance for simple number facts was atypical and maladaptive. Number facts are single-digit mental calculations and are generally encoded and retrieved from long-term memory (Ashcraft, 1992). On the contrary, many children with MD find it hard to store and/or retrieve number facts, despite average non-numerical memory and intact procedural arithmetic skills (for a respective single case study, see Kaufmann, 2002).

RM's performance for single-digit number facts was highly deficient albeit very accurate (addition 100%, subtraction 100%, multiplication 99% correct). Her solution strategies were highly unusual for an adult: Across all three operations, RM used procedural strategies (PS) considerably more often than direct fact retrieval (FR; **Table 1**). For nearly all problems where she used PS she also used finger counting. Consequently, RM's processing times were considerably longer on problems that were solved procedurally. In addition and subtraction, the most dominant procedural strategy was "counting up/down by one," in multiplication "counting up by ones and twos," and a combination of "retrieval of a 5-table with subsequent counting up/down."

It is interesting to note that RM utilized her 5-table knowledge to solve multiplication facts by combining FR with a counting up strategy (for an example, see below). Nonetheless, RM was not able to utilize (parts of a) 2-table or 10-table knowledge similarly [as most children with and without MD would; e.g., $4*3=(2*3)+(2*3)$ or $9*3=(10*3)-(1*3)$].

A typical example of RM's solution strategy for multiplication facts: upon solving the problem $7*8$, she calculated $5*8 = 40$ (using 5-table knowledge), then added two sets of eight by counting up. Thereby, RM had to add the two sets of eight by the time consuming strategy of counting up by ones ($40+1+1+1+1+1+1+1+1=48$; then $48+1+1+1+1+1+1+1+1=56$). For both sets (as well as for all other problems solved by finger counting) she started the counting procedure by bending first her left-hand thumb, then the index, middle, ring and little finger and continued the counting process with her right-hand thumb. The solution time for this problem was 18.5 s. Notably, it took RM 39.6 s to solve the reversed problem presented several trials earlier. This complicated back-up strategy demonstrates clearly that RM has excellent conceptual and procedural arithmetic knowledge, but due to her patchy fact knowledge and severe difficulty to perform carry procedures, her solution strategies (while errorless) become very time consuming.

In essence, RM's fact knowledge was restricted to rule-based number facts ($n+0$, $n+1$, $n*0$, $n*1$). Out of 32 addition facts that were solved by direct memory retrieval (total $n=100$), 25 were classified as so-called "rule-based facts" (15 number facts were of the type $n+0$, 10 further number facts were of the type $n+1$). Out of 22 subtraction facts solved by retrieval (total $n=42$), 15 were rule-based facts. Out of 54 multiplication problems (total $n=100$) solved by direct memory retrieval, 19 were $n*0$, 17 $n*1$, and 15 $n*5$ problems.

II. SYNOPSIS

To summarize, we argue that (i) finger usage in calculation is not restricted to children; and (ii) the qualitative analysis of finger use and its function (in children and adults) may provide important indirect insights into the organization of number fact representations. It is plausible that children and adults with MD who use finger-based calculation strategies develop and employ their finger counting strategies to a much higher and more complex level.

Table 1 | Solution strategies employed by RM upon solving number facts (single-digit problems). Procedural strategies (PS) are differentiated from fact retrieval (FR). For PS the various counting strategies employed by RM are described. Reported are frequency of use in % and mean reaction times (RT) with standard deviations (SD) where applicable.

Solution strategy	Frequency of use [correct out of maximum possible] (mean RT/SD)		
	Addition (*n*=100)	**Subtraction (*n*=42)**	**Multiplication (*n*=100)**
FR overall	32.0% [32/100] (1.8 s/0.8 s)	52.4% [22/42] (1.5 s/0.6 s)	54.0% [54/100] (1.6 s/0.9 s)
PS overall	68.0% [68/100] (3.1 s/1.3 s)	47.6% [20/42] (4.7 s/2.1 s)	46.0% [46/100] (12.0 s/8.9 s)
PS: FR after change of operands	11.8% [8/68] (2.0 s/0.6 s)	n.a.	n.a.
PS: Counting up/down by ones	88.2% [60/68] (3.2 s/1.3 s)	95% [19/20] (4.8 s/2.2 s)	13.0% [6/46] (10.1 s/6.6 s)
PS: Counting up in twos	n.a.	n.a.	23.9% [11/46] (3.8 s/2.3 s)
PS: Combined FR AND count up/count down	n.a.	5.0% [1/20] (3.3 s)	63.0% [29/46]* (16.2 s/8.6 s)

Abbreviation: n.a., not applicable.

**Notes: Among the 29 problems solved by a combination of FR and counting up, 27 were n∗5 problems, one was a n∗6 problem and one was solved by a combination of retrieving a 5-table and subtracting one operand from this result (6∗4=6∗5–6).*

For addition and multiplication number facts, all problems with operands from 0 to 9 were presented (summing up to 100 problems per operation). Each problem was presented only once, reversed digit order was considered a separate problem (2+3, 3+2). In addition and multiplication, 36 out of the 100 problems were so-called "rule-based number facts" (i.e., problems containing either a 0 or a 1). For subtraction, 42 single-digit problems with minuends and subtrahends between 9 and 1 were presented (please note that due to experimental failure two problems (8–2 and 4–1) were not administered).

RM demonstrated preserved rule-based fact knowledge but had severe difficulties to solve the remaining number facts. This observation further supports the notion that rule-based number facts are stored and encoded differently (Ashcraft, 1992; for evidence from brain imaging studies, see Jost et al., 2004, 2009). Notably, RM was not able to directly retrieve multiplication facts other than the 5-tables. RM's prolonged and extensive finger use might have specifically facilitated the storage and access of the 5-tables because fingers of one hand sum up to five (Domahs et al., 2008). Importantly, some of the solution strategies employed by RM (especially the extensive use of 5-tables in combination with counting up or down) reflect excellent conceptual and procedural arithmetical knowledge. With respect to acquired calculation disorders as observed in neurological patients that have sustained cerebral injury to number-relevant brain regions, previous case studies have shown that conceptual arithmetical knowledge (i) may be dissociated from other aspects of numerical cognition, and (ii) may be effectively used to bypass deficient number fact knowledge (Hittmair-Delazer et al., 1994; Delazer and Benke, 1997). Furthermore, in the developmental literature, the close interplay between conceptual and procedural knowledge has been repeatedly emphasized (e.g., Rittle-Johnson et al., 2001). The case of a developmental MD in adulthood reported here corroborates both the neuropsychological and the developmental literature because it shows that conceptual arithmetical knowledge – in tandem with procedural knowledge – constitutes a valuable tool for bypassing impaired or patchy number fact knowledge. Thus, conceptual arithmetical knowledge should be assigned a key role in developmental and adult calculation models alike. An open question is whether RM's mental number representations are deficient *per se* (storage deficit) or whether they are difficult to access. Importantly, finger usage while solving number facts does neither indicate the absence or presence of number fact representations nor does it enable us to differentiate between storage and access problems. Instead, systematic investigations targeted at examining interference, consistency and problem size effects may aid us in disentangling storage and access deficits in numerical cognition research (Kaufmann et al., 2004). Though it could be argued that the usage of elaborate strategies instead of fact retrieval shows a good understanding of the number system and relations between operations, the characteristic feature of the finger use displayed by RM reflects a highly immature and inflexible use of fingers as an external token system. Within the developmental framework proposed by Kucian and Kaufmann (2009) RM's counting behavior suggests that the developmental shift from concrete and notation-specific to a more abstract and notation-independent number representation might not have taken place yet.

Overall, this case study shows that (i) finger-based calculation strategies might accompany MD in adults; and (ii) immature calculation strategies may persist despite excellent procedural arithmetic skills and average working memory resources. Nonetheless, RM's persistent finger usage upon solving simple number facts does not allow us to disentangle storage from access problems. A further unresolved issue concerns the question whether in RM the excessive use of finger counting reflects a back-up strategy employed to circumvent poor math skills or whether RM's overly reliance on finger counting might have had detrimental effects on early math development (see Moeller et al., 2011). Though we believe that the finger counting observed in RM most likely reflects a strategy to deal with MD, the latter assumption remains speculative thus far. As a final note we would like to draw the reader's attention to the fact that though average calculating adults do not typically use overt finger counting strategies, their calculation performance may reveal some reliance on finger-based number representations (Klein et al., 2011). However interestingly, with respect to acquired calculation disorders (evolving as a sequence of traumatic brain injury) the current literature does not report the use of overt finger counting behavior as a back-up strategy to solve number fact retrieval (e.g., Hittmair-Delazer et al., 1994; Zaunmüller et al., 2009). A limitation of the present study is the lack of information about RM's early math development which possibly could aid us in disentangling the nature of the excessive finger counting displayed by RM (i.e., finger counting reflecting a strategy to circumvent poor math skills versus finger counting fostering poor math skills by hampering the adoption of mature calculation strategies). Future studies are clearly needed to investigate finger-based calculation strategies in adults with MD in detail and to identify and characterize potential commonalities as well as divergences with (initial and prolonged) finger usage during children's acquisition of arithmetic skills.

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The role of finger representations and saccades for number processing: an fMRI study in children

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A possible functional role of finger representations for the development of early numerical cognition has been the subject of recent debate; however, until now, only behavioral studies have directly supported this view. Working from recent models of number processing, we focused on the neural networks involved in numerical tasks and their relationship to the areas underlying finger representations and saccades in children aged 6–12 years. We were able to differentiate three parietal circuits that were related to distinct aspects of number processing. Abstract magnitude processing was subserved by an association area also activated by saccades and visually guided finger movements. Addition processes led to activation in an area only engaged during saccade encoding, whereas counting processes resulted in the activation of an area only activated during visually guided finger movements, namely in the anterior intraparietal sulcus. Apart from this area, a large network of specifically finger-related brain areas including the ventral precentral sulcus, supplementary motor area, dorso-lateral prefrontal cortex, insula, thalamus, midbrain, and cerebellum was activated during (particularly non-symbolic) exact addition but not during magnitude comparison. Moreover, a finger-related activation cluster in the right ventral precentral sulcus was only present during non-symbolic addition and magnitude comparison, but not during symbolic number processing tasks. We conclude that finger counting may critically mediate the step from non-symbolic to symbolic and exact number processing via somatosensory integration processes and therefore represents an important example of embodied cognition.

Keywords: canonical numerical hand shapes, movement vocabulary, ordinal aspects of cognition

INTRODUCTION

A POSSIBLE ROLE FOR FINGERS IN NUMERICAL COGNITION

A possible functional role for finger representations in the development of numerical cognition has recently been debated (e.g., Andres et al., 2008). This discussion has received support from different studies in both children and adults. Recent findings in children included the following: that finger gnosis was a better predictor than was global development for calculation skills 1 year later but not for reading (Noël, 2005); that a pure finger gnosis training improved some numerical skills (Gracia-Bafalluy and Noël, 2008); and that finger-related split-five-errors occurred in a high percentage of primary school children, especially when they were starting to retrieve the results of simple addition and subtraction as arithmetical facts from long-term memory (Domahs et al., 2008). In adults, it has been shown that directional finger counting habits have an effect on individual cognitive spatial–numerical associations (Di Luca et al., 2006; Fischer, 2008; Sato and Lalain, 2008; but see Brozzoli et al., 2008, for contrasting results) and that even in adults, finger counting-related sub-base-5 representations have an impact in Arabic number magnitude comparisons (Domahs et al., 2010).

This functional relationship between finger counting and numerical representations might be related to the anatomical proximity of relevant brain areas (for a recent review, see Dehaene, 2009). Thus far, the only imaging study investigating numerical processing using pictures of canonical hand shapes for numbers (Kaufmann et al., 2008) has revealed respective activations in the bilateral supramarginal gyrus and anterior intraparietal sulcus (aIPS) extending to the post- and precentral gyrus; these activations were stronger in children than in adults.

From a cognitive point of view, canonical finger configurations as used for showing numbers might serve as iconic representations of numerosities (Fayol and Seron, 2005). It has been shown that, at least in adults, canonical hand shapes for numbers automatically activate exact number semantics, whereas non-canonical ones do not (Di Luca and Pesenti, 2008). Furthermore, canonical hand shapes for numbers are cognitively processed similar to number symbols, whereas non-canonical hand shapes are processed like non-symbolic magnitudes (Di Luca et al., 2010). This pattern of findings points to a possible role of number-related finger configurations as a "missing link" (Fayol and Seron, 2005) or "missing tool" (Andres et al., 2008) for connecting non-symbolic numerosities and symbolic number representations as needed for arithmetic. However, it remains unknown to what extent the symbolic processing of numerical canonical hand shapes is present in children, and if so, whether it becomes more or less relevant during development.

EMBODIED COGNITION

It has been suggested that finger counting is a prototypical example for embodied cognition (Wilson, 2002; see also Fischer and Brugger, 2011). Children learn the ordinal aspects of number processing by (finger) counting (Brannon and Van de Walle, 2001). This process requires somatosensory integration, a process that may play a major role in cognitive development (Piaget, 1952) and may be paralleled by an integrated involvement of parietal and frontal brain areas. The theory of embodied cognition similarly postulates that mental concepts may be built up out of cognitive primitives that are, themselves, somatosensory in nature (Wilson, 2002) or are at least influenced by bodily constraints (Anderson, 2003), such as the fact that we have five fingers on each hand (Domahs et al., 2010). The neural mechanism that has been suggested to underlie all forms of embodied cognition is the repeated firing of similar neural populations in a similar pattern (see Niedenthal et al., 2005, for a review).

In any case, trying to understand the functional role of finger-related brain areas for numerical cognition requires knowledge about the neural correlates for finger representations. This topic will be explored in the next section.

BRAIN REGIONS ASSOCIATED WITH FINGER REPRESENTATION

The brain systems engaged in the sensory- and motor-related aspects of the fingers are distinct in nature and are organized along the ascending and descending pathways of the brain. The somatotopic organization of the brain related to the fingers is found along the pathways from the fingers themselves up to the higher representations in the motor cortex. They include systems in the spinal cord, medulla, ventral basal complex, S1, S2 (insula), anterior and posterior parietal lobule, anterior IPS, and SMA. In general, the somatotopic organization in the motor cortex is substantially less precise than in the sensory cortex (FitzGerald, 1985).

The premotor and motor cortex areas code for the directions of movements and are hierarchical in their organization. Actual movement execution is organized by lower motor systems in the peripheral nervous system; yet, the cerebral motor cortex is tightly interconnected with the basal ganglia and the thalamus, from which it receives input via a feedback loop (FitzGerald, 1985). Abstract motor programs (as needed for finger counting) are believed to also include the activation of the pre-supplementary motor area (preSMA), the SMA proper, the frontal eye fields (FEF), and the IPS (FitzGerald, 1985). In addition, the frontal operculum (FOP) may be engaged in the linking of verbal labels to sequences because it is active in both verbal as well as in imagined movements of the tongue and hand (Schubotz and von Cramon, 2001).

In a review paper, Rizzolatti and Lupino (2001) explained that in the primate motor cortical areas, at least three types of higher cognitive functions are already subserved: somatosensory transformations, action understanding, and decision processing regarding action execution. Specifically, the primate brain area F5, which is located in the ventral premotor cortex (vPMC) and receives the most input from the anterior intraparietal (AIP) region (see also Koten et al., 2009 for the genetic functional connectivity of these two areas in humans) is thought to underlie the organization of hand and mouth movements by coding for specific actions (and not the single movements that form them) in the sense of a "motor vocabulary" (Rizzolatti and Lupino, 2001). More specifically, in humans, the vPMC and the intraparietal areas (among other areas including the inferior frontal gyrus) have been shown to be related to finger sequence complexity (Harrington et al., 2000; Haslinger et al., 2002) and to encoding interval (and ordinal) aspects of visually presented sequences (Schubotz and von Cramon, 2001). Furthermore, the vPMC and the anterior part of the IPS have been found to be active during the observation of actions, with an interesting lateralization of the vPMC activation that was stronger on the left side for watching actions with wrong objects and stronger on the right side for wrong movements (Manthey et al., 2003). Two reviews have pointed to similar roles of the vPMC, namely for task representations (Brass et al., 2005) and for higher aspects of goal-directed (finger) actions in humans (Binkofski et al., 1999). Taken together, the vPMC and anterior parietal cortex seem to subserve higher cognitive aspects of hand motor sequences and action encoding and may, therefore, be optimal candidates for the neural correlates of finger counting-related embodied cognition in number processing. The next section will focus on the possible additional role of these cortical areas in numerical cognition.

BRAIN REGIONS FOR NUMBER REPRESENTATION

Non-human primate studies and studies in other mammal species suggest that there are three classes of number neurons in the intraparietal sulcus in different areas that may be linked to distinct forms of number processing (see also Dehaene, 2009). First, the accumulation of visually presented objects might rely on the neural systems located in the lateral intraparietal area (LIP) in the monkey, systems which might also be related to the memory for saccadic positions (Roitman et al., 2007). In humans, it has been shown that the neural circuitry involved in eye movements seems to be differentially recruited for mental arithmetic: addition seems to activate neurons subserving rightward saccades, whereas subtraction shows a relatively stronger activation of neurons subserving leftward saccades (Knops et al., 2009). The LIP area is located in the lateral aspects of the monkey brain, but the human homolog of this area remains a matter of debate (Shikata et al., 2008). A recent study found such accumulating number-sensitive neurons in the human posterior superior parietal lobe (PSPL: Santens et al., 2010). Second, counting behavior might rely on number neurons that code for action in the AIP area, which is closely linked to representations of the hand (monkey brain: Sawamura et al., 2002). This area corresponds to the aIPS/postcentral sulcus in humans, which was found to be active in children in a numerical task using hand pictures as stimuli (Kaufmann et al., 2008). Third, abstract representations of numbers are assumed to be linked to multi- or polymodal brain systems such as the ventral intraparietal area (cat brain: VIP; Thompson et al., 1970), which processes number magnitude information independent of stimulus modality (human brain: Piazza et al., 2007).

Recently, Bongard and Nieder (2010) suggested that successful rule applications, as needed for arithmetic operations, might depend on prefrontal cortex (PFC) areas in monkeys. In humans, both intraparietal and dorso-lateral prefrontal (DLPF) areas, among others, were shown to be active during number processing and calculation (see Arsalidou and Taylor, 2011 for a recent meta-analysis). The (bilateral) vPMC was also among the brain areas identified in this meta-analysis, although its function in number processing was hardly discussed (but see Pesenti et al., 2000; Venkatraman et al., 2005 for exceptions relating this vPMC activation to finger counting in both adults and children, respectively). A recent study found that only the right vPMC showed overlapping activations during the numerical judgment of sequentially as well as simultaneously presented visual stimuli, which points to a role of the right vPMC in some kind of internal numerical representations (Dormal et al., 2010). A study using transcranial magnetic stimulation (TMS) confirmed the functional role of the vPMC in counting (Kansaku et al., 2007), and two studies have shown that number processing changed the motor excitability of the hand (Andres et al., 2007; Sato et al., 2007), thus adding strong evidence to the role of the vPMC for numerical processing. Furthermore, the first study investigating the use of pictures of hands with different numbers of raised fingers as numerical stimuli identified the post-central sulcus extending into the aIPS as a possible key region for finger-based numerical representations (Kaufmann et al., 2008). A recent meta-analysis found that this region was more active in dyscalculic children than in typically developing children and was more active in the latter compared to adults. Neural activity in this key brain region was also increased in children during non-symbolic compared to symbolic number processing (Kaufmann et al., 2011). One may conclude that the acquired motor programs for finger counting (presumably subserved by the vPMC and aIPS) might still be active during (non-symbolic) number processing, even when children do not continue to use fingers for calculation, and also that the importance of finger areas might decrease with age.

RESEARCH QUESTIONS

The findings from different fields of research as described above lead to the following assumptions:

If the ordinal aspects of number processing such as finger counting play a role for the development of numerical cognition due to the somatosensory integration of finger representations into number representations, brain areas related to the motor loop system for fingers such as the S1, aIPS, S2 (insula), vPMC, (pre)SMA, M1, FEF, thalamus, and basal ganglia may be active during number processing tasks in children. Of these areas, specifically, the aIPS/postcentral sulcus (somatosensory finger representations) and the vPMC ("motor vocabulary") might be key candidate areas for finger-based number representations.

To ensure that the activation in our finger movement task (see Materials and Methods) was exclusively related to finger representation and not to other cognitive aspects such as vision or eye movement, we used the encoding phase of a visual working memory task as a control condition. This choice should enable us to differentiate different aspects (finger-related, saccade-related, polymodal) of numerical processing in intraparietal areas (see Dehaene, 2009 for a similar approach) with inclusion and exclusion analyses (see Materials and Methods). The latter is of importance because visually guided finger movements activate large parts of the brain that might completely overlap with number tasks and, therefore, show very little differentiation.

Specifically, we expect that polymodal (non-symbolic as well as symbolic) number representations should be found in the polymodal association cortex (VIP), which should also be active in both the finger movement and the saccade tasks. Furthermore, activation related to addition should be found in areas that are coactivated by visually guided saccades (LIP). Counting operations (as needed for the non-symbolic exact addition task) might go along with coactivation of the somatosensory and premotor cortex (AIP and vPMC).

In general, finger-related activations might be more active in addition than in magnitude comparison because finger counting is more frequently used and more important for calculation. However, at least in adults, cognitive traces of finger-based number representations have also been found for more basic tasks such as number comparison. Furthermore, finger-related activation should be more active during non-symbolic activation than during number processing because finger-based numerical representations might provide a link to exact magnitude representations, which can be directly accessed by number symbols. Finally, we expect a decrease of number-related activations in finger-related areas with age.

MATERIALS AND METHODS

PARTICIPANTS

Overall, 33 school-aged children participated in our study. Among them, 10 children moved more than 3.5 mm during at least one of the functional tasks and were therefore excluded from the data analysis. Technical problems during functional data acquisition led to the exclusion of two more children; one child was only correct in approximately 50% of all trials of one task (non-symbolic addition) and thus was also excluded. Finally, the functional data of 20 children (9 girls) between 69 and 150 months of age (mean age: 108 months, SD: 21 months) were included in the study. Their estimated IQ (Colored Progressive Matrices; Bulheller and Häcker, 2002) ranged from the 32nd to the 100th percentile with a mean percentile of 66 (SD = 21). All children attended normal schooling, had normal or corrected to normal vision, and had no reported history of major medical illness, neurological, developmental, or psychiatric disorder (except for one child with known attention-deficit disorder). The study was approved by the local ethics committee and was conducted according to the Convention of Helsinki. Written and informed consent was obtained from all caregivers of the children. The children received a small financial compensation for participation.

TASKS AND STIMULI

The children were familiarized with all tasks outside the scanner on a computer screen. In the scanner, they started with a visually guided finger movement task, followed by four numerical tasks in pseudo-random order, and a visual working memory task (of which the encoding phase was used for this study) in the end. Between the tasks, the scanner was stopped, children were asked if everything was all right, told which task was to complete next, and, if necessary, reminded to lie still. It is important to note that the children could not use their fingers for counting in the scanner because they had to keep their right and left index fingers on the response buttons as a task requirement. Furthermore, the children were observed from outside the scanner to check whether they had removed their fingers from the response device placed over their stomachs; fortunately, no child did so during the study period.

During the visually guided finger movement task, children observed four horizontally aligned black dots (approximately 2 cm in diameter) against a white background that turned red in pseudo-randomized order. Each dot corresponded to a finger: the leftmost dot to the left middle finger, the next one to the left index finger, the third dot to the right index finger, and the rightmost dot to the right middle finger. The children were asked to press the correct button as soon as a corresponding dot turned red. In the scanner, an MR-compatible response box with four horizontally aligned response buttons was centrally placed on the participants. Stimuli were presented in 4 blocks of 12 stimuli each. Rest conditions were included for 14 s between the blocks. This task was used to elicit brain activations related to finger representations that are thought to be needed for finger counting as well, as in both instances the differentiation of specific fingers is necessary.

The four numerical tasks represented symbolic and non-symbolic magnitude comparison as well as symbolic and non-symbolic addition. In each task, two numerosities were presented simultaneously on the screen until the children pressed a button (left or right index finger) in response. In the scanner, an MR-compatible response box with four response buttons was centrally placed on the participants, and responses were given by pressing the leftmost or the rightmost button, respectively. In a recently published pilot study, we showed that this self-paced stimulus presentation paradigm was much more reliable and was at least as sensitive as a fixed stimulus presentation paradigm (Krinzinger et al., 2011). In the magnitude comparison tasks, children had to press the button corresponding to the side with the larger stimulus, and a vertical white line was always present in the middle of the black screen and also in the rest condition. In total, 24 stimuli were presented in two blocks of 12 stimuli each, with a rest condition of 14 s after each block. In the addition task, children had to press the right button if the two numerosities added up to 7 and the left button if the respective result was smaller or larger than 7. A white plus sign was always present during the addition tasks. The presented numerosities ranged from 2 to 5 (identical numerosities were never presented within one item so that the same stimuli could be used for the magnitude comparison and the addition tasks). The 24 addition stimuli were presented in 6 blocks comprising 4 stimuli each. The rest condition was again 14 s between blocks. The 24 stimulus combinations employed in each task were designed such that half of them added up to 7, the other half added up equally often to a number smaller (5 or 6) or larger (8 or 9) than 7, and the larger numerosity was presented on the left side and the right side equally often. In the non-symbolic tasks, two dot arrays (black randomly distributed dots in a white circle against a black background) were used as stimuli. These dot arrays were created using a Matlab program available on www.unicog.org). In half of the pairs, dots of both arrays had the same size, and in the other half, the overall area of dots was equal (see **Figure 1** for an example stimulus of exact non-symbolic addition with equal overall area of dot arrays). For the symbolic tasks, Arabic digits were presented in white and appeared approximately as large as the dot patterns on the screen (approximately 9 cm).

During the visual working memory task, the children observed three randomly distributed large dots which turned blue for 1 s, one after the other, a fixation cross for 3 s, and then the same three dots which turned blue in either the same or a different order. They then had to decide whether the sequence was the same (right button press) or not the same (left button press). This task was repeated with 24 differently shaped stimuli, with rest periods for 14 s after sets of 4 stimuli each. In the scanner, an MR-compatible response box with four response buttons was centrally placed on the participants, and responses were given by pressing the leftmost or the rightmost button, respectively. Only activation data from the encoding phase (visually guided saccades) was used for this study. It is important to note that no finger movements were required during this encoding phase.

Stimulus presentation and data recording were accomplished using Presentation (Neurobehavioral Systems, Albany, CA, USA)[1]. In the MR scanner, participants viewed the stimuli via MRI-compatible video goggles (VisuaStim XGA, Resonance Technology) with a horizontal viewing angle of 30° and a vertical viewing angle of 22.5°.

MRI IMAGE ACQUISITION

Imaging was performed on a 3-T magnetic resonance scanner (Siemens Trio, Siemens Medical Systems, Erlangen, Germany) using a 16-channel head coil. To minimize head movement, children's heads were comfortably stabilized with foam cushions. Previous child studies showed partly disappointing results with

[1] http://www.neurobs.com

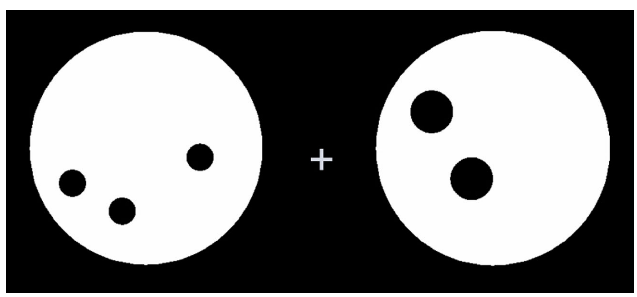

FIGURE 1 | Example stimulus of the exact non-symbolic addition task with equal overall area of dots for both arrays.

conventional sequences. Here, we applied a parallel imaging technique that allows for relatively fast acquisition times at the cost of reduced signal to noise ratio. The benefit of this method is that data are less prone to spatial distortions, and corrections for head movements can be applied with greater precision compared to normal sequences with relatively slow TR times. Functional images were obtained using an echo-planar image (EPI) 2D bold Grappa sequence with an acceleration factor of 2 sensitive to blood oxygen level-dependent (BOLD) contrast with the following parameters: repetition time (TR) = 1.600 ms, echo time (TE) = 30 ms, flip angle (FA) = 72˚, field of view (FOV) = 384 × 384, slice thickness (ST) = 3.5 mm with 10% gap, matrix size (MS) = 64 × 64, spatial resolution = 3.5 mm × 3.5 mm × 3.5 mm, and 30 axial slices parallel to the AC–PC line. A T1-weighted anatomical data set was obtained from each child (TR = 1.900 ms, TE = 2.52 ms, FA = 9˚, FOV = 256 × 256, ST = 1 mm, spatial resolution 0.98 mm × 0.98 mm × 1 mm).

FUNCTIONAL IMAGING DATA PREPROCESSING

The structural T1 scans of all children were brought into Talairach space (Talairach and Tournoux, 1988) using semi-automatic procedures. The co-registration file obtained during this step was used for all further co-registration purposes described below. The EPI sequences were processed with the following procedure: a slice scan time correction was executed using sinc interpolation. Subsequently, data were corrected for head movements using sinc interpolation, and 10 children with head movements larger than one voxel size (3.5 mm) were not included in the sample (see above). Next, linear trends were removed from the time courses using fast Fourier transformation methods, and a high pass filter was applied with two cycles. Subsequently, data were spatially smoothed with a smoothing kernel of 7 mm. The functional data were than co-registered with the anatomical scans in native space using sinc interpolation. This step was necessary for the creation of so-called volume time course maps (VTC). Finally, the time courses were aligned in Talairach space using the alignment files that were obtained in the previous steps and re-sampled on a 3-mm iso-voxel grid using sinc interpolation.

In addition, a child template in Talairach space was produced based on children's brain scans obtained in another study (Krinzinger et al., 2011). Finally, this template was used for the projection of all significant brain activation maps. In contrast to this previous study, the data were not cortically aligned in the actual study. Therefore, our results do not have the precision and quality of cortex-based aligned studies, and conclusions about the exact localization of brain activation spots have to be interpreted with caution for two reasons. First, part of the spatial resolution of data is lost due to spatial smoothing. Second, transformations that do not rely on cortex-based alignment can be corrupted by large mismatches in spatial correspondences of individual anatomical structures (Ghosh et al., 2010). Nevertheless, a true child template in Talairach space is to be preferred over the usually applied adult template in Talairach space. Although the anatomical structures of higher cortical systems in the children's brains will not likely correspond to the anatomical structures of an individual female adult brain (Talairach and Tournoux, 1988; Giedd et al., 1999), we will refer to the Talairach coordinates in this study, to make our results more comparable to previous (and future) findings.

FUNCTIONAL DATA ANALYSES

From the VTC data, linear contrast beta weights were estimated at the first level, with the standard general linear model (GLM) as implemented in BVQX 2.3[2] using the separate subject option. Percent signal change normalization was applied such that the data from distinct runs can be compared for further statistical analysis. The variance caused by head movements was removed from the data with the head movement data as predictors of no interest in the GLM. Next, beta weight estimates for experimental design parameters corrected for head movements were imported into Matlab using BVQX tools[3]. Subsequently, the beta weights of the six tasks under study were analyzed at the second level for deviation from zero using t-tests. The maps resulting from the t-test were used for inclusion and exclusion analyses.

For the inclusion (or conjunction) analysis, the logic of Nichols et al. (2005) was followed. They based their approach on the minimum t-statistics, providing very conservative estimates for the conjunctions of brain activation data (Friston et al., 2005). All the areas of activation in our analyses arise from conjunction analyses obtained from a varying number of contrasts (two to six). Depending on the statistical philosophy in use, all conjunctions are either declared significant at $p = 0.01$ (Nichols et al., 2005) or conjunctions are significant in a p-value range between $p = 0.01^2$ and $p = 0.01^6$ (see for example the computation in Price and Ansari, 2011, p. 1207). In the exclusion (or disjunction) analyses (concerned with two sets of paradigms/contrasts), only those voxels are considered significantly activated, which are activated above a certain threshold in all "included" paradigms (see Nichols et al., 2005), but not in any of the "excluded" paradigms. This approach does not test for relative activation differences but does test for the presence or absence of activation in two (non-empty, non-overlapping) sets of contrasts.

The combined use of conjunction/disjunction analysis is less conventional, but it is similar to the "masked conjunction analysis" procedure introduced in 1997 (Price et al., 1997; see also Xu et al., 2001). Masking is a very conventional method within the SPM philosophy. In our study, conjunction/disjunction (or inclusion/exclusion) analyses have some advantages over direct contrasts for the following reasons: first, inclusion/exclusion analyses do not suffer from an artificial boost of activation differences, as observed in unmasked direct contrasts, in which areas of deactivation may be subtracted from areas of activation. Second, inclusion/exclusion analyses do not suffer from masking artifacts that might occur when direct contrasts are masked for deactivated areas. Third, inclusion/exclusion analyses can show higher test–retest reliability when compared to direct contrasts that may suffer from poor functional signal to noise ratio.

The results of the conventional second level analyses as well as the inclusion and exclusion analyses were thresholded at an uncorrected $p = 0.01$ and corrected for multiple testing with a 3D Monte Carlo cluster-threshold estimation as implemented in BVQX using

[2] www.brainvoyager.com
[3] www.support.brainvoyager.com

1000 iterations. For the Monte Carlo simulation, no mask was used to restrict the 3D space to gray matter only. All reported results are significant at a cluster-threshold corrected p-value of 0.05. Clusters that survived the critical cluster size were re-imported into Matlab using BVQX tools. Subsequently, the data were analyzed with tools programmed by one of the authors (Jan Willem Koten). BVQX coordinates were transformed into Talairach space, and the voxel with the peak activation within each significantly activated cluster was extracted.

Finally, the developmental effects on the link between finger representations and numerical processing were studied by analyzing the correlations between age and individual beta weights of the numerical tasks as well as the visually guided finger movement task for all clusters specifically activated only during the visually guided finger movement task (short: finger task) and the numerical tasks (but not the visually guided saccades task). The correlations were Fisher's-z transformed and averaged over all the voxels of each cluster of interest. Finally, the averaged correlations were retransformed and tested for departure from zero including a Bonferroni correction for the cluster resulting from each inclusion–exclusion analysis.

RESULTS

BEHAVIORAL RESULTS

Mean accuracy rates were very high for all tasks (0.93−0.96), and reaction times (RT) varied considerably between children. Descriptive statistics for RT and accuracy for the six tasks can be obtained from **Table 1**.

Significant speed-accuracy trade-offs were not found for any task, although it tended to be significant for the visual working memory task ($r = -0.437$, $p = 0.057$). This task was the only one for which accuracy ($r = 0.689$, $p = 0.001$), but not RT ($r = -0.325$, $p = 0.162$), correlated significantly with age (Bonferroni-corrected $\alpha = 0.0024$ for all correlations with age or IQ). For all other tasks, age did not correlate with accuracy (all $r < -0.31$, all $p < 0.17$) but did correlate with the RT of all tasks (all $r \leq -0.689$, all $p \leq 0.001$) except for the non-symbolic addition task ($r = -0.629$, $p = 0.003$). Estimated IQ did not correlate significantly with the RT (all $r \leq 0.624$, all $p \geq 0.004$) or accuracy (all $r \geq -0.581$, $p \geq 0.009$) of any task. Within the accuracy rates (Bonferroni-corrected $\alpha = 0.0033$), only the accuracy of the finger representation task and the non-symbolic addition task ($r = 0.655$, $p = 0.002$) as well as the accuracy of the symbolic and the non-symbolic magnitude comparison tasks were significantly correlated ($r = 0.661$, $p = 0.001$; all other $r < 0.525$, all $p > 0.018$). Among the RT measures (Bonferroni-corrected $\alpha = 0.0033$), the RT of the finger representation task was significantly correlated with the RT of both comparison tasks (both $r > 0.731$, both $p < 0.001$, all other $r \leq 0.619$, all $p \geq 0.004$). The RT of the working memory task did not correlate significantly with the RT of any other task (all $r \leq 0.578$, all $p \geq 0.008$), but the RTs of all four numerical tasks were significantly correlated (all $r > 0.723$, all $p < 0.001$).

Partial correlations for all significant correlations controlling for effects of age, estimated IQ, and respective accuracy rates or RT of all other tasks were still significant for accuracy rates of finger representation and non-symbolic addition ($r = 0.686$, $p = 0.010$) and the accuracy of symbolic and non-symbolic comparison ($r = 0.582$, $p = 0.046$). No other partial correlations remained significant.

In summary, specific behavioral relationships were found between finger representation and non-symbolic addition as well as between symbolic and non-symbolic comparison.

Table 1 | Descriptive statistics of behavioral results (reaction times in seconds).

Task		Mean	SD	Range
Visually guided finger movement	Accuracy	0.96	0.03	0.88–1.00
	RT	0.71	0.18	0.40–1.11
Symbolic comparison	Accuracy	0.99	0.02	0.92–1.00
	RT	0.82	0.24	0.51–1.28
Non-symbolic comparison	Accuracy	0.96	0.01	0.92–0.96
	RT	1.08	0.32	0.54–1.77
Symbolic addition	Accuracy	0.95	0.06	0.83–1.00
	RT	2.20	1.60	0.70–5.71
Non-symbolic addition	Accuracy	0.93	0.06	0.75–1.00
	RT	3.84	1.60	1.24–6.59
Visual working memory	Accuracy	0.91	0.08	0.75–1.00
	RT	2.25	0.54	1.57–3.80

BRAIN IMAGING RESULTS

Results of the second level GLM analyses for the six separate task contrasts against rest are presented in **Figure 2**. The symbolic (light blue) and the non-symbolic (light orange) number comparison task (**Figure 2A**) showed a highly similar activation pattern located in the dorsal stream of visual processing. In both tasks (overlap shown in light green), lower and higher visual systems were activated bilaterally including the superior posterior aspects of the parietal cortex extending into the medial aspects of the IPS. In the frontal part of the brain, activations for both magnitude comparison tasks were found on the left side corresponding to the FEF (for the symbolic comparison task bilaterally), while overlapping bilateral activations on the medial side of the brain corresponded to the supplementary eye fields (SEF) and SMA activations. In addition, a right insular activation was exclusively found for the non-symbolic number comparison task.

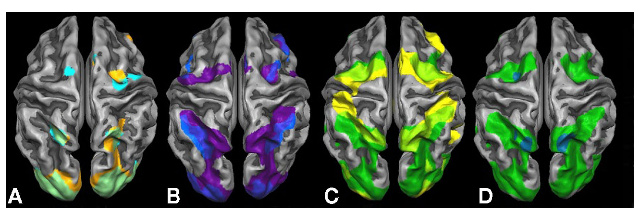

FIGURE 2 | Brain activation contrasts against rest for all six tasks projected onto a Talairach child template. Brain activations significant at a cluster-threshold corrected p-value of 0.05 are depicted: **(A)** symbolic (light blue) and non-symbolic (light orange) magnitude comparison; **(B)** symbolic (dark blue) and non-symbolic (purple) exact addition; **(C)** visually guided finger movements (yellow) and visually guided saccades (dark green); and **(D)** visually guided saccades/encoding phase (dark green) and sustained activity phase (turquoise) of the visual working memory task.

Significant brain activations of the symbolic (dark blue) and the non-symbolic (purple) exact addition tasks are shown in **Figure 2B**. Overlapping brain activations for both addition tasks were found in the lower and higher visual areas including the superior posterior aspects of the parietal cortex extending into the medial and lateral aspects of the IPS. Extended overlap was also found in the bilateral anterior insula, left vPMC, right FEF, and right DLPFC. Finally, bilateral overlap was found on the medial side of the brain including areas that correspond to the SEF and SMA. The symbolic addition task showed more extended activations in the lateral aspects of the IPS and the left DLPFC, whereas the non-symbolic addition task showed higher activations in the left FEF and right vPMC.

Figure 2C shows significant brain activation for the encoding phase of the visual working memory task (visually guided saccades; dark green) and the visually guided finger movement task (yellow). The finger task and the saccades task showed both individualized and overlapping areas of brain activation. Overlapping areas were found in the lower and higher visual areas including the superior posterior aspects of the parietal system extending into the medial aspects of the IPS accumulating in larger rostral IPS activations. Very large parts of the ventral and dorsal PMC, possibly extending into the SEF, were found to be overlapping bilaterally. Additionally, saccade-related activations were found in the ventral visual systems extending into the parieto-occipital sulcus and the lateral aspects of the IPS. (**Figure 2D** shows the regions active during the sustained activity phase of the visual working memory task, namely the left FEF and bilateral PSPL.) The finger task showed additional activations in finger-related sensory motor systems covering an extended band from the aIPS over the primary somatosensory systems into the primary motor systems on the left side of the brain, while an "interrupted" pattern was found on the right side. Moreover, extended activations were found in the bilateral insular cortex and the right DLPFC for the finger task only. The highly overlapping areas for the visually guided finger task and the visually guided saccade task clearly indicate that purely finger-related aspects of cognition cannot be traced without also employing a visual task. This phenomenon is particularly true for the activation pattern in the IPS that is subdivided into visual and finger-related aspects of cognition.

Further inspection of **Figure 2** suggests that the medial aspects of the IPS are activated in all number tasks. This "number area" seems to show overlap with an area that is activated in both the visually guided saccades and the visually guided finger movement task. Moreover, additions seem to activate the lateral aspects of the IPS and show overlap with an area that is activated in the saccade task but not in the finger task. Finally, additions compared to magnitude comparisons seem to activate larger dorsal as well as ventral premotor areas, the FOP, and the DLPFC, which might possibly overlap with motor-related aspects of cognition as activated by the finger task. These impressions were assessed more formally using an inclusion–exclusion analysis approach. The respective results can be found in **Figures 3** and **4**.

Figure 3A shows areas commonly activated by the visually guided finger movement and the visually guided saccades task (red), exclusively activated by the saccades task (green), and

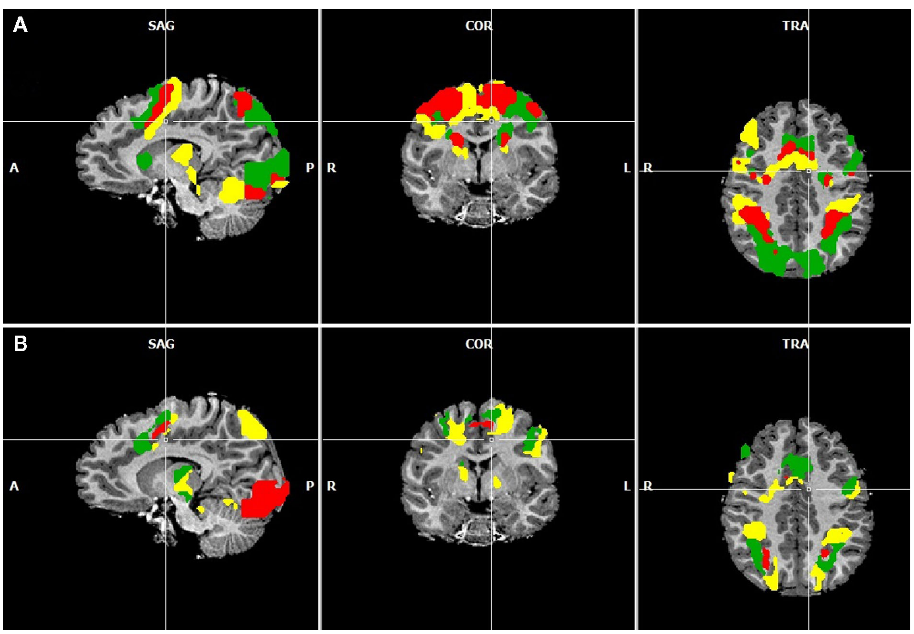

FIGURE 3 | (A) Overlapping regions for the non-numerical tasks using inclusion and exclusion analyses: regions commonly activated during the visually guided finger movement and saccades task (red), exclusively activated during the saccades task (green), and exclusively activated during the finger task (yellow). **(B)** Overlapping regions for the numerical tasks using inclusion and exclusion analyses: regions commonly activated during all four numerical tasks (red), regions exclusively activated during symbolic and non-symbolic exact addition (green), and regions exclusively activated during the non-symbolic addition task. All group activations are projected onto a single child brain in Talairach space and are each significant at a cluster-threshold corrected *p*-value of 0.05.

exclusively activated by the finger task (yellow). **Figure 3B** shows areas commonly activated by all four numerical tasks (red), exclusively activated by both addition tasks (green), and exclusively activated by the non-symbolic addition task (yellow).

It can be observed that areas that showed common activation for both non-numerical tasks and areas showing common activation for all four numerical tasks (depicted in red in both cases) seem to be located in the same IPS region, likely reflecting the polymodal area VIP. Moreover, an area exclusively activated during both the symbolic and the non-symbolic addition tasks (depicted in green in **Figure 3B**) showed spatial overlap in the LIP with an area that was exclusively activated during the visually guided saccades task (depicted in green in **Figure 3A**). The area exclusively activated during non-symbolic addition showed spatial overlap with an area that was exclusively activated by the finger task in the very anterior parts of the IPS extending into the wall of the somatotopic cortex (BA2: depicted in yellow in both **Figures 3A,B**). These specific overlaps are visualized more clearly in **Figure 4A** for parietal activation clusters (in red, green, and yellow as described above as well as blue for overlapping activation for both non-numerical and both addition tasks but not for the magnitude comparison tasks), in **Figure 4B** for medial activation clusters, in **Figure 4C** for frontal activation clusters, and in **Figure 4D** for subcortical activation clusters. The anatomical labels, cluster volumes, and corresponding Talairach coordinates for peak activations can be found in **Tables 2–6**. The estimated cluster thresholds were seven voxels for all clusters.

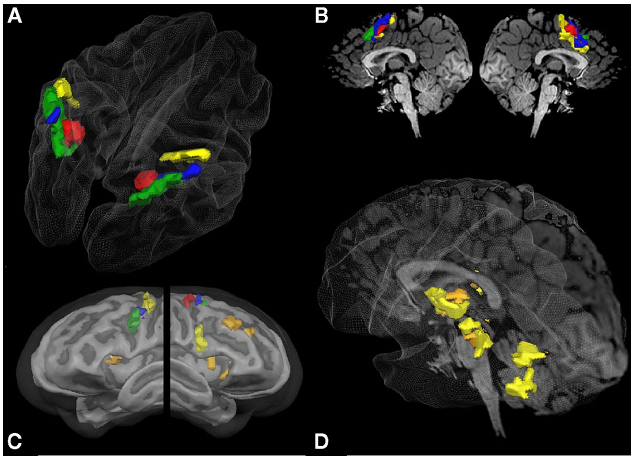

FIGURE 4 | Overlapping regions between specific numerical and non-numerical tasks using inclusion and exclusion analyses: conjunction of all six tasks (red); areas commonly activated in the visually guided saccades task and the visually guided finger task in conjunction with both addition tasks but not the two magnitude comparison tasks (blue); areas exclusively activated during the saccades task but not the finger task in conjunction with both addition tasks but not the magnitude comparison tasks (green); areas activated exclusively during the finger task in conjunction with both addition tasks (orange); and areas exclusively activated during the finger task and the non-symbolic addition task (yellow). All group activations are projected onto a Talairach child template [**(A)** parietal activation cluster; **(C)** lateral frontal activation clusters; **(D)** subcortical activation clusters] or a single child brain in Talairach space [**(B)** medial frontal activation clusters; **(D)** subcortical activation clusters] and are significant at a cluster-threshold corrected *p*-value of 0.05.

In addition to activations in the parietal cortex, activation of the frontal and subcortical structures might be of equal importance. **Figure 3** visualizes that the brain activity pattern found for the parietal cortex is inversely copied at the medial side of the brain (SMA). In this area, exclusively saccade-related activations are found in the rostral areas, while exclusively finger-related aspects are found in the caudal areas (**Figures 3A** and **4B**). This finding might mirror SEF and SMA-related systems. Activation during addition in this area might also be related to visual and finger representation or to polymodal components in the overlapping parts (**Figure 4B**). It has indeed been shown that parietal systems project to the medial aspects of the brain (Martin, 1996), making these similarities of activation patterns unsurprising.

Figure 4C shows the results for the inclusion and exclusion analyses for the frontal cortex. Not surprisingly, a cluster activated by all six tasks (red) was found in the FEF, suggesting that organized eye movements are of importance in all tasks. All other reported clusters showed activation during the addition but not the magnitude comparison tasks. In the left hemisphere, three different respective clusters were found originating in the precentral gyrus, extending in a rostral and ventral direction. The most ventral cluster was only active during both addition and the saccades tasks (green), whereas the most dorsal patch in M1 was only active during non-symbolic addition and the finger task (yellow). The intermediate cluster (blue) was activated in both the saccades and

Table 2 | Anatomical labels and volumes in cubic millimeter of clusters significantly activated in all tasks (depicted in red in Figure 3) with respective Talairach coordinates (*x y z*) of peak values for all included tasks.

Anatomical label (volume in mm³)	Visually guided finger movement			Visually guided saccades			Symbolic magnitude comp.			Non-symbolic magnitude comp.			Symbolic exact addition			Non-symbolic exact addition		
Bilateral supplementary motor area (1410)	−5	−3	50	4	3	47	13	3	44	13	3	44	7	12	38	13	6	41
Left ventral intraparietal area (889)	−20	−54	44	−23	−51	38	−17	−54	38	−17	−54	41	−29	−54	41	−17	−54	38
Right ventral intraparietal area (736)	28	−60	44	28	−60	44	28	−57	38	31	−57	41	31	−54	38	31	−57	41
Right frontal eye fields (273)	31	−9	50	31	−9	50	31	−12	56	31	−9	50	34	−6	59	34	−6	56

Table 3 | Anatomical labels and volumes in cubic millimeter of clusters significantly activated only in the visually guided finger movement task as well as in the symbolic and the non-symbolic exact addition tasks, but not during the visually guided saccades task as well as the symbolic and non-symbolic magnitude comparison tasks (depicted in orange in Figure 3) with respective Talairach coordinates (*x y z*) of peak values for all included tasks.

Anatomical label (volume in mm³)	Visually guided finger movement			Symbolic exact addition			Non-symbolic exact addition		
Right thalamus (1482)	10	−18	11	19	−12	20	13	−18	14
Left frontal operculum (879)	−23	15	5	−23	15	5	−23	15	5
Right dorso-lateral prefrontal cortex (778)	37	33	32	46	27	32	40	27	35
Left thalamus (746)	−8	−15	8	−11	−9	17	−8	−15	8
Right dorso-lateral prefrontal cortex (741)	28	33	23	37	33	20	28	33	26
Right frontal operculum/insula (541)	37	15	5	37	12	2	37	15	2
Bilateral midbrain (481)	1	−24	−13	1	−24	−13	1	−21	−13
Right frontal operculum/insula (329)	31	18	−1	25	18	2	31	18	−1
Left supplementary motor area (197)	−5	−9	56	−8	−6	59	1	−6	56
Bilateral supplementary motor area (172)	1	6	41	4	9	41	4	6	41
Right supplementary motor area (171)	13	0	50	7	−3	53	7	−3	53
Right cerebellum (122)	28	−60	−28	28	−66	−25	28	−60	−28

Table 4 | Anatomical labels and volumes in cubic millimeter of clusters significantly activated only in the visually guided finger movement task and the symbolic exact addition tasks, but in no other task (depicted in yellow in Figure 3) with respective Talairach coordinates (*x y z*) of peak values for all included tasks.

Anatomical label (volume in mm³)	Visually guided finger movement			Symbolic exact addition		
Right ventral premotor cortex (1327)	55	3	26	55	3	17
Bilateral supplementary motor area (1125)	−8	−12	56	16	6	38
Bilateral cerebellum (1099)	10	−57	−13	7	−48	−13
Right supplementary motor area (1050)	−2	0	41	1	0	41
Right anterior intraparietal area (920)	46	−27	53	49	−33	50
Bilateral midbrain (796)	1	−27	−13	7	−30	−10
Left thalamus (792)	−5	−18	8	−5	−15	8
Left anterior intraparietal area (750)	−44	−33	53	−44	−39	56
Right cerebellum (733)	10	−63	−19	13	−66	−19
Right thalamus (650)	16	−18	8	16	−21	8
Left motor area (598)	−38	−9	56	−41	−9	56

Table 5 | Anatomical labels and volumes in cubic millimeter of clusters significantly only in the visually guided saccades task as well as in the symbolic and the non-symbolic exact addition tasks, but not the visually guided finger movement task and the symbolic and non-symbolic magnitude comparison tasks (depicted in green in Figure 3) with respective Talairach coordinates (*x y z*) of peak values for all included tasks.

Anatomical label (volume in mm³)	Visually guided saccades			Symbolic exact addition			Non-symbolic exact addition		
Left lateral intraparietal area (3307)	−35	−48	53	−41	−51	56	−29	−54	41
Right lateral intraparietal area (1845)	28	−69	44	37	−51	35	28	−72	41
Bilateral supplementary motor area (1268)	−5	18	32	10	18	41	1	15	38
Left ventral premotor cortex (1136)	−44	0	47	−47	0	44	−47	0	35
Right frontal eye field (64)	31	3	53	34	0	50	34	0	50

finger tasks. Bilateral activation clusters in the insula and in the right DLPF cortex were found for symbolic and non-symbolic addition in conjunction with the finger task but not the saccades task (orange). Furthermore, a cluster in the right vPMC was exclusively activated during the non-symbolic addition and the finger task (yellow).

Furthermore, the addition tasks showed large overlap in subcortical systems, which were exclusively activated by the finger task but not the saccades task (**Figure 4D**: orange clusters). They included the more ventral basal aspects of the thalamus, the basal ganglia, and substantial parts of the midbrain. For the non-symbolic addition task, the more dorsal aspect of the posterior

Table 6 | Anatomical labels and volumes in cubic millimeter of clusters significantly in the visually guided finger movement and saccades tasks as well as in the symbolic and the non-symbolic exact addition tasks, but not in the symbolic and non-symbolic magnitude comparison tasks (depicted in blue in Figure 3) with respective Talairach coordinates (*x y z*) of peak values for all included tasks.

Anatomical label (volume in mm^3)	Visually guided finger movement			Visually guided saccades			Symbolic exact addition			Non-symbolic exact addition		
Bilateral supplementary motor area (2653)	−8	−6	56	1	6	44	7	12	38	16	9	38
Right intraparietal sulcus (736)	49	−39	44	34	−51	41	37	−48	35	37	−48	35
Right frontal eye field (438)	28	−6	44	31	0	53	34	−3	56	34	−3	53
Left premotor cortex (234)	−44	−3	47	−47	0	47	−44	0	44	−38	−3	44
Left intraparietal sulcus (157)	−32	−54	47	−32	−54	53	−35	−54	50	−32	−51	50

lobe of the cerebellum was found to be active as well (yellow). Activations in the thalamus and cerebellum may correspond to the respective somatotopic representations of the fingers (Martin, 1996).

Of all the clusters significantly activated only during the finger task and any numerical task (see **Tables 3** and **4**: depicted in orange and yellow in **Figure 4**), the overall highest correlation with age was found for the mean activation during the finger task in the smaller right DLPF cortex cluster ($r = 0.445$, two-sided uncorrected $p = 0.0492$). No correlation coefficient survived the Bonferroni correction. Therefore, correlations with age were not substantial and never explained more than 20% of the variance of brain activations common to finger representation and number processing.

Finally, we were interested in the non-symbolic and symbolic aspects of number processing and their overlap with saccades- and finger-related brain activation patterns. No cortical area was found to be exclusively active in both symbolic tasks, but not in the non-symbolic numerical tasks. Cortical brain areas exclusively activated during both non-symbolic numerical tasks, but not during the symbolic numerical tasks, showed specific patterns of overlap with the visually guided saccades task (green) and finger movement task (yellow) or with both (red: depicted in **Figure 5**).

Areas that were exclusively activated during non-symbolic number processing in conjunction with exclusively saccades-related activation (green) were found in bilateral areas of the primary visual cortex and a large cluster in the right hemisphere connecting the lateral occipital complex to the caudal aspects of the IPS via the parieto-occipital sulcus. Overlapping activation with both the visually guided saccades and the finger task (red) included the bilateral posterior eye fields (PEF), the right FEF, and the right parieto-occipital sulcus. Finally, a purely finger-related activation cluster was found in the right ventral precentral sulcus.

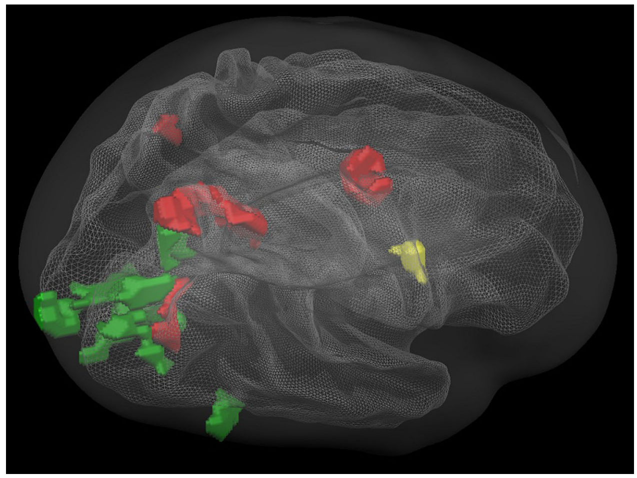

FIGURE 5 | Overlapping regions between specific non-symbolic numerical (magnitude comparison and exact addition) and non-numerical tasks using inclusion and exclusion analyses: regions commonly activated during all tasks (red); regions commonly activated during the non-symbolic number processing tasks and the finger movement task, but not the saccades task (yellow); regions commonly activated during the non-symbolic number processing tasks and the saccades task, but not the finger movement task (green). All group activations are projected onto a Talairach child template. All clusters are significant at a cluster-threshold corrected *p*-value of 0.05.

DISCUSSION

This study aimed to relate brain activations subserving numerical cognition in children to areas involved in finger representation. Another aim was the identification of areas underlying distinct types of numerical representations by means of inclusion–exclusion analyses using four numerical tasks and two non-numerical localizer tasks.

First, we tried to tease apart modality-specific and polymodal number processing areas in the cortex. The activation patterns we found were highly similar to the findings reported for the monkey as well as for the human brain. The number processing areas related to saccades in the lateral IPS showed high overlap with the monkey LIP area containing number neurons of the accumulating/monotonic magnitude coding type (Roitman et al., 2007), whereas the finger-related number processing areas in the aIPS (extending into the postcentral sulcus) were highly similar to the monkey AIP region (Sawamura et al., 2002) and human homologs (Kaufmann et al., 2008, 2011). The number processing area active during both the finger and the saccades task was found in a similar region to the monkey VIP, possibly related to polymodal number representation (cat brain: Thompson et al., 1970; human brain: Piazza et al., 2007; Dehaene, 2009).

Although these similarities are striking, they may not necessarily be correct. In particular, it has been discussed recently whether the human homolog of the LIP area may be located in the lateral aspects of the IPS (where we found overlapping activation related to saccades and addition; see also Culham and Kanwisher, 2001) or in the superior parietal lobe (where we found overlapping activation for both visually guided saccades and finger movements as well as non-symbolic number processing; see also Grefkes and Fink, 2005). Considering the accumulating characteristics of number neurons in the monkey LIP (Roitman et al., 2007), it may be speculated that these number neurons play a role in the addition processes. Concerning visual processes in the LIP region, one may speculate that the lateral posterior aspects of the IPS are related to the actual encoding of saccades, whereas the PSPL may be related to the maintenance of visual information in the absence of actual vision. An analysis of the visual working memory task during the sustained activity phase indeed showed active areas corresponding to the FEF and the PSPL. However, this discussion has not yet been resolved (Shikata et al., 2008).

The most important result was that the contribution of finger-related systems was stronger for calculation than for magnitude comparison and stronger for non-symbolic exact addition compared to symbolic addition. In our study, activation exclusively related to non-symbolic exact addition (for which counting and ordinal cognitive processes are required) was concordant with exclusively finger-related activation clusters in the bilateral aIPS (extending into the postcentral sulcus), left M1, right ventral precentral sulcus, bilateral SMA, bilateral thalamus, and midbrain as well as the finger-related areas in the cerebellum. (We have no consistent explanation as to why the homolog of the ventral precentral sulcus in the left hemisphere was exclusively activated during the visually guided saccades, but not the visually guided finger movement task). Our results showed that some of the frontal and subcortical regions were also active during symbolic addition, namely the right DLPFC, bilateral insula, aspects of the SMA, as well as the thalamus and midbrain. This putative (visually guided) finger movement network might be an important somatosensory integration system (Piaget, 1952) that is also activated during symbolic additions, which are generally not solved by counting, as the relatively short reaction times show. None of these regions showed decreases (or increases) in activation strength with age, meaning that, contrary to our expectations in our sample (from 6 to 12 years of age), no developmental changes concerning the activation of finger-related brain areas during calculation could be found.

Furthermore, finger-related activation in the ventral precentral sulcus was found to be present during non-symbolic, but not during symbolic, number processing. The very short reaction times for the non-symbolic magnitude comparison task clearly showed that no counting process could be involved in solving this task: 11-year-old children need on average 1.5 s to count five dots and 3 s to count nine dots (Schleifer and Landerl, 2010), whereas it took the slowest child in our sample of 6- to 12-year-old children 1.77 s on average to compare two arrays comprising overall five to nine dots. Therefore, the (right) vPMC may be interpreted as an area responsible for coding canonical hand shapes (and not counting procedures) used for showing numbers up to 10 (in analogy to a so-called "movement vocabulary" coded in the vPMC: Rizzolatti and Lupino, 2001): only the last step of the counting process is a static hand shape or finger posture that represents the exact cardinal aspect of numbers. The specific finger postures may be associated with exact number magnitudes during cognitive development and therefore turn into abstract symbols themselves (Di Luca and Pesenti, 2008). This speculative interpretation has to be taken with caution because we could not directly test this hypothesis with our design. We believe that disentangling the roles of finger counting procedures and canonical hand shapes for (non-symbolic) number processing and calculation will be a worthwhile endeavor for future studies.

In general, accumulating evidence points to the important role of finger representations for the development of exact, non-symbolic addition, possibly mediated by access to exact number magnitude representations for non-symbolic numerosities via the representations of number-related canonical hand shapes (Di Luca and Pesenti, 2008; Kaufmann et al., 2011). In conclusion, finger counting might critically mediate the step from non-symbolic to symbolic and exact number processing and therefore represent an important example of embodied cognition.

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The influence of implicit hand-based representations on mental arithmetic

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Recently, a strong functional relationship between finger counting and number processing has been suggested. It has been argued that bodily experiences such as finger counting may influence the structure of the basic mental representations of numbers even in adults. However, to date it remains unclear whether the structure of finger counting systems also influences educated adults' performance in mental arithmetic. In the present study, we pursued this question by examining finger-based sub-base-five effects in an addition production task. With the standard effect of a carry operation (i.e., base-10 crossing) being replicated, we observed an additional sub-base-five effect such that crossing a sub-base-five boundary led to a relative response time increase. For the case of mental arithmetic sub-base-five effects have previously been reported only in children. However, it remains unclear whether finger-based numerical effects in mental arithmetic reflect an important but transitory step in the development of arithmetical skills. The current findings suggest that even in adults embodied representations such as finger counting patterns modulate arithmetic performance. Thus, they support the general idea that even seemingly abstract cognition in adults may at least partly be rooted in our bodily experiences.

Keywords: mental arithmetic, finger counting, embodied cognition, sub-base-five

INTRODUCTION

In recent years, accumulating evidence suggests a functional relationship between the mental representation of number magnitude and bodily representations of finger movements (e.g., Fayol et al., 1998; Noël, 2005; Fischer, 2008). In particular, it was found that finger counting habits exhibit a reliable influence on the mental processing of number magnitude (e.g., Domahs et al., 2010, this issue; Imbo et al., this issue; Lindemann et al., 2011; Di Luca and Pesenti, this issue; but see also Andres et al., 2004; Badets et al., 2007; Song and Nakayama, 2008 for reciprocal influences of number magnitude on finger movements). Based on such data, it is argued that finger counting habits may influence the structure of the basic mental representations of numbers even in adults.

This is in line with recent findings in neuroscience (e.g., Andres et al., 2008 for a review) stating that the motor system not just controls and/or monitors actions, but also contributes to cognitive representations. As a possible explanation for these findings, several theories of embodied cognition have been proposed (see Wilson, 2002, for an overview). The most basic interpretation is that human cognition is originally rooted in sensorimotor processes and, thus, determined by bodily experiences. Such an interaction between the cognitive and physical world has been theoretically elaborated by Hommel et al. (2001) in the Theory of Event Coding. This theory provides an interpretative framework for many of the respective findings. While Hommel and colleagues did not examine the connection of numerical magnitude and motor activity explicitly, the idea of an embodied representation of numerosity has been considered by other researchers (e.g., Fischer, 2008). For instance, Fischer was able to show that finger counting habits are strongly related to spatial numerical processing. Moreover, Badets et al. (2010) found first evidence for a general effect of finger counting when pictures of finger gestures were explicitly presented in simple addition in adults. However, as the authors reported a main effect of presentation format (finger gestures vs. rods) the case of finger-based representations in arithmetic involving symbolic digital input remains to be evaluated.

So far, the influence of finger-based representations has only been investigated for more basic numerical task. For instance, in a magnitude comparison task with Arabic numbers performed by adult participants, Domahs et al. (2010) observed that whenever one of the to-be-compared number was larger than five (i.e., exceeding the magnitude which can be represented by one hand in the German finger counting system, e.g., 4_6) RT increased more strongly (compared to e.g., 2_4) than could be expected from the higher problem size of the former example. Importantly, this effect was observed in a number comparison task on symbolically presented numbers assumed to preclude any explicit reference to finger-based representations containing a sub-base-five system. Moreover, the authors were able to provide further evidence suggesting the origin of this effect to be rooted in influences of finger-based representations. When comparing this so-called 5 break effect between German and Chinese participants they found the 5 break effect to be present in the former but absent in the latter. Taking into account that the Chinese finger counting system allows for representing numbers from 1 to 9 on only one hand, whereas in the German finger counting system the numbers 6–10 are represented using both hands, this finding further corroborates the notion that even in adult numerical cognition finger counting is still influential for number processing. Interestingly, these behavioral findings converge with results from neuro-imaging data (e.g., Simon et al., 2002; Rusconi et al., 2005; Kaufmann et al., 2008) which pointed to shared or neighboring neuronal substrates of finger and number representations. These findings support the idea that the establishment of seemingly abstract representations is at least partially rooted in our bodily experiences.

Against this background evaluating the influence of bodily representations like finger patterns on number processing in children seems particularly promising, because almost all children recruit their fingers to aid counting and/or first arithmetic at some point of their numerical development (e.g., Butterworth, 1999). Accordingly, influences of finger gnosia on numerical development were observed (Fayol, et al., 1998; Noël, 2005) and it was also shown that training bodily experiences of numerical information is capable of improving numerical development (Gracia-Bafalluy and Noël, 2008; Fischer et al., 2011). Importantly, for children there is first evidence indicating that influences of bodily representations such as finger counting habits generalize to mental arithmetic (Domahs et al., 2008). In a longitudinal study, the authors examined the development of simple and complex addition and subtraction in grades 1 and 2. In line with the notion of finger-based influences, they observed that so-called split-five errors in simple calculation (i.e., errors with a difference of five from the correct result, i.e., erroneous results differing from the correct result by "a full hand") were reliably more frequent than expected at the beginning of grade 2. Domahs et al. (2008) interpreted these split-five errors as a failure to retrieve and/or keep track of the number of fives (i.e., full hands) involved while children calculated the result, possibly recruiting their fingers and hands. Nevertheless, most children use their hands in initial arithmetic (e.g., Butterworth, 1999). Moreover, Domahs et al. (2008) observed that the proportion of split-five errors decreased back to normal at the end of grade 2. Thus, it might be claimed that such sub-base-five effects may only be a transient stage during numerical development. Therefore, Domahs et al. (2008) concluded that mental number representations may at least temporarily inherit features of early external finger representations. This conclusion is further corroborated by the description of an addition strategy reported by Thompson (1999): solving the problem 6 + 7, Scott, a young boy, explained: "13... I took 5 out of the 6 and 5 out of the 7 and I was left with 3...." Although Scott is not reported to rely on overt finger counting anymore, this description indicates a specific role for the sub-base-five in his calculation procedure. Therefore, it seems plausible to assume that he used a mental representation that inherited characteristics of finger-based representations. In fact, in finger calculation it makes no considerable difference to refer to one or two full hands.

In sum, there is evidence for a functional relationship between finger and number representations in mental arithmetic at least during numerical development.

However, it remains unclear whether there are similar influences of finger-based representations on mental arithmetic performance of educated adults. In the present study we pursue this issue in a simple addition task requiring participants to verbally produce the result of the addition problems. We hypothesize that finger-based representations may not only influence mental arithmetic at a specific developmental stage, but that this influence generalizes to adult mental arithmetic. Consequently, if the influence of finger-based representations on mental arithmetic were only a transient stage during numerical development, no influences of finger-based sub-base-five effects should be found in adult mental arithmetic. On the other hand, we argue that when influences of finger-based representations persist into adulthood, we should observe sub-base-five effects in the current addition task. In particular, we expect addition problems, in which the sum of the unit digits exceeds 5 (e.g., 4 + 3 = 7) and thus crosses the sub-base-five boundary, reflecting the numerosity coded by one hand in German finger counting, to be significantly more difficult than problems in which adding the units does not cross the sub-base-five boundary (e.g., 5 + 2 = 7). As outlined above, comparable sub-base-five effects were recently observed for adults in a simple magnitude comparison task (Domahs et al., 2010). Yet, the present study is the first aiming at evaluating sub-base-five influences in mental arithmetic in educated adults. Such an effect of embodied numerosity would indicate that mental finger-based representations of numerosity are not restricted to a transient stage during numerical development. Instead, it would imply finger-based embodied representations of number to be used even by numerate adults in seemingly abstract operations. In turn, this would corroborate the notion that not only language and its comprehension (e.g., Glenberg and Kaschak, 2002; Hauk et al., 2004; Tettamanti et al., 2005; Zwaan and Taylor, 2006) but also mental arithmetic may be grounded in embodied experiences.

MATERIALS AND METHODS

PARTICIPANTS

Twenty-two students from the Medical Faculty of the RWTH Aachen University (mean age: 24.6 years; SD = 3.5 years), participated in this study. It should be noted that none of the participants of the present study did show any signs of mathematics difficulties. This is important because people with math difficulties may use immature strategies such as finger counting to solve simple math problems even in adulthood (e.g., Butterworth, 1999; Kaufmann et al., this issue), which in turn would have biased the current results. All of them were native speakers of German and had normal or corrected to normal vision. They gave their informed consent and were paid for participation.

STIMULI

In an addition production paradigm, 54 simple addition problems as well as 31 filler items were presented. The 54 critical addition problems consisted of three conditions. In the first condition (comprising 18 items) a sub-base-five boundary was crossed in the addition problem (e.g., in 12 + 4 the sum of 2 + 4 is larger than 5). In the second condition (comprising 18 items), the sub-base-10 boundary had to be crossed as these items involved a carry operation (e.g., 7 + 4). Generally, a carry operation is necessary whenever the sum of the unit digits (here: 7 + 4) is equal to or larger than 10. In the third condition (also comparison 18 items), neither a sub-base-5 nor a sub-base-10 boundary had to be crossed (e.g., 7 + 2). Finally, of the 31 filler items 21 included a sub-base-5 break, while none of the fillers required a base-10 break. Moreover, filler items included the digit 0 or 5 in unit position of either the first operand or the sum. For an overview of the whole stimulus set the reader is referred to the Appendix.

While the first summand in all critical items ranged from 4 to 37, the second summand was always 2, 3, or 4; thus, the position of the smaller addend within the problem was always on the right side. To ensure the validity of the collected data, absolute as well as logarithmic sum, mean magnitude of the unit and decade digit of the sum, and the parity of the correct result were matched between the three stimulus categories and the filler items where appropriate. No multiples of 10 or problems with a 5 in unit position were included in the critical addition problems as either addends or sum of the equation. Finally, no addition problem was part of a multiplication table.

PROCEDURE

Participants were seated approximately 50 cm from the screen of a laptop computer in a dimly lit room. All stimuli were presented in white NRC-7-BIT 172 size (approximately 2.0 cm height and up to 1.4 cm width per digit) against a black background using ERTS software version 3.18 (BeriSoft Cooperation, Frankfurt, Germany; Beringer, 1996). In each trial, an addition problem was presented in central position. Addition problems were presented in Arabic notation, while responses were given orally. Response time data was measured using a voice-key. Each response had to be initiated with the same word: "macht" ("*equals*") before the actual result was named, ensuring that all responses started with the same phoneme. Importantly, participants were instructed to respond in a fluent manner, so there were no pauses between the words "macht" and the actual result. Trials on which this was not the case were excluded from analyses (see Korvorst et al., 2006, for a similar procedure).

Instructions focused on both speed and accuracy. To familiarize participants with display layout and task requirements, 10 additional practice problems had to be solved before starting the experiment. None of these practice problems was repeated during the experiment. All addition problems were presented pseudo-randomized in blocks of 21 items. Between the blocks a short pause was incorporated to ensure that participants could have a short resting period. Each problem was presented until a response was given or the time limit of 5 s was reached.

ANALYSIS

Response times measured by voice-key were evaluated in an item-based approach. Only RTs for correct responses were entered into the analyses. Moreover, problems, where participants made an irrelevant noise or a self-correction, were disregarded in the RT analyses. Furthermore, response latencies shorter than 300 ms were not considered and in a second step responses outside the interval of ±3 SD around the individual mean were excluded. Considering erroneous responses and trimming this resulted in a total loss of 4.4% of the data. As error rates were very low ($M = 3.8\%$; SD = 3.6%) the following analyses will focus on response latencies.

First, we ran an item-based univariate ANCOVA (i.e., no break vs. 5 break vs. 10 break) incorporating unit sum (reflecting the sum of the unit digits of the summands) as the covariate to compensate for any systematic disadvantages in solving the addition problems due to increasing unit sum (see Klein et al., 2010a,b for a more detailed evaluation of possible influences of unit sum). Please note that this covariate was necessary as only the conditions 5 break and no break were matched for absolute and logarithmic mean of the individual summands, overall sum, and unit sum. On the other hand, it is mathematically impossible to match the carry condition with the conditions 5 break and no break with regard to the factor unit sum because unit sum needs to be larger than 10 in the carry and smaller than 10 in the other conditions per definition.

Second, results were analyzed using a stepwise multiple linear regression analysis on mean item RT. The stepwise regression analysis was stopped when the inclusion of another predictor would not lead to an additional significant increase of R^2 (at $p < 0.05$). Predictors included presence or absence of 5 break (e.g., 23 + 4 crossing 25) or carry operation (e.g., 28 + 4 crossing 30) as well as more general structural variables such as *problem size* (measured as the sum of the addends), and *unit sum* (Deschuyteneer et al., 2005; Klein et al., 2010a,b) as well as the interaction terms of problem size and unit sum and problem size and presence of a 5 break. The predictors for 5 break and carry operation were coded categorically: +1 in the case the addition problem required a carry of sub-base-5 or base-10 and −1 for problems not requiring a carry, while the predictor *unit sum* simply reflects the sum of the digits at the unit position of the two addends, respectively (Klein et al., 2010a,b). For instance, the unit sum ranged from 3 (as in 31 + 2) to 9 (as in 26 + 3). Further predictors were included into the regression analysis which were directly or indirectly motivated from models and/or previous findings reported in the literature (see **Table 1**).

RESULTS

ANCOVA

To control for any systematic disadvantages in solving the addition problems due to increasing unit sum, we additionally ran an ANCOVA incorporating this variable as a covariate. The ANCOVA revealed a main effect of item group [$F(50, 3) = 12.06$, $p < 0.001$]. Moreover, Bonferroni–Holm corrected pairwise comparisons (Holm, 1979) revealed that all possible group differences

Table 1 | Critical predictors (necessary for testing our hypotheses) and controlled predictors (motivated by the literature on mental addition and included to substantiate the results) included in the stepwise multiple regression analysis.

Critical predictors	
Break 5	
Carry	
Problem size	
Unit sum	
Break 5 × carry	
Problem size × carry	
Problem size × break 5 × carry	
Controlled predictors	**Citation**
Size of the second (smaller) summand	Groen and Parkman (1972)
Logarithmic sum	Butterworth et al. (2001)
Logarithmic unit sum	Dehaene (2007), Deschuyteneer et al. (2005)
Square of the sum	Ashcraft and Battaglia (1978)
Product of the summands	Widaman et al. (1989)
Sum of the square of the addends (SSA)	Widaman et al. (1989)
Parity of the two summands	Campbell et al. (2004) Lemaire and Siegler (1995) Vandorpe et al. (2005)

For the latter, the respective citation (referencing one or more studies indicating the impact of this predictor) is provided.

were significant (see **Figure 1**) with no break problems being responded to fastest followed by 5 break and 10 break problems ($\Delta_{\text{no break vs. 5 break}} = 91$ ms, $\Delta_{\text{no break vs. 10 break}} = 209$ ms, $\Delta_{\text{5 break vs. 10 break}} = 118$ ms, all $p < 0.05$). Additionally, there was no reliable influence of the covariate unit sum [$F(1, 33) < 1$].

REGRESSION ANALYSIS

The final model comprised only the predictors carry and 5 break [$R^2 = 0.418$, adjusted $R^2 = 0.395$, $F(2, 51) = 18.3$, $p < 0.001$], while the predictors problem size and unit sum failed to explain significant amounts of additional variance. Inspection of the individual beta weights indicated a significant influence of both the fact whether a base-10 [$b = 0.75$, $t(20) = 6.0$, $p < 0.001$] or a sub-base-five was crossed [$b = 0.34$, $t(20) = 2.28$, $p < 0.001$]. This means that the addition of two numbers became relatively slower when a 5 break as well as when a 10 break had to be crossed (for detailed results for all variables entered in the stepwise multiple regression analysis see **Table 2**).

DISCUSSION

There is growing evidence suggesting that bodily experiences such as finger-based representations may exert reliable influences on number processing even in educated adults (e.g., Domahs et al., 2010). For the case of mental arithmetic so far such a finger-based effect was only reported for children (Domahs et al., 2008). Therefore, it was argued that such finger-based effects on mental arithmetic may be limited to an important but transitory step in numerical development during which children recruit their fingers for counting/arithmetical processes. The present study aimed at evaluating the influence of finger-based representations in numerate adults solving an addition production task. Crucially, reliable influences of finger-based representations in adults were indicated by a detrimental 5 break effect in mental addition. This means that addition problems in which the sum of the unit digits exceeds 5 (e.g., 3 + 4 = 7) were more difficult to solve than problems without such a break (e.g., 5 + 2 = 7), even when controlling for overall unit sum (i.e., 7 in the present examples).

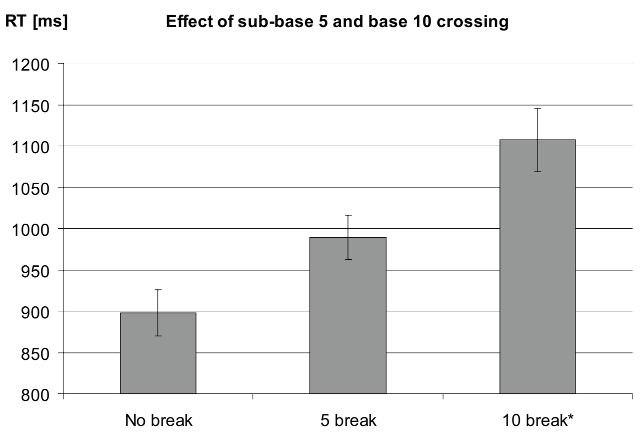

FIGURE 1 | Response latencies for addition problems with and without 5 break as well as for problems with 10 break (carry). Error bars depict 1 standard error of the mean (SEM). *Please note that problems with a 10 break could not be fully matched regarding the units of the result with the two other groups (problems with and without 5 break).

In line with our hypothesis we indeed observed consistent sub-base-five effects: when summing up the unit digits crossed the sub-base-five boundary, this was associated with a significant increase of response times. First, the comparison of addition problems involving a 5 break with no break problems revealed reliably prolonged reaction times for the former. Importantly, these two problem categories were matched for variables such as size of the global sum or unit sum, etc. indicating that it was indeed the 5 break which delayed responses. Second, this finding was replicated in a regression analysis. Here, we observed that apart from the well known carry effect, the presence of a 5 break was the only reliable predictor of item RT. The current findings thus suggest that even in numerate adults finger-based representations of numerosity moderate arithmetic performance. Importantly, the response modality used in our paradigm further corroborates this interpretation. As participants were required to produce the result to the addition problems verbally, the recruitment of any kind of finger-based representations should not have been triggered by finger and/or hand movements related to the answer modality. Additionally, there were no obvious signs of actual finger movements while participants completed the addition task. However, it has to be noted that corticospinal excitability of fibers enervating hand muscles has been associated with the processing of numerical information even in the absence of finger movements (e.g., Andres et al., 2007). But based on the methodology of our study we cannot evaluate whether the finger-based influence of the sub-base-five effect is driven by entirely abstract mental representations of embodied origin or generalizes to neural activity/excitability associated with finger movements. This question is open to future studies using neuro-cognitive methods such as fMRI or TMS.

Moreover, we consistently observed a carry effect (i.e., an RT-increase due to the crossing of a 10 break, e.g., 28 + 6 vs. 31 + 3) in both the ANCOVA and the regression analysis. This

Table 2 | Results for all variables entered in the stepwise multiple regression analysis.

Variables included in the model	Standardized beta	*t*	Sign.
Break 10 (carry)	0.746	6.044	<0.001
Break 5	0.341	2.765	<0.01
Variables excluded from the model	**Standardized beta**	***t***	**Sign.**
Problem size	–0.004	–0.037	0.970
Unit sum	–0.053	–0.263	0.794
Logarithmic sum	0.017	0.159	0.874
Logarithmic unit sum	–0.024	–0.144	0.886
Squared problem size	–0.007	–0.064	0.949
Product of summands	0.026	0.234	0.816
SSA	–0.012	–0.111	0.912
Parity of summand 1	0.028	0.245	0.807
Parity of summand 2	0.097	0.906	0.369
Break 10 × problem size	–0.027	–0.098	0.923
Break 5 × break 10 × problem size	–0.12	–0.433	0.667

is a standard finding in mental addition (Deschuyteneer et al., 2005; Kong et al., 2005; Imbo et al., 2007; Klein et al., 2010a,b). Therefore, we are confident that the current task assessed the processing of addition problems in an appropriate way. However, while base-10 effects may be caused by the structure of both the stimuli or the internal representations related to different notations (e.g., Arabic digits, finger counting patterns), this is not true for sub-base-five effects. The latter cannot be related to the Arabic notation as the number 5 is not of particular importance as regards the organization principle of the base-10 Arabic number system. However, sub-base-five effects may index traces of finger-based representations influencing mental numerical representations.

Nevertheless, the fact that we did not observe a problem size effect was unexpected and deserves further discussion. Generally, most previous studies indicated that addition performance – like performance in all kinds of mental arithmetic – is largely determined by overall problem size, i.e., response performance declines as the size of the numbers involved increases (e.g., 8 + 4 is less difficult than 38 + 4, see Ashcraft, 1995; Zbrodoff and Logan, 2005 for reviews). However, it must be considered that the largest addend was always presented first (e.g., 34 + 2) and did not change substantially in size due to the addition operation itself as only 2, 3, or 4 had to be added. This means that overall problem size was reflected almost entirely by the first summand and did not change substantially by adding the second summand. However, we observed a substantial correlation between the predictor "unit of the second summand" (which was either 2, 3, or 4) and overall RT ($r = 0.44$, $p < 0.001$). This continuous increase of reaction time with the increase of the second addend is in line with the literature (Groen and Parkman, 1972) and indicates negative influences of increasing digit magnitude on task performance. From a broader perspective this indicates that adults may have indeed relied on counting or even finger-counting related strategies to solve the current addition task, because such a correlation is hard to reconcile with participants relying on arithmetic fact retrieval (see Domahs et al., 2006, for a disappearing problem size effect in multiplication when controlling for structural variables). Furthermore, this correlation of the unit of the second summand with overall RT can be interpreted as a problem size effect for the unit of the second summand. This interpretation of digit specific influences of increasing magnitude are corroborated by the fact that the raw correlation of unit sum with overall RT (which is one possible measure of problem size in addition) was highly significant ($r = 0.48$, $p < 0.001$). As the predictors carry (which was considered in the final model) and unit sum are highly intercorrelated ($r = 0.81$) unit sum may not have been incorporated in the final regression model. Nevertheless, it is well conceivable that parts of the variance associated with unit sum as a measure of problem size are accounted for by the categorical carry predictor in the final model. This suggests that the carry effect observed may partially reflect influences of (unit) problem size as well (cf. Klein et al., 2010a). This indicates that, although we did not observe an effect of problem size overall, we nevertheless observed specific results reflecting an negative influence of increasing magnitude on performance as expected by the problem size effect. Finally, it has been argued that overall problem size seems to affect primarily carry addition problems (Deschuyteneer et al., 2005). As the majority of the current stimuli were non-carry problems, this property in combination with the above mentioned argument, might have further reduced the influence of overall problem size[1].

Taken together, we are well aware that we used a specific stimulus set (i.e., adding a single-digit to a two-digit number); thus, the lack of a standard problem size effect may be driven by our stimulus selection. In particular, the use of very small symbolic numbers as addends (2, 3, 4) makes it very likely that even in educated numerate adults processes related to (finger) counting may have been recruited. However, using exclusively symbolic digital stimulus material should not have triggered explicitly the access to finger-based representations such as the presentation of finger gestures (cf. Badets et al., 2010). From this we suggest that in adult numerical cognition finger-based representations affect mental arithmetic because the presence or absence of a 5 break exerted a reliable influence on response latencies. In summary, this strongly suggests that finger-based representations exhibit a reliable influence on mental arithmetic not only during a transitory developmental phase in children's arithmetic performance but even in educated numerate adults.

To conclude, the present study provides first evidence that the influence of finger-based (sub-base-five) representations on number processing in adults generalizes to the case of mental arithmetic. This was observed for arithmetical problems presented in purely digital-symbolic notation with verbal responses given. Importantly, the structure of both, input and output (Arabic numbers and spoken number words, respectively) do not reference sub-base-five representations in any way. Thus, the present findings support the general idea of embodied numerosity: even seemingly abstract numerical representations and operations involved in adult mental arithmetic may at least partially be rooted in bodily sensorimotor experiences.

[1]Additionally, it should be noted that in the domain of mental arithmetic a distinction between simple (single-digit) and complex (multi-digit) addition has been suggested. However, the results of additional analyses exploring possible differential processing of exclusively single-digit problems and those involving two-digit summands did not differ from the overall regression analysis with respect to the influence of problem size. This means that problem size was a reliable predictor neither for simple nor for complex problems in our study while "carry," representing a measure of the problem size of the units, was.

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APPENDIX

Overview of the whole stimulus set used.

	No break	5 Break	10 Break	Filler items
1	6 + 3	4 + 2	7 + 4	3 + 2
2	7 + 2	4 + 3	8 + 3	11 + 4
3	11 + 2	12 + 4	8 + 4	12 + 3
4	11 + 3	13 + 3	9 + 2	13 + 2
5	12 + 2	13 + 4	9 + 3	21 + 4
6	16 + 2	14 + 2	9 + 4	22 + 3
7	16 + 3	14 + 3	17 + 4	23 + 2
8	17 + 2	14 + 4	18 + 3	31 + 4
9	21 + 2	22 + 4	18 + 4	32 + 3
10	21 + 3	23 + 3	19 + 2	33 + 2
11	22 + 2	23 + 4	19 + 3	10 + 2
12	26 + 2	24 + 2	19 + 4	10 + 3
13	26 + 3	24 + 3	27 + 4	10 + 4
14	31 + 2	32 + 4	28 + 3	20 + 2
15	31 + 3	33 + 3	28 + 4	20 + 3
16	32 + 2	33 + 4	29 + 2	20 + 4
17	36 + 3	34 + 2	29 + 3	30 + 2
18	37 + 2	34 + 3	29 + 4	30 + 3
19				30 + 4
20				5 + 2
21				5 + 3
22				5 + 4
23				15 + 2
24				15 + 3
25				15 + 4
26				25 + 2
27				25 + 3
28				25 + 4
29				35 + 2
30				35 + 3
31				35 + 4

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Effects of finger counting on numerical development – the opposing views of neurocognition and mathematics education

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Children typically learn basic numerical and arithmetic principles using finger-based representations. However, whether or not reliance on finger-based representations is beneficial or detrimental is the subject of an ongoing debate between researchers in neurocognition and mathematics education. From the neurocognitive perspective, finger counting provides multisensory input, which conveys both cardinal and ordinal aspects of numbers. Recent data indicate that children with good finger-based numerical representations show better arithmetic skills and that training finger gnosis, or "finger sense," enhances mathematical skills. Therefore neurocognitive researchers conclude that elaborate finger-based numerical representations are beneficial for later numerical development. However, research in mathematics education recommends fostering mentally based numerical representations so as to induce children to abandon finger counting. More precisely, mathematics education recommends first using finger counting, then concrete structured representations and, finally, mental representations of numbers to perform numerical operations. Taken together, these results reveal an important debate between neurocognitive and mathematics education research concerning the benefits and detriments of finger-based strategies for numerical development. In the present review, the rationale of both lines of evidence will be discussed.

Keywords: finger counting, numerical development, neurocognitive, mathematics education

At an early stage of development, children learn the basic principles of numbers and arithmetic with the help of external finger-based representations of numerical quantity (e.g., Butterworth, 1999). Indeed, accumulated evidence suggests that such early finger-based representations have a considerable influence on children's manipulation of symbolic Arabic digits, as well as on the development of both basic numerical competencies (e.g., understanding of numerical magnitude) and arithmetical competencies (e.g., successful performance of the carry operation in addition later on), hereafter referred to by the acronym numerical/arithmetical competencies. However, the question as to whether reliance on finger-based representations remains beneficial or whether it becomes detrimental is subject of an ongoing debate between researchers in neurocognitive science and mathematics education. In the present article, the state of the art in neurocognitive and mathematics education literature shall be reviewed. In a second step, we ask important questions relevant to an integrated view of finger-based strategies in numerical/arithmetical development in neurocognitive and mathematics education research.

NEUROCOGNITIVE PERSPECTIVE

From a neurocognitive perspective, finger counting provides multisensory input that conveys information on both cardinal and ordinal aspects of numbers. Here, the number of fingers and their arrangement on both hands plays a fundamental role in first applications of externalized representations of numerical magnitude in initial counting and calculation. The importance of such embodied finger-based representations of number magnitude is further illustrated by findings suggesting that blind children (Crollen et al., 2011) and even children with amputated hands and forearms (Poeck, 1964) use their (phantom) hands and fingers as external quantifiers.

In line with such findings, recent neurocognitive data indicate that finger gnosis is associated with children's numerical/arithmetical competencies, including computational skills (e.g., Noël, 2005; Penner-Wilger et al., 2007a,b). Even in adults, recent evidence suggests that the link between finger (counting) patterns and semantic cardinal number magnitudes is stronger for canonical (e.g., 7 represented by 5 and 2 fingers) as compared to non-canonical finger patterns (e.g., 7 represented by 4 and 3 fingers; Di Luca and Pesenti, 2008; Di Luca et al., 2010). This suggests a close link between finger counting and the representation of abstract number magnitude in healthy adults (Di Luca et al., 2006; Di Luca and Pesenti, 2010). However, the exact origin of this link is still debated. On the one hand, Brozzoli et al. (2008) showed that the association of numbers and fingers is modulated by palm orientation. This suggests a more general association of relatively smaller and larger numbers with "left" and "right," respectively, independent of specific fingers (e.g., see also Ishihara et al., 2006). On the other hand, Di Luca et al. (2006, 2010; see also Di Luca and Pesenti, 2008, 2010) have presented converging evidence indicating a direct association of specific numbers embodied as specific fingers/finger patterns.

Finally, recent neuroimaging data suggest that the neural correlates of finger and number representations are located in neighboring or even overlapping cortex areas (see e.g., Kaufmann et al., 2008). From a neurocognitive view, this link seems to be functional and not exclusively correlational. For instance, Gracia-Bafalluy and Noël (2008) observed that systematic training of finger gnosis led to an improvement of numerical performance. Moreover, Badets and Pesenti (2011) showed that learning to associate certain finger movements with meaningless syllables automatically associated certain magnitudes with the same syllables (see also Andres et al., 2008b for a review on finger-based numerical associations).

Yet, recent research not only investigated associations between finger-based representations and numerical/arithmetical competencies but also specified the importance of mode and structure in the interrelation of finger and number representations, with *space* and *base* being particularly relevant in this context.

In terms of *space*, recent studies indicate a reliable influence of finger-based representations on the spatial representation of number magnitude. For individuals (Fischer, 2008) and cultures (Lindemann et al., 2011) that start counting predominantly with their left hand – that is, associating small numbers with the left – indications of a left-to-right-oriented mental number line dominate. A successful and functioning spatial representation of numbers in children is associated with more elaborate calculation skills (e.g., Bachot et al., 2005; Booth and Siegler, 2008). Thus, an indirect influence of embodied finger-based representations of numbers on general numerical/arithmetical competencies can be expected (Gracia-Bafalluy and Noël, 2008, see also Fischer and Brugger, 2011 for a review).

Second, with respect to the representation of *base* the German and many other, but not all, finger counting systems are so-called sub-base 5 systems. In sub-base 5 systems, numbers such as 7 are always coded as $5 + 2$ (i.e., one whole hand and two more fingers), but never as, for instance, $4 + 3$ (e.g., Brissiaud, 1992). Moreover, the finger symbol for 2 within the finger symbol for 7 is identical to the finger symbol for the number 2. Interestingly, this structural ambiguity seems to influence the processing of symbolic Arabic digits: specific sub-base 5 effects have been observed for deaf signers (Iversen et al., 2004, 2006; Domahs et al., 2010), children (Domahs et al., 2008), and even healthy adult participants (Domahs et al., 2010). In the latter study, sub-base 5 effects in a magnitude comparison task were found to be more pronounced for German as compared to Chinese adults. Importantly, the German, not the Chinese, finger counting system involves a sub-base of 5. In the Chinese system numbers between 6 and 10 are coded symbolically using only one rather than two hands. Finally, in the study by Domahs et al. (2008), primary school children were required to solve simple (sum < 10) or complex (sum > 10) addition problems. Importantly, the probability that numbers differing from the correct result by 5, and thus by one hand, were produced as erroneous responses was reliably higher than expected on the basis of their distance to the correct result. This increased probability of wrong-by-5 errors is interpreted as a direct influence of the structure of finger-based representations on mental arithmetic involving symbolic Arabic digits (see also Klein et al., 2011 for sub-base 5 effects in addition in adults).

In summary, the above-reviewed evidence indicates that there is a functional link between both the spatial layout as well as the base structure of finger counting systems and numerical/arithmetical competencies. Therefore, neurocognitive researchers conclude that successful finger counting and finger-based arithmetic serve as building blocks for later numerical/arithmetical development and thus should be taught early in kindergarten and primary school.

Nevertheless, the study of Domahs et al. (2008) is also relevant to the direction of embodied finger-based influences. Generally proficient finger gnosis and finger counting/calculation abilities are regarded as beneficial for numerical/arithmetic development in the neurocognitive literature (see above). However, the data of Domahs et al. (2008) suggest that this may only be part of the story: Driven by the sub-base 5 structure of the finger counting system, the probability of specific split-5 errors is increased and finger-based representations are seen as the reasons for these errors. Thus, in this specific case finger-based representations are not beneficial but detrimental instead – a view held prominently in the literature of mathematics education research presented in the following section.

MATHEMATICS EDUCATION PERSPECTIVE

Research in mathematics education assumes that young children begin performing calculations by counting, mostly using their fingers (Schipper, 2005). Nevertheless, a problem may arise when first elements of numeracy anchored on finger counting are perpetuated to the point of hindering the necessary passage to an understanding of numerosity, of operations, and of computational strategies. Krauthausen and Scherer (2001, see also Padberg and Benz, 2011) report several findings that reveal the tension between the relevance of counting on the one hand and the problems this may cause on the other:

- Counting is a fundamental competency. However, persistent use of this strategy alone may lead to severe problems with computational tasks.
- Weaker children have trouble generating computational strategies from finger counting. In the long run, children who only use counting strategies tend to obtain fewer correct results than those who also use other computational strategies.

Mathematics education research recommends fostering mental numerical representations so as to induce children to abandon finger counting at the end of first or beginning of second grade, at the latest. More precisely, this entails shifting from finger counting to performing computations with the help of concrete structured representations and finally, to base computations on abstract mental representations of numbers (e.g., Floer, 1995; Kaufmann and Wesselowski, 2006). At the end of these phases numbers should no longer be represented as sequences of single units (e.g., fingers), but as decomposable into larger entities. In fact, the failure to abandon finger-based representations is seen as one possible reason for children's computing errors in second grade.

The goal in current mathematics education is to ensure that children understand their computations and acquire computational flexibility. One priority is that early counting should implicitly convey mathematical features, such as the associative and commutative properties of addition and multiplication. For example:

$$7 + 8 = 7 + (3 + 5) = (7 + 3) + 5 = 10 + 5 = 15$$

or

$$7 + 8 = 7 + (7 + 1) = (7 + 7) + 1 = 14 + 1 = 15$$

or

$$7 + 8 = (5 + 2) + (5 + 3) = (5 + 5) + (2 + 3) = 10 + 5 = 15$$

These examples illustrate that adequate decompositions and compositions of numbers become a basis for flexible calculation, where, for example, 8 can be seen as $3 + 5$, $7 + 1$, or as $5 + 3$. Making conscious use of these decompositions requires that these become automatic in children's minds. This automatism should not be acquired through memorization but rather emerge through children's handling of representations both enactively and mentally (Wessolowski, 2010).

Most frameworks for early arithmetic in mathematics education are characterized by a debate between the positions of different representation methodologies (Maier, 1990; Butterworth et al., 2011). Accordingly, it is questioned whether such decompositions can be developed through mere use of one's fingers? Most authors agree that fingers should be treated as belonging to possible representational devices. Some mathematics educators do propose using fingers not only for sequential counting but also for representing numbers (Lorenz and Radatz, 1993). Schipper (2005, 2009) describes exercises with fingers for subitizing and quasi-subitizing numbers up to 10 (see also Eckstein, 2011 for finger-based strategies for numbers up to 1,000). However, comparable to neurocognitive research it has been observed that the use of fingers for counting and performing numerical operations stresses a cognitive anchoring on 5 and 10, that is, on sequential strategies that do not foster representations of numbers as cardinal entities (Moser Opitz, 2009; Gaidoschik, 2010).

In the end, flexibility with regard to representational changes is considered a core component of performing successful arithmetical operations. Yet, in the first phase of this debate methodologies strictly based on counting had a strong impetus (Eckstein, 2011) and were practiced for more than four decades. The birth of the "New Math" era in the 1960s led educators to promote a methodology whereby counting with fingers was to be exclusively used at an early stage. The New Math era stressed the importance of developing a feeling for both cardinality and ordinality rather than for just ordinality. An interest in finger counting re-emerged in the 1990s, especially in connection with dyscalculia.

Recent studies on early arithmetic, in particular those that bridge mathematics education with cognitive psychology and neuroscience, indicate that the brain contains a special device for making sense of numbers (e.g., Dehaene, 1997; Butterworth, 1999). Children begin to enumerate objects at an early age, just as they begin to differentiate between colors (e.g., Wynn, 1998; Feigenson et al., 2002). Nevertheless, instruction in numerical operations is indispensible for acquiring the basic competency called numeracy (e.g., Floer, 1995).

Successful primary school children acquire flexibility for juggling between different types of representations when counting and operating with numbers; this is not true of dyscalculic children. To foster elementary numeracy in dyscalculic children, educators propose working mainly with one central representational framework, namely, number imaging, both enactively (i.e., using their hands to operate with structured materials, such as blocks and cubes) and iconically (i.e., looking at pictorial representations, like dots or icons). A typical symptom of dyscalculic children is firmly consolidated sequential counting, often anchored on finger counting. Adequate treatment with structured, enactive materials that foster number images, number decompositions and the cardinal aspect of numbers can enhance the understanding of numbers, so that decompositions like $8 = 7 + 1 = 5 + 3 = 3 + 5$ are handled more easily.

Furthermore, the participation of parents is crucial in fostering their children's early computational abilities and in motivating them to successfully implement the aforementioned representational changes (e.g., Mehlhuish et al., 2008). It is known, for instance, that boys tend to abandon finger counting earlier than girls (Pawelec and Kurz-Milcke, 2009), apparently because parents are somewhat stricter with boys. The feminist literature tends to view this unequal treatment and corresponding effects as disadvantageous for girls (Carr and Jessup, 1997; Martignon, 2010).

DISSOCIATIONS, LIMITATIONS, AND INTEGRATION OF EDUCATIONAL AND NEUROCOGNITIVE APPROACHES

There is obviously some discrepancy between neurocognitive and mathematics education communities concerning the beneficial and/or detrimental influences of finger-based counting/calculation strategies on numerical development. On the one hand, much of the neurocognitive literature indicates a functional and beneficial interrelation between finger-based numerical representations and numerical/arithmetical development in terms of an embodied numerosity representation (e.g., Domahs et al., 2010). On the other hand, mathematics education research sees finger-based strategies in counting and calculation as a starting point that should be overcome in favor of more elaborate and abstract representations upon which numerical cognition is assumed to operate.

Basically, the rationale behind the neurocognitive argument is based on correlational associations between different cognitive measures or different brain activations of numerical/arithmetical competencies and indicators of finger-based representations. To our knowledge, in the neurocognitive literature, there is only one intervention study that has trained finger gnosis and showed transfer effects (Gracia-Bafalluy and Noël, 2008). In contrast, the view held by mathematics education researchers is often falsely drawn on the observation that children using finger-based back-up strategies show poor numerical/arithmetical performance. Both views are problematic: in first case causal conclusions may be drawn on correlational data, while in the latter case it is unknown whether children exhibit poor numerical/arithmetical competencies because they still use their fingers or whether they use their fingers because this is their only available cognitive strategy.

Despite such methodological constraints, the current state of the art in both neurocognitive as well as mathematics education research suggests that the question whether or not finger-based counting and/or calculation strategies are beneficial may be too broad to be answered definitively at the moment. For instance, the effects of age and individual differences must be considered. Moreover, differences may arise with the differing presuppositions employed by neurocognitive and mathematics education researchers. Consider, for instance, the role of age. Mathematics education research suggests that reliance on finger-based representations should be overcome and replaced by more abstract numerical representations by the end of first grade to prevent detrimental influences. Neurocognitive research, however, predicts that finger-based representations influence number processing and arithmetic even in numerate adults as an additional, and sometimes helpful, embodied representation (i.e., without excluding the role of other representations, such as place-value representation) in arithmetic development.

Moreover, in contrast to mathematics education research, the neurocognitive perspective does not consider fingers as just another external material for learning to count and/or to calculate (like blocks or marbles, for example). Instead, based on the concept of embodied cognition, finger-based representations are considered to be a natural numerical representation, which is firmly grounded on sensory-bodily experience, and prevails even when more abstract or conceptual representations are built up.

Finally, there may also be task- and individual-related differences. Finger-based representations may be more beneficial for some subgroups of children, for instance less skilled children, as a multisensory experience that helps build abstract mental representations. Furthermore, finger-based representations may be particularly useful for specific tasks but not for others. For example, finger-based representations may be more beneficial in operations involving addition than multiplication, as even most single-digit multiplications exceed the number range possible to code easily by two hands. However, considering that multidigit numbers are processed decomposed into the single digits of units, tens, hundreds, etc. (see Nuerk et al., 2011 for a review), which can be represented by fingers, and considering that the same representations of these digits are recruited in single- as well as in multidigit number processing (e.g., Verguts and De Moor, 2005), it is conceivable that influences of finger-based representations may not only be limited to numbers up to 10.

Even though neurocognitive and mathematics education research agrees that children make use of finger-based numerical representations, they disagree on the consequences of reliance on such numerical representations. On the one hand, the neurocognitive literature suggests that embodied numerical representations, including finger-based ones, are important in numerical cognition in general (even present in educated adults, see Domahs et al., 2010). On the other hand, mathematics education research recommends the reliance on external representations, including finger-based ones, only as an aid in the transition to mental representations of numbers. These are then assumed to underlie adult numerical cognition (see also Rips et al., 2008, for the development of number concepts). In sum, the different views clearly show that there is a lack of systematic communication between the two disciplines. Further, the theoretical postulates and assumptions arising from the two different fields need to be addressed. To remedy this situation, interdisciplinary discourse between neurocognitive science and mathematics education is urgently needed.

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Nature or nurture in finger counting: a review on the determinants of the direction of number–finger mapping

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The spontaneous use of finger counting has been for long recognized as critical to the acquisition of number skills. Recently, the great interest on space–number associations shifted attention to the practice of finger counting itself, and specifically, to its spatial components. Besides general cross-cultural differences in mapping numbers onto fingers, contrasting results have been reported with regard to the directional features of this mapping. The key issue we address is to what extent directionality is culturally mediated, i.e., linked to the conventional reading–writing system direction, and/or biologically determined, i.e., linked to hand dominance. Although the preferred starting-hand for counting seems to depend on the surveyed population, even within the same population high inter-individual variability minimizes the role of cultural factors. Even if so far largely overlooked, handedness represents a sound candidate for shaping finger counting direction. Here we discuss adults and developmental evidence in support of this view and we reconsider the plausibility of multiple and coexistent number–space mapping in physical and representational space.

Keywords: finger counting, handedness, numerical mapping

COUNTING ON FINGERS TO COUNT

The spontaneous use of fingers and other body parts to count and express numerosities has been reported since the pre-historic age (Ifrah, 1981) and appears to be almost universal, although highly variable across cultures. For example, for some tribes people (i.e., New Guineans), counting practice includes the whole body surface, as they orderly name and touch parts of the body starting with the little finger of the right-hand and ending with the left little finger, passing through the wrist, elbow, shoulder, eyes, nose, mouth, and ears (Ifrah, 1985), providing a track of the counted elements. With regard to the hands, while some ancient cultures, such as the Romans, used the left-hand alone to sign even large numerosities, e.g., 99, in others, such as the Greeks, the right-hand was used as a counting tool (Lindemann et al., 2011). Interestingly, unimanual counting systems are still in use, mainly in Far-East cultures (e.g., Chinese, Japanese, and Korean Sign Language) although data on which of the two hands is used for counting are missing or mostly anecdotal.

Further evidence for the value of finger counting comes from its supportive role across development. The role of fingers in the development of numerical skills is well reflected by their massive use in the acquisition of simple arithmetic. Although the use of fingers mainly characterizes the initial stage of learning, this practice evolves with the increasing mastery of arithmetic knowledge (Jordan et al., 2008). Accordingly, indirect evidence for the role of fingers in supporting numerical development comes from studies reporting finger gnosis as a significant predictor of arithmetic performance in school-aged children (Fayol et al., 1998; Noël, 2005; Gracia-Bafalluy and Noël, 2008).

Recently, the long-lasting link between finger counting and number processing has received renewed attention within the embodied cognition approach, according to which cognitive processes are deeply shaped by the body's interaction with its environment (Wilson, 2002; Gibbs, 2006). In particular, number-to-finger associations have been shown to influence number processing (Sato et al., 2007; Domahs et al., 2011; Fischer and Brugger, 2011) and to modulate numerical mental representation (Di Luca et al., 2006; Fischer, 2008; Domahs et al., 2010). Specifically, there is evidence for an influence of finger counting direction on the direction of the mental numerical representation (Fischer, 2008) as well as for the specific structure of the finger counting system (e.g., the sub-base-five system) both on children's mental calculation (Domahs et al., 2008) and on adults' single-digit number comparison (Domahs et al., 2010). However, the functional relationship between fingers and number representation appears less obvious in specific sensory conditions. For example, it is worth noting that although blind children use their fingers in a less canonical way and less spontaneously than sighted children (Crollen et al., 2011), blind and sighted adults showed similar features in their mental representation of numbers (Castronovo and Seron, 2007; Sallilas et al., 2009). These results suggest that the contribution of finger counting to the mapping of numbers in the representational space may be less critical than considered thus far. Besides an increasing interest in finger counting practice, systematic investigations of its structural features, such as directionality, are still limited and mostly focused on cross-cultural differences (Lindemann et al., 2011). Yet, as with all motor actions, finger counting practice is expected to be modulated by hand preference, although it remains to be established to what extent handedness may further modulate abstract concepts (but see Casasanto, 2009; Casasanto and Chrysikou, 2011).

In this contribution we review the studies which have reported on finger counting practice disclosing the respective contributions of the cultural and biological determinants of its directionality

Box 1 | Key findings on finger counting direction.

- Finger counting direction influences number processing (Di Luca et al., 2006; Sato et al., 2007).
- Finger counting direction shapes the mental numerical representation (Fischer, 2008; Domahs et al., 2010).
- The reading–writing system direction modulates finger counting direction (Lindemann et al., 2011).
- Different methods testing finger counting practice provide discrepant results (Sato and Lalain, 2008 vs. Fischer, 2008).

(**Box 1**). We first consider the evidence favoring the importance of cultural factors in shaping finger counting direction. Then, we turn our attention to the available data elucidating the influence of handedness in the adult population. Finally we will look to the recent developmental evidence that reflects the incremental influence of both biological and cultural factors in counting practice. We conclude that different space–number mappings (i.e., determined by cultural factors and/or finger counting habits) do coexist and distinctly emerge depending on the tasks' procedures and demands.

DO CROSS-CULTURAL FACTORS DETERMINE DIFFERENT FINGER COUNTING DIRECTIONS?

Although finger counting has been described in virtually all cultures (Ifrah, 1981), no universal counting routines have been observed, suggesting a great influence of cultural exposure in shaping the development of the finger counting practice (Pika et al., 2009). Indeed, different conventional patterns are used in finger-digit mapping, revealing a large cultural variability in the finger counting systems varying, for example, in dimensionality (i.e., base or sub-base systems), base size (i.e., 10 or 20 base), or extent (i.e., 27 or 30; Bender and Beller, 2011). This specificity has been observed also in counting direction asymmetries, as signed by the preferred starting-hand, which is the structural dimension we focus on. These cultural discrepancies are commonly attributed to the reverse orientation of the reading–writing system (i.e., left-to-right vs. right-to-left) that might induce a visuo-spatial asymmetry linked to the direction of scanning habits. In line with this interpretation, a large-scale online survey revealed a reversed preferential direction in Western (i.e., European and American) and Middle-Eastern (i.e., Iranian) populations. Indeed most Western participants (68%) start counting preferentially on the left-hand, while Middle-Eastern individuals reported a reversed pattern with a preference to start with the right-hand (63%; Lindemann et al., 2011). A further source of variability which emerged in this survey is related to the relative order of finger counting within a single hand. In particular, while Western populations reported to start counting on the thumb and to continue sequentially until the pinkie, Middle-Eastern individuals usually counted following the opposite order (i.e., from the pinkie to the thumb; Lindemann et al., 2011). Currently, the causal link between the relative direction in counting fingers within a hand (i.e., starting from the thumb or from the pinkie) and the starting-hand preference (i.e., starting from the left or right-hand) remains to be clarified due to the still limited evidence emerging from counting practice in Middle-Eastern populations. If the conventional scanning habit is a determinant of finger counting direction, intra-cultural differences should be minimal or absent. In contrast, this practice is not homogeneous even within the same Western sample, since the left-hand starting preference is marked in Anglo-Saxon countries (i.e., UK, USA, and Canada), but not in Belgians and Italians. This evidence partially confirms the role of cultural effects but minimizes the influence of the writing system direction in predicting starting preference.

For example, a large-scale questionnaire used to investigate finger counting patterns in a Scottish sample reported a preference (66%) to start counting on the left-hand (Fischer, 2008). On the contrary, a direct test of hand preference in Italian (Di Luca et al., 2006; Sato et al., 2007) and French (Sato and Lalain, 2008) populations revealed that most individuals preferred to start counting on their right-hand (82% overall, 100 and 69% respectively). These contradictory results may well be attributed to the different methods adopted to assess finger counting, that is via written questionnaire or via direct observation. Aware of this difference, Lindemann et al. (2011) ran a control experiment comparing the two modalities within a group of participants on the basis of which they denied a modulation effect of the response mode. However, they considered only a homogeneous subgroup of individuals (English speakers of unknown handedness) different from those tested by enacting the finger count (Di Luca et al., 2006; Sato et al., 2007; Sato and Lalain, 2008). Yet, since the focus of our attention is a motor routine, a spontaneous and overlearned practice, the possible gap between enacting and reporting is expected to be significant. While the former procedural task involved an obvious implicit component, the latter requires explicit access to finger counting representations. For these reasons, we believe that task specific effects on finger counting deserve further attention in future research.

In conclusion, all data collected thus far clearly indicate that finger counting habits may vary substantially both within and between cultures, suggesting that reading–writing system direction is not the only factor that modulates the starting-hand preference during finger counting execution. Individual differences within the same population could be explained by taking handedness into consideration, since handedness indeed shapes many other motor activities.

IS LEFT- AND RIGHT- STARTING A DOMINANCE MATTER?

In principle, at least in Western cultures whose counting system involves two hands, finger counting practice is expected to be shaped, as any other bimanual action, by the lateral asymmetry determining hand dominance. For this reason, most studies adopt right-handedness as a recruiting criterion (Di Luca et al., 2006; Sato et al., 2007; Brozzoli et al., 2008) preventing any conclusive remarks on the role of hand dominance in finger counting direction. Indeed, when right-handed participants were recruited they showed a preference to start counting with their right-hand (Di Luca et al., 2006; Sato et al., 2007). Although a cultural effect might not be excluded (i.e., in both studies participants were Italians), homogeneous right-handedness may well be a confounding factor.

Moreover, regardless of handedness, assessment of finger counting direction has thus far not been systematic even in studies focused on embodied numerosities (Domahs et al., 2010).

The first study to directly investigate the link between handedness and direction of finger counting in adulthood did not find any association between the two (Fischer, 2008); the proportion of the left- and right-hand starters (i.e., participants who started to count with the left- and the right-hand respectively) was the same among left- (70 and 30% respectively) and right- handed (66 and 34% respectively) Scottish individuals. This pattern would suggest that finger counting direction is unrelated to hand preference ($p > 0.05$), although in this case the testing modality, i.e., written questionnaire, might have favored a left-to-right mapping, consistent with the Scottish reading habit direction.

In contrast, a more pronounced left-starting preference among left-handers has also been observed (Sato and Lalain, 2008; Previtali and Girelli, 2009; Lindemann et al., 2011). In particular, when finger counting was directly observed during its execution, a significant interaction between number–finger mapping and hand dominance was found. That is, French participants who started to count with their right-hand showed higher right-hand preference in unimanual activities (Sato and Lalain, 2008). It worth noting that in this study only three left-handers were tested but, despite this highly unbalanced sample (i.e., 3 vs. 97), the left-handed individuals consistently started to count with the left-hand.

A larger sample of left-handers was recently evaluated through an online survey (Lindemann et al., 2011), but in this case handedness was further qualified by cross-cultural differences. Indeed, the authors reported a more pronounced left-starting preference among Western left-handers (36/40, $p < 0.01$) but not within Middle-Eastern left-handers ($p > 0.1$) reflecting the interplay of both biological and cultural determinants in modeling finger counting practice.

However, a further contribution on a considerable number of left-handed ($N = 30$) and right-handed ($N = 57$) Italian participants reports a highly significant correlation between handedness and finger counting direction. An assessment of handedness by the Edinburgh Handedness Inventory (Oldfield, 1971) and a direct observation of finger counting revealed that 83% of left-handers were left-starters and 86% of right-handers were right-starters (Previtali and Girelli, 2009).

This effect of laterality also emerged in deaf signers who, like hearing speakers, exhibit a prevalence of right-hand dominance with the relative preference to sign numbers up to five with the right-hand and, for two-handed numbers (6–10), to sign the five-hand shape with the left-hand (Iversen et al., 2006). Similarly, a recent study on blind and sighted children (Crollen et al., 2011) showed that while sighted participants started to count with the dominant hand, i.e., 92% ($N = 11/12$) of the right-handed children started counting with their right-hand and the only left-handed child started counting with his/her left-hand, in blind participants the modulation of hand dominance was less systematic [54%, ($N = 6/11$) of the right-handers were right-starters, the only left-hander was also a left-starter]. Whether the reduced laterality effect in blind participants is due to their less systematic use of finger counting and/or to the role of sighting in typical cerebral lateralization or handedness (Caliskan and Dane, 2009) remains to be established. Although the low proportion of left-handers in the general population is a critical drawback that necessitates further cumulative data, handedness appears, so far, to be an effective predictor of the structural components of finger counting routines. Thus, as with any other bimanual action, the use of fingers in counting practice is intrinsically related to hand dominance.

LOOKING BACK FOR EARLY INDEXES OF DIRECTIONALITY: HOW DO CHILDREN COUNT?

Developmental data may provide a critical argument to the nature–nurture debate on the origin of the finger counting practice. Indeed, fingers are spontaneously used very early in development, well before the acquisition of reading and writing abilities (Fuson, 1988; Noël, 2005) and even occasionally preceed verbal labels in counting practice (Brissaud, 1992), although the influence of biological and cultural factors both increase incrementally over time. On the one hand, the influence of the dominant scanning direction associated with the writing system has been shown to emerge early in development, contributing to the occurrence of visuo-spatial asymmetries (Fagard and Dahmen, 2003; Opfer et al., 2010). On the other hand, although the first signs of lateral asymmetries emerge very early, handedness develops slowly, influenced by both genetic and cultural factors (Fagard and Dahmen, 2004), and increases in consistency during childhood (Mc Manus et al., 1988).

Importantly, the only study that has effectively examined potential differences across development (Sato and Lalain, 2008) suggests a stability of finger counting direction from childhood to adulthood. In fact, four different age groups (4–5 years old, 6–7 years old, 10–11 years old, and 24–47 years old) of French individuals evaluated in a finger counting task revealed, irrespectively of age, the same pattern in finger–number mapping (i.e., the right-hand used to count from one to five and the left-hand used to count from six to nine).

In contrast, in a large Finnish group, right-handers were mostly right-starters (60%) across ages, while a shift in finger counting direction occurred for left-handers, i.e., 100% of left-handed preschoolers were left-starters while only 50% of left-handed fourth graders started to count with their left-hand. This evidence supports the hypothesis that cultural factors modulate counting routines to some extent, although starting to count on the dominant hand is more frequent in both left- and right-handed participants of all ages (Räsänen and Koponen, 2010).

Finally, a recent study by Rinaldi and Girelli (2011) investigated the development of number–space associations in both the extra-personal physical space (e.g., counting visual arrays of elements), and in the personal space (i.e., finger counting), in 90 Italian-speaking 3- to 6- year-old preschoolers. Finger-digit mapping was assessed by spontaneous finger counting (from 1 to 10) and by requiring number–finger configurations (montring task, e.g., "Show me *four* with your fingers," $N = 1$–9).

Seventy-three percent of the children started to count with their right-hand and 65% of children used the right-hand first to show numerosities, supporting the idea of a strong relationship between small digits and *right-hand* fingers and between large digits and *left-hand* fingers (Di Luca et al., 2006; Sato et al., 2007). In particular, the number of preschoolers who showed a stable association in both the counting and the montring tasks (32 children from right-to-left, 10 from left-to-right) increased with age and, interestingly, these children outperformed their peers in number comprehension. With regard to handedness, no systematic relation was found with the direction of finger counting (note that only five subjects were left-handers). Finally, the results revealed no stable relationship between the *embodied*, i.e., related to finger mapping, and *disembodied*, i.e., related to the spatial arrangement of the counted elements, mapping, suggesting flexible use depending on the context (Di Luca et al., 2006). Specifically, children counting right-to-left on their fingers (*embodied* mapping) point left-to-right counting elements in the extra-personal space (*disembodied* mapping) and vice versa. In conclusion, this study may suggest that these two types of spatial mapping (i.e., embodied and disembodied) may differ, but coexist to support numerical comprehension from a very early age.

The relevance of finger counting in the acquisition and development of numerical skills has been long recognized, but only recently has this routine been linked to the way in which numbers are processed and mentally represented both throughout development and in adulthood (Di Luca et al., 2006; Sato et al., 2007; Brozzoli et al., 2008; Fischer, 2008; Sato and Lalain, 2008). However, despite this renewed attention, detailed investigations on the structural features, i.e., directionality, of finger counting are still missing. Due to the differences observed in testing different populations, cultural determinants (i.e., the writing system direction) in shaping finger counting routines have been acknowledged (Lindemann et al., 2011). Nevertheless, when controlled for, the prediction that handedness represented a sound candidate for shaping finger counting direction was confirmed (Sato and Lalain, 2008; Previtali and Girelli, 2009). In conclusion, the interplay of cultural and biological determinants well account for both adults' (Lindemann et al., 2011) and children's (Räsänen and Koponen, 2010) counting practice, but further studies are needed to fully understand their relative role in shaping finger counting direction. In particular, within the embodied cognition approach, structural features of finger counting practice should be systematically assessed in order to significantly enlarge samples, especially those of left-handed participants. Finally, developmental and cross-cultural studies represent an ideal approach to disentangle the relative contribution of cultural, e.g., the reading–writing system direction, and biological, e.g., manual laterality, factors in shaping finger–number associations, especially due to their relevance in supporting number comprehension (Noël, 2005; Rinaldi and Girelli, 2011).

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Five- to 7-year-olds' finger gnosia and calculation abilities

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The research examined the relationship between 65 5- to 7-year-olds' finger gnosia, visuo-spatial working memory, and finger-use in solving single-digit addition problems. Their non-verbal IQ and basic reaction time were also assessed. Previous research has found significant changes in children's representational abilities between 5 and 7 years. One aim of the research was to determine whether changes in finger representational abilities (finger gnosia) occur across these ages and whether they are associated with finger-use in computation. A second aim was to determine whether visuo-spatial working memory is associated with finger gnosia and computation abilities. We used latent class profile analysis to identify patterns of similarities and differences in finger gnosia and computation/finger-use abilities. The analysis yielded four finger gnosia subgroups that differed in finger representation ability. It also yielded four finger/computation subgroups that differed in the relationship between finger-use and computation success. Analysis revealed associations between computation finger-use/success subgroups, finger gnosia subgroups, and visuo-spatial working memory. A multinomial logistic regression analysis showed that finger gnosia subgroup membership and visuo-spatial working memory uniquely contribute to a model predicting finger-use in computation group membership. The results show that finger gnosia abilities change in the early school years, and that these changes are associated with the ability to use fingers to aid computation.

Keywords: finger gnosia, computational finger-use, spatial processes, individual differences, young children

INTRODUCTION

Fingers have long been thought to play an important role in the development of counting and computation abilities (Butterworth, 2005). Many preschool children spontaneously use fingers to support their initial counting behaviors (Gelman and Gallistel, 1978; Fuson, 1998), and school-aged children often use fingers when executing arithmetic operations [e.g., single-digit addition (SDA): see Geary, 2004, 2007; Geary and Hoard, 2005]. Although fingers provide a seemingly natural way of instantiating counting principles (e.g., one-to-one, stable order and cardinality principles) as well as different aspect of computation knowledge (e.g., base-10 knowledge; Di Luca et al., 2006; Domahs et al., 2008), little is known about developmental constraints that may affect the role of fingers in the acquisition of computation abilities. Indeed, Crollen et al. (this issue) review the question of whether finger counting is part of a necessary stage for the development of numerical cognition and whether its use is spontaneous in every child. We suggest that at least two factors may constrain the development of finger-use in computation: namely, (1) developmental limitations in children's ability to manipulate cognitive representations; and (2) individual differences in spatial processing capacities.

Fifty years ago White (1965) described 21 changes in cognitive capacities between 5- and 7-years of age (often referred to as the 5- to 7-shift: see Sameroff and Haith, 1996). While the 5- to 7-year shift was originally conceptualized in Piagetian terms (i.e., the transition from inflexible, pre-operational thought to more flexible concrete operational thought), it has recently been reconceptualized in terms of developmental changes in the integration and/or coordination of cognitive capacities (Siegler and Chen, 2008; Sameroff, 2010). The claim is that young children's reasoning is limited by an inability to coordinate cognitive representations because of limited processing capacities. Although little work has investigated finger gnosia and its applications in terms of the 5- to 7-shift, at least two developmental stages may be proposed: (1) the acquisition of a flexible representation of fingers; and (2) a flexible ability to use fingers as a cognitive tool in the service of number cognition. It is unlikely that children who are yet to acquire a flexible representation of fingers will be able to use them effectively as computation aids.

It is possible that finger–number representation is associated with a pre-existing spatial, non-symbolic magnitude system (de Hevia and Spelke, 2009, 2010; Mundy and Gilmore, 2009). The symbolic system for representing numbers is thought to be mapped onto the pre-existing non-symbolic, spatial magnitude system (Fias and Fischer, 2005; Brozzoli et al., 2008; Holloway and Ansari, 2009; Mundy and Gilmore, 2009). Some researchers claim that it is too simplistic to assume that the symbolic system spontaneously maps onto the non-symbolic magnitude system, and suggest that fingers may serve an intermediate role in the mapping processes (Fayol and Seron, 2005).

The possibility that finger, number, and spatial representations are linked was first raised by Gerstmann in the 1920s who observed that finger agnosia (the inability to distinguish among fingers) and difficulties in left-to-right orientation are often associated with acalculia (see Benton, 1987, 1992; Miller and Hynd, 2004). More recently, it has been suggested that they are likely to be linked because they are associated with neighboring neuroanatomical regions of the intraparietal cortex (Dehaene et al., 2003; Butterworth, 2005). The parietal cortex, and specifically the intraparietal sulcus (IPS) and left angular gyrus, are implicated in number representation (Pesenti et al., 2000; Fias et al., 2003; Feigenson et al., 2004; Pinel et al., 2004; Hubbard et al., 2005; Nieder and Dehaene, 2009), while finger agnosia is associated with left parietal damage (Rusconi et al., 2009). The parietal lobe contains regions responsible for representing number (Hubbard et al., 2005; Nieder and Dehaene, 2009), but fMRI indicates that it is also involved with hand movements (Sato et al., 2007), particularly regions surrounding the IPS (Hubbard et al., 2005). Sato et al. (2007) demonstrated that transcranial magnetic stimulation (TMS) to the left angular gyrus disrupts the ability to perform tasks that require access to finger representations, as well as interfering with the capacity to make number judgments. This extensive body of findings support claims for an association between finger and number representations; however, it is silent about how these representations emerge in the course of development.

The precise mediating role fingers serve in numerical cognition is a matter of debate (Sato and Lalain, 2008; Wood and Fischer, 2008). Some claim that habitual finger counting practices influence the long-term associations between number and fingers and, *ipso facto*, how number is represented cognitively (Di Luca et al., 2006; Domahs et al., 2008, 2010). For example, finger counting strategies can modify the SNARC effect: individuals who start counting on their right hand exhibit a reduced SNARC effect (Fischer, 2008). However, neuropsychological research that shows number, finger, and spatial representations are related caution against a purely "practice" account of finger–number associations (Fias and Fischer, 2005; Hubbard et al., 2005). It should be noted that adherents of the so-called neurological and cultural-practice views emphasize the importance of spatial properties of fingers/hands, even though they may disagree on the reasons for their importance (see Bender and Beller, this issue; Klein et al., this issue, for detailed discussion of these issues). Nevertheless, neither approach has much to say about the reasons for, or implications of, developmental differences in finger gnosia abilities.

Poor finger gnosia is associated with poor arithmetic performance (Fayol et al., 1998; Fayol and Seron, 2005; Noël, 2005; Gracia-Bafalluy and Noël, 2008). Noël (2005), for example, found that finger gnosia predicts calculation errors, but not general abilities (e.g., reading abilities). Fayol et al. (1998) reported that performance on perceptuo-tactile tasks was a better predictor of maths performance than general developmental tests (see also Gracia-Bafalluy and Noël, 2008). In these studies finger gnosia was assessed by an interviewer touching a child's finger; the child either pointed to a fingers/hand diagram to indicate the touched finger or recalled a number assigned to a finger (Fayol et al., 1998; Noël, 2005; Gracia-Bafalluy and Noël, 2008). Like many finger gnosia tasks, these tasks comprised both a motor and a finger representation component, making it difficult to identify which of them is associated with arithmetic difficulties. Indeed, psychomotor difficulties are often associated with developmental disorders (Holsti et al., 2002). It has long been known that some school-related difficulties (arithmetic and writing) are associated with motor and psychomotor difficulties (Rourke and Strang, 1978; Ozols and Rourke, 1988; Rourke, 1995). It is possible that the association between poor finger gnosia and arithmetic difficulty observed in previous research reflects psychomotor difficulties, rather than difficulties associated with finger–number relationships *per se*. Indeed, the visual-motor structure and movement of fingers is thought to support the creation of an internal representation of number (Pesenti et al., 2000). In the present research we minimize the potential impact of motor difficulties by employing a finger gnosia task that eliminates the motor component, and which focuses explicitly on finger–hand knowledge.

One difficulty interpreting previous research findings on the relationship between finger gnosia and arithmetic abilities is that they have tended to focus on general arithmetic performance, rather than finger-use in specific arithmetic problem solving. Research examining the acquisition of SDA abilities may provide a framework for remedying this oversight. The acquisition of SDA problem solving abilities has been well described (Geary et al., 2004, 2007; Kaufmann and Nuerk, 2005), and most models of SDA development assume finger-use is an integral part of problem solving development (Geary and Hoard, 2005; Geary et al., 2007). Although fingers may be analogous to external computation aids, developmental constraints may affect their use as tools in numerical cognition. In particular, flexible finger gnosia representations and spatial capacities may affect finger-use in computation.

In summary, given the mediating role attributed to fingers in numerical cognition, at least three questions require answers. First, how should finger representation (finger gnosia) be assessed? Most finger gnosia tests conflate motor movement (e.g., pointing) and finger representation. Since a link between developmental motor disorders and arithmetic ability has been found (Holsti et al., 2002), it is important to minimize the motor component in finger gnosia assessments. Second, what is the relationship between 5- to 7-year-olds' finger gnosia and finger-use in computation? Third, are finger gnosia and spatial ability associated; and to what degree do finger gnosia and spatial ability separately predict finger-use in computation ability?

THE CURRENT STUDY

We examined the relationship between 5- to 7-year-olds finger representations on a non-motoric finger gnosia task and finger-use/success solving SDA problems. We also assessed their performances on a visuo-spatial working memory task (Corsi, 1972), the Ravens Colored Progressive Matrices task (Raven et al., 1986: hereafter referred to as Ravens) and on a basic reaction time (RT) task.

The relationship between visuo-spatial working memory and math abilities has been observed in several studies in older elementary school children (i.e., older than 7 years; Bull et al., 2008; Holmes et al., 2008; Lonnemann et al., 2008; Passolunghi and Cornoldi, 2008). However, relatively little is known about the association between visuo-spatial working memory and enumeration abilities in younger children. Further, since finger representations are thought to provide links between non-symbolic quantities and symbolic numbers, it is important to determine whether finger gnosia *per se* is associated with visuo-spatial ability and finger-use in computation.

Processing speed is considered an index of IQ (Kail, 2007), and is related to math abilities in older students (Bull and Johnston, 1997; Floyd et al., 2003). A processing speed measure is important for two reasons. First, it is important to determine whether processing speed is an important determinant of SDA problem solving ability; and second, whether it is associated with speed of making finger gnosia judgments. The Ravens is a standardized measure of non-verbal reasoning ability, which has long been regarded as a measure of general intelligence (Spearman, 1946).

On the basis of previous SDA research findings, we expect age-related changes, as well as individual differences, in 5- to 7-year-olds' SDA abilities (Canobi et al., 1998, 2003; Geary, 2007). Insofar as finger-use is associated with the acquisition of SDA ability, we expect that finger gnosia would be associated with finger-use and success in SDA across age. (It should be noted that mature SDA ability is associated with an absence of finger-use since children are able to retrieve answers to problem from memory without having to resort to effortful computational process – see Geary, 2007.) Also on the basis of previous research, which has found a relationship between visuo-spatial work memory and math ability (Lonnemann et al., 2008), we expect that a similar relationship would be observed in the present research. However, we make no explicit predictions about the relationships between finger gnosia and visuo-spatial working memory and their impact on age-related changes in SDA abilities. Further, we make no explicit predictions about the moderating impact of Ravens and RT.

MATERIALS AND METHODS

PARTICIPANTS

Thirty Kindergarten ($M = 5$ years 10 months, $SD = 3.30$ months) and 35 Year One ($M = 6$ years 11 months, $SD = 4.14$ months) children, comprising approximately equal numbers of males and females from a non-government school in a middle-class suburb of a large Australian city, participated. These children were selected to approximately represent a 5- to 7-year-olds shift sample. All children had normal or corrected to normal vision. According to their teachers, no child had known learning difficulties. The study was conducted in accordance with the authors' University's Human Ethics Committee requirements.

MATERIALS AND PROCEDURE

Children were interviewed individually in a quiet room at their school. They completed five tasks on four successive days; namely: (1) a Non-motoric Finger Gnosia (Finger Gnosia) test; (2) a SDA test; (3) the Corsi Blocks (Corsi) visual spatial working memory test; (4) the Ravens Colored Progressive Matrices (Ravens) test; and (5) a basic RT task. The Corsi and RT tasks were completed on day one; and the Finger Gnosia, SDA, and Ravens tests were presented on the subsequent 3 days (task order was randomized). Children's handedness was also determined on day one. Each test/day sessions lasted between 10 and 20 min. Stimuli for the SDA and RT tasks were presented on 15½″ laptop computer screen in which presentation was controlled using DMDX (Version 2) software (Forster and Forster, 2001).

Handedness was assessed in three ways: (1) teacher's report; (2) the hand children used to pick-up and pass an object to the interviewer; and (3) the hand with which children used to write. The three indices were 100% consistent; on the basis of which 60 children were deemed right-handed and five left-handed. A formal handedness assessment was not used (e.g., Edinburgh Handedness Inventory-Oldfield, 1971) because pilot work revealed children had difficulty understanding the test language.

The Finger Gnosia test apparatus comprised (1) a 34-cm × 25.5-cm × 16-cm box that had a 17-cm × 6-cm opening on one side and open on the opposite side, and (2) a schematic outline of a palms-down pair of hands (**Figure 1** is a photo of the Finger Gnosia apparatus). The 17-cm × 6-cm opening was large enough for children to put their hands through. Children placed their hands, palm down, through the 17-cm × 6-cm opening so that the examiner could see them from the opposite side of the box, but the child could not see them. The examiner touched one of the children's fingers and simultaneously pointed to a finger on the schematic drawing of the hands (which was placed to left of the box; see **Figures 1** and **2**). Children were instructed to indicate as quickly and as accurately as possible whether the "touched" finger and the finger pointed to on the diagram were the same by saying "yes" or "no."

FIGURE 1 | The non-motoric finger gnosia test apparatus.

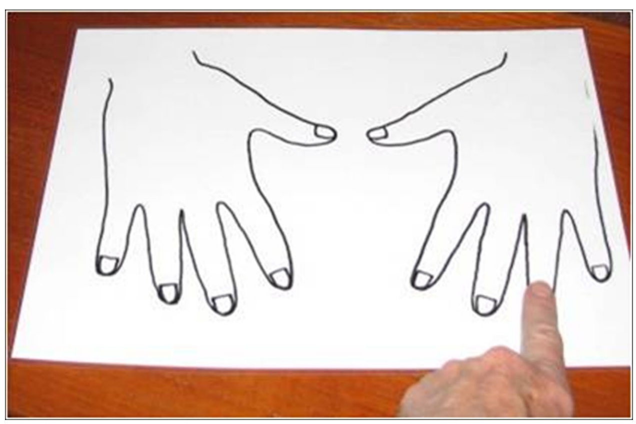

FIGURE 2 | Investigator pointing to finger on diagram.

Only four of the eight fingers and two thumbs were used in the Finger Gnosia test; namely, the left and right ring finger (fingers 2 and 9 respectively), and the left and right index finger (fingers 4 and 7 respectively). These fingers were selected to avoid the anchoring properties of the outside digits, as well as the saliency of the middle finger, and to require discrimination among the fingers on each of the hands. The Finger Gnosia test sequence involved four practice, and 72 test trials. The test trials comprised one correct and three incorrect finger–hand correspondence categories: (1) Correct Finger, Correct Hand – CFCH (e.g., touched finger 2-pointed to finger 2); (2) Incorrect Finger, Correct Hand – IFCH (e.g., touched finger 2-pointed to finger 4); (3) Correct Finger, Incorrect Hand – CFIH (e.g., touched finger 2-pointed to finger 7); and (4) Incorrect Finger, Incorrect Hand – IFIH (e.g., touched finger 2-pointed to finger 9). Thirty-six of the Finger Gnosia judgment trials comprised correct finger–correct hand relations, and 36 trials comprised instances of the three incorrect finger–hand relationships. The purpose of the practice trials was to familiarize children with judgment procedures and to emphasize that judgment were to be made about finger relations when hands were palm down. All children were able to describe the procedure and successfully completed the practice trials. Of interest were the number of correct judgments and response times for the four finger–hand judgment categories. As the interviewer touched/pointed to fingers, she said "this one," the sound of which activated an audio timing mechanism, and response times were measured from this point to children responding either "yes" or "no."

Single-digit addition competence was assessed by the ability to solve 30 two-term SDA problems of the form "a + b" = ? Children encounter SDA problems as part of their school curricula, and thus were familiar with the problem format. Addends comprised the numbers "2" to "7" presented in both orders (e.g., 2 + 7 and 7 + 2) and excluded tied pairs (e.g., 2 + 2). SDA problems were present via the laptop computer screen. When a child gave an answer to a problem, the interviewer (1) pressed a response key to record the time taken to solve problems, (2) recorded the answer to the problem, and (3) noted whether the child used fingers to aid problem solving.

Corsi Blocks (Corsi, 1972) is a measure of visuo-spatial working memory, performance, which is associated with math performance in older children (Kyttala and Lehto, 2008). It comprises nine 2.5 cm × 2.5 cm × 2.5 cm blocks fixed in random arrangement on a 25-cm × 25-cm board. The interviewer taps a sequence of blocks, one per second, and children attempt to repeat the tap sequence in the same (forward span) or reversed (backward span). In two practice trials, children were encouraged to wait for 5 s before acting, to limit impetuous responding and to instantiate task requirements. In the actual test, children responded immediately after the interviewer said "now." Within a trial, a tap sequence begins with the interviewer tapping two blocks. The two-block tap sequence is repeated and if one or both sequences have been successfully completed, the sequence is increased in length by one block. Two sequences are presented before increasing again by one block. A trial is discontinued after the child fails to correctly reproduce both tap sequences of the same length. There has been considerable inconsistency in the administration and scoring of the Corsi Blocks test (Berch et al., 1998). We adopt the Corsi administrative methodology used by Kessels et al. (2000). Consistent with Kessels et al. (2000), we report the raw span score.

Ravens Colored Progressive Matrices (Raven et al., 1986) is a standardized measure of non-verbal reasoning ability which has long been regarded as a measure of general intelligence (Spearman, 1946). It comprises 36 stimuli in which a section of a colored pattern is missing and participants attempt to complete the pattern by selecting from among six possible options. The 1998 test guidelines and age norms were used to administer and calculate Ravens scores.

Basic RT task

A black target dot appears on the laptop screen between 500 and 1000 ms after the appearance of a fixation point. Children pressed the computer shift key using their dominant hand as soon as the dot appeared. Basic processing speed was based on the average time taken to respond to the target dot on nine trials. Different ISIs were included to prevent target prediction effects.

ANALYTIC APPROACH

To identify possible Finger Gnosia and SDA subgroups, we used Latent Gold's latent profile analysis to determine whether different data structures (different subgroups) are embedded within the overall Finger Gnosia and SDA data structures (see Vermunt and Magidson, 2000, 2003; Notelaers et al., 2006). We used latent profile analysis for two reasons. First, it makes no assumptions about the measurement properties of stimuli (e.g., it does not assume that measures are continuous in nature). Second, Latent Gold's latent profile model technique has advantages over traditional clustering techniques in that it does not rely on traditional modeling assumptions (i.e., linear relationships, normal distributions, homogeneity). The technique identifies subgroups by grouping people who share similar characteristics via probability-based classification. Further, replication analyses select the best start seed to insure groups are unaffected by local maxima. This analytic approach stands in contrast to more traditional methods in which age is treated as a factor. Nevertheless, given the occurrence of large within-age individual differences in young children's numerical cognition (Canobi et al., 1998, 2003), we suggest latent profile analysis has much to recommend it to those interesting in characterizing developmental changes in math ability.

Finger Gnosia subgroups were determined by including in the analysis correct responses for the four finger judgment categories (i.e., CFCH; IFCH; CFIH; and IFIH judgments). SDA subgroups were determined by including problem solving accuracy and finger-use in calculating answers. Kindergarten and Year 1 children were included in the same analyses to determine the degree to which age was associated with subgroup membership. However, this approach does not obviate examining age-related changes.

RESULTS

No relationship was found between handedness or gender or any of the other factors in the study; consequently, neither handedness nor gender were considered further.

Although no significant grade-related differences were observed in the cognitive indices (Corsi: Kindergarten $M = 4.00$, SD = 0.12; Year 1 $M = 4.07$, SD = 0.10; Ravens: Kindergarten $M = 58.50$, SD = 27.01; Year 1 $M = 59.14$, SD = 23.50; RT: Kindergarten $M = 717.83$, SD = 100.12; Year 1 $M = 698.69$, SD = 97.56), possibly because of within-age variability in the measures, age-related trends were observed across the measures.

FINGER GNOSIA PROFILES

Inspection of the four Finger Gnosia measures (see Materials and Methods for a description of these measures) revealed substantial variability in correct judgments in each of the four judgment categories: CFCH ($M = 86.54$, SD = 12.5); IFCH ($M = 74.03$, SD = 30.0); CFIH ($M = 80.8$, SD = 23.4); and IFIH ($M = 80.8$, SD = 19.1).

To explore the significance of variability among the four Finger Gnosia measures, Latent profile analysis was conducted and revealed a four group solution, which accounted for 71% of the variance in the pattern of correct judgments. The four group solution was selected on the basis of the Bayesian information criterion (BIC) representing a significant model fit [BIC (LL) = 206; $p > 0.05$].

The correctness patterns of the four groups are presented in **Figure 3**. These correctness patterns can be characterized as: (1) a finger/hand confusion (FHC) subgroup ($n = 13$), (2) a finger confusion (FC) subgroup ($n = 9$), (3) a good finger gnosia (GFG) subgroup ($n = 24$), and (4) a high finger gnosia (HFG) subgroup ($n = 19$).

One-way ANOVAs showed that the four subgroups differed from each other on each of the four Finger Gnosia judgment measures. Specifically, for CFCH judgments: $F\ (3, 61) = 14.87$, $p < 0.001$; $\eta^2 = 0.42$; for IFCH: $F\ (3, 61) = 106.55$, $p < 0.001$; $\eta^2 = 0.84$; for CFIH: $F\ (3, 61) = 43.12$, $p < 0.001$; $\eta^2 = 0.68$; for IFIH: $F\ (3, 61) = 27.55$, $p < 0.001$; $\eta^2 = 0.58$. Moreover, there was an interaction between judgment condition and subgroup [$F\ (9, 183) = 22.26$, $p < 0.001$; $\eta^2 = 0.52$]. The HFG subgroup was more successful than other subgroups for all conditions (ps < 0.05). For the IFCH measure, the FC subgroup performed significantly worse than FHC subgroup, which in turn performed worse than the GFG subgroup (ps < 0.05). For CFIH measure, the FHC subgroup performed worse than the FC and GFG subgroups (ps < 0.05); and for IFIH measure, the four subgroups were different from each other (ps < 0.05). These patterns of findings support the use of the FHC, FC, GFG, HFG subgroup labels.

Table 1 reports the relationship between finger gnosia subgroups and grade, which revealed a significant association between the two factors (χ^2 (3, $N = 65$) = 22.41, $p < 0.001$; $\gamma = 0.74$, $p < 0.001$). Although Kindergarten and Year 1 children were present in all subgroups, age-related changes in finger gnosia abilities are evident.

FINGER GNOSIA JUDGMENT MEASURE AND SUBGROUP RESPONSE TIMES

The speed of making correct and incorrect judgments for the four Finger Gnosia subgroups (averaged across finger gnosia measures) is presented in **Table 2**. Initial analysis revealed no differences in judgment decision times for the three incorrect judgment measures (i.e., IFCH, CFIH, and IFIH measures). As a consequence, the data for these three judgment conditions were combined into one error judgment condition (i.e., time taken to make a decision).

With the exception of the HFG subgroup, subgroups did not differ in the time taken to make error and correct judgments, suggesting that judgment error was not due to children making judgments quickly [$t\ (18) = 3.57$, $p < 0.01$ for the HFG subgroup].

PROFILES OF SDA FINGER-USE

The number of SDA problems children solved correctly and the percentage of occasions on which they used fingers to compute

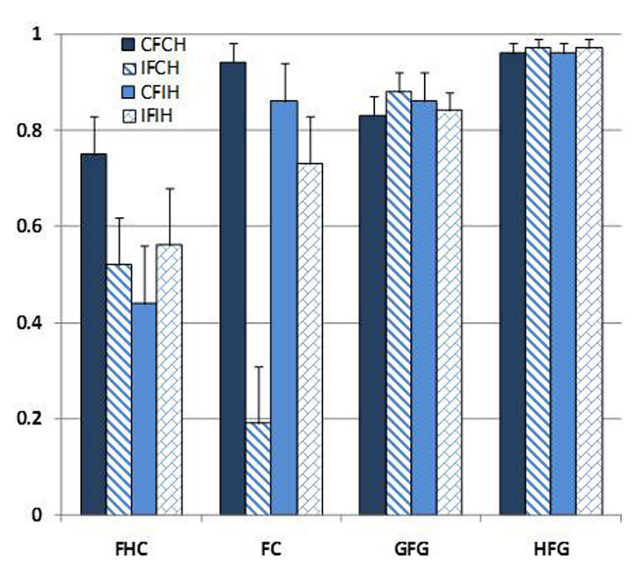

FIGURE 3 | Proportion CFCH, IFCH, CFIH, and IFIH judgments correct as a function of NMFG subgroup membership.

Table 1 | Cross tabulation between finger gnosia subgroup membership and grade.

Grade	FHC[1]	FC[2]	GFG[3]	HFG[4]
Kindergarten	12	7	7	4
Year 1	1	2	17	15

[1]Finger–Hand Confusion; [2]Finger Confusion; [3]Good Finger Gnosia; [4]High Finger Gnosia.

Table 2 | Average judgment times for finger gnosia correct and error conditions as a function of subgroup membership.

	FHC[1]		FC[2]		GFG[3]		HFG[4]	
	M	**SD**	***M***	**SD**	***M***	**SD**	***M***	**SD**
Correct	2034	356	1510	181	1780	161	1123	111
Error	2217	331	1634	228	1898	167	1408	146

[1]Finger–Hand Confusion; [2]Finger Confusion; [3]Good Finger Gnosia; [4]High Finger Gnosia.

answers was subjected to Latent Gold's latent profile analysis. (It should be noted that students were always successful in solving SDA problems when they used their fingers.) The analysis yielded four subgroups ($n = 15, 24, 11, 15$), which accounted for 94% of the variance in the pattern of responses in the data. The four subgroup solution was selected on the basis of a significant model fit [BIC (LL) = 1183; $p > 0.05$]. The four subgroups showed that SDA problem solving and finger-use varied orthogonally (Hi/Lo finger-use × Hi/Lo SDA problem solving success; see **Figure 4** for the SDA, Finger-use subgroups). Two subgroups were characterized by low finger-use, one of which had low accuracy (LFLA), and the other showed successful performance (LFHA). The other two subgroups showed moderate accuracy, one with high finger-use (HFMA), the other with moderate finger-use (MFMA).

The SDA Finger-use subgroups differed from each other in accuracy and computational finger-use [Accuracy: $F(3, 61) = 245.29$, $p < 0.001$; $\eta^2 = 0.92$; Finger-Use: $F(3, 61) = 378.37$, $p < 0.001$; $\eta^2 = 0.95$]. Further, there was an interaction effect between success and finger-use [$F(3, 61) = 175.03$, $p < 0.001$; $\eta^2 = 0.90$]. *Post hoc* analysis revealed that the LFLA subgroup performed significantly worse in solving SDA problems than the other subgroups ($ps < 0.05$); the LFHA subgroup solved more SDA problems correctly than the other three subgroups ($ps < 0.05$); however, the two finger-use subgroups did not differ in SDA problem solving ability.

Of interest is whether there is an aged-based relationship between grade and SDA finger-use subgroups (see **Table 3**). The LFLA subgroup comprises Kindergarten children only, but both grades are represented in the other three subgroups. As expected, a relationship was found between the SDA finger-use subgroup and age [$\chi^2(3, N = 65) = 29.29$, $p < 0.001$; $\gamma = 0.77$, $p < 0.001$]. The presence of Kindergarten children in all four subgroups, and of Year 1 children in three of the four subgroups, highlights SDA variability.

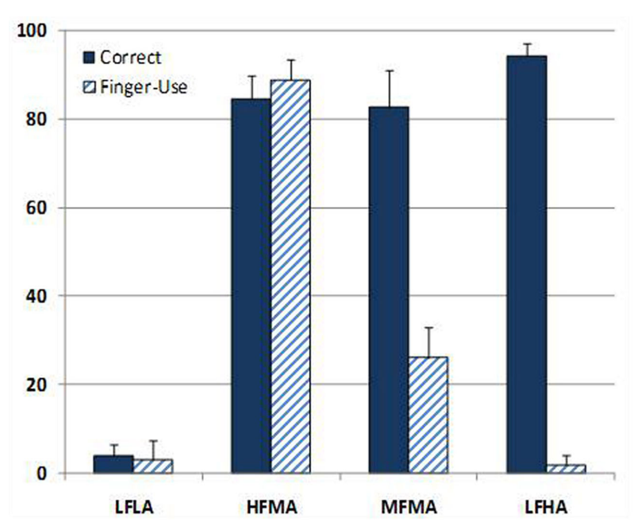

FIGURE 4 | Single-digit addition percentage correct as a function of SDA finger-use subgroups.

In what follows we focus only on the SDA and Finger Gnosia subgroups.

RELATIONSHIP BETWEEN FINGER GNOSIA AND SDA SUBGROUPS AND COGNITIVE ABILITY

One-way ANOVAs examined Finger Gnosia and SDA subgroup differences in RT, Ravens, and Corsi abilities (see **Tables 4** and **5** for means and SDs for all measures).

Analyses showed that neither the Finger Gnosia subgroups nor the SDA finger-use subgroups differed in RT or Raven's performance. However, both the Finger Gnosia and SDA subgroups differed in Corsi span [Finger Gnosia: $F(3, 61) = 2.88$, $p < 0.05$; $\eta^2 = 0.13$; SDA Finger-use: $F(3, 61) = 6.89$, $p < 0.001$; $\eta^2 = 0.25$]. *Post hoc* tests showed that the HFG subgroup had a longer Corsi span than the two subgroups exhibiting finger representation difficulties (i.e., FHC and FC). Similarly, the Low Finger-use, High Ability SDA subgroup had a longer span than the other three subgroups ($ps < 0.05$), which did not differ from each other.

RELATIONSHIPS BETWEEN FINGER GNOSIA AND SDA SUBGROUPS

Table 6 reports the cross tabulation between Finger Gnosia and SDA finger-use subgroup memberships. Analyses showed a significant relationship between subgroup membership for the two measures [$\chi^2(9, N = 65) = 30.31$, $p < 0.001$; $\gamma = 0.70$, $p < 0.001$]. The findings provide support for the hypothesis that differences in children's finger gnosia are associated with their use of fingers as computational aids in solving simple addition problems.

PREDICTING SDA FINGER-USE FROM FINGER GNOSIA AND CORSI SPAN

Results show that SDA Finger-use subgroups were associated with the Finger Gnosia subgroups and Corsi span. To further investigate the relationships between the three measures, a multinomial logistic regression analysis was conducted in which SDA Finger-use subgroup membership was predicted from Finger Gnosia subgroup membership and Corsi span. The results showed that the goodness of fit for the overall model was very good [Pearson $\chi^2(174, N = 65) = 134.17$, $p = 0.98$; pseudo r^2 (Cox and Snell) = 0.55]. Overall, 58.5% of the children were correctly assigned to SDA finger-use subgroups. More specifically, Corsi span and Finger Gnosia subgroup membership made significant unique contributions to the overall model [$\chi^2(3, N = 65) = 14.07$, $p < 0.01$ and $\chi^2(9, N = 65) = 37.99$, $p < 0.001$ respectively].

DISCUSSION

The research was designed to investigate the developmental relationship between differences in finger gnosia representations,

Table 3 | Cross tabulation between SDA finger-use subgroup and grade.

Grade	LFLA[1]	HFMA[2]	MFMA[3]	LFHA[4]
Kindergarten	15	10	2	3
Year 1	0	14	9	12

[1] Low finger-use, low accuracy; [2] High finger-use, moderate accuracy; [3] Moderate finger-use, moderate accuracy; [4] Low finger-use, high accuracy.

Table 4 | Reaction time, Ravens and Corsi measures as a function of Finger Gnosia subgroup.

	FHC[1]		FC[2]		GFG[3]		HFG[4]	
	M	SD	*M*	SD	*M*	SD	*M*	SD
BPS	751.58	28.82	730.36	36.83	704.16	20.10	671.51	18.43
Ravens	51.92	7.06	65.00	6.29	58.12	4.91	68.42	5.46
Corsi	3.83	0.21	3.75	0.20	4.09	0.11	4.25	0.14

[1] Finger–Hand Confusion; [2] Finger Confusion; [3] Good Finger Gnosia; [4] High Finger Gnosia.

Table 5 | Reaction time, Ravens and Corsi measures as a function of SDA finger-use subgroup.

	LFLA[1]		HFMA[2]		MFMA[3]		LFHA[4]	
	M	SD	*M*	SD	*M*	SD	*M*	SD
BPS	705.16	25.54	723.66	17.09	719.76	31.01	675.11	30.28
Ravens	48.67	7.63	59.38	4.77	53.64	6.00	72.00	5.67
Corsi	3.95	0.16	4.03	0.11	3.61	0.17	4.45	0.15

[1] Low finger-use, low accuracy; [2] High finger-use, moderate accuracy; [3] Moderate finger-use, moderate accuracy; [4] Low finger-use, high accuracy.

Table 6 | Cross tabulation between SDA finger-use subgroup membership and NMFG subgroup membership.

		SDA subgroup			
		LFLA	HFMA	MFMA	LFHA
Finger gnosia subgroup	FHC	9	4	0	0
	FC	3	4	2	0
	GFG	3	10	4	7
	HFG	0	6	5	8

visuo-spatial working memory, and finger-use in SDA problem solving. The results demonstrate a strong relationship between finger gnosia subgroup membership and SDA finger-use/problem solving success subgroups. Even though visuo-spatial working memory was associated with finger gnosia and SDA subgroup membership, finger gnosia subgroup membership predicted SDA finger-use subgroups over and above the contribution of visuo-spatial working memory. These findings demonstrate for the first time that finger gnosia representations change between 5- and 7-years, and these changes are related to finger-use in computation. Furthermore, visuo-spatial abilities and finger gnosia are independently associated with computation abilities.

MEASURING FINGER GNOSIA

The results suggest that the non-motoric finger gnosia measure provided a good characterization of individual differences in finger representation. Moreover, given the association between psychomotor difficulties, developmental disorders, and problems in number processing (Rourke, 1995; Holsti et al., 2002), our findings provide direct evidence for the importance of a measure of finger gnosia, uncontaminated by motor activity, in predicting arithmetic abilities. Furthermore, the results show that within the 5- to 7-age range, there is substantial improvement in finger representation. Kindergarten children initially exhibit problems discriminating fingers within and between hands. In contrast, most of the Year 1 students exhibited good or very good finger representation.

PERFORMANCE PROFILES

Our findings revealed the existence of individual differences in finger gnosia judgment ability. Specifically, four distinctly different profiles of finger gnosia judgment were identified. The subgroups were characterized by the differential ability to accurately judge the four finger gnosia measures (i.e., relationships between the touched finger and the indicated diagram finger). It should be noted that all subgroups were slightly slower in making incorrect than correct judgments, which suggests that error judgment *per se* did not reflect impulsive responding. Although, as expected, there was a significant association between finger gnosia subgroup membership and age, children from both age groups were represented across all the subgroups. This finding highlights the importance of taking into account of the wide range of difference in young children's abilities in addition to age-related changes. It also suggests that subgroups provided a detailed characterization of children's finger representation development.

Four SDA finger-use profiles were identified, which varied orthogonally as a function of problem solving ability and finger-use. These subgroups were also associated with age, but children from both ages were represented in three of the four groups, suggesting that subgroup membership is more informative about SDA finger-use than age alone. It is evident that even within a narrow age range, large individual differences exist in computation ability and finger-use.

RELATIONSHIPS BETWEEN FINGER GNOSIA, SDA FINGER-USE, AND COGNITIVE ABILITIES

The findings showed that the non-motoric finger gnosia and computational finger-use subgroups were systematically associated with each other. Specifically, children who showed poor finger gnosia, characterized by FHC or FC, were largely assigned to the low finger-use, low ability SDA subgroup. Moreover, all children in the high computational ability subgroup were classified in the good and HFG subgroups.

These findings support previous research, which show that poor finger gnosia is associated with poor arithmetic performance (Fayol et al., 1998; Fayol and Seron, 2005; Noël, 2005; Gracia-Bafalluy and Noël, 2008). However, our findings add to previous research in two ways. First, prior research did not investigate the relationship between the finger gnosia and finger-use in computation. Second, by partitioning finger gnosia performance data, we identified profiles of finger representation that were systematically associated with SDA finger-use and success. In particular, the association was not confined to the relationship between poor finger gnosia and a lack of arithmetic problem solving success; it also showed that children with HFG exhibited high calculation ability.

We found no association between subgroup membership on either of the tasks and basic RT or performance on the Ravens test. This finding is important because it shows that the response speed differences between the finger gnosia subgroups were not an artifact of basic RT, but of finger representation ability. Furthermore, although some research has shown that differences in arithmetic success are related to overall processing speed (Geary and Brown, 1991; Kail, 2007), our findings are consistent with research that found little relationship between general measures of ability and numerical cognition in young children (Butterworth, 2005).

However, for both the Finger Gnosia and SDA finger-use subgroups, there was an association with visuo-spatial working memory performance. This result is not unexpected, and is consistent with previous research showing that Corsi span is associated with computational ability (Landerl et al., 2009). Nevertheless, this particular finding provides additional important information about the relationship between spatial ability and number competence: it showed that visuo-spatial working memory was systematically associated with SDA abilities in young children.

Although visuo-spatial working memory was associated with performance profiles on both the finger gnosia and SDA tasks, finger gnosia subgroup membership predicted SDA subgroup membership over and above the contribution of visuo-spatial working memory. This suggests that the finger gnosia and visuo-spatial working memory are independently related to computation ability.

Overall, the findings suggest an important relationship between both age-related and individual differences in children's finger representations, and the ways in which they use fingers in computation. They also suggest that finger representations become more precise with age, which in turn, is related to the way in which fingers are used to solve computation problems. Furthermore, they provide more detailed information about the nature of finger representation and its unique contribution to computational finger-use.

FINGER REPRESENTATION, SPATIAL ABILITY, AND ARITHMETIC COMPETENCE

Previous research has considered the relationship between computational finger-use and arithmetic ability (Di Luca et al., 2006; Domahs et al., 2008), finger gnosia and number ability (Fayol et al., 1998; Gracia-Bafalluy and Noël, 2008), and the relationship between visuo-spatial working memory and arithmetic competence (Lonnemann et al., 2008; Landerl et al., 2009). However, with the exception of our research, no study has examined the three-way relationship between finger representation, computational finger-use, and spatial working memory. Indeed, our research suggests that finger gnosia is partially independent of spatial working memory.

While many studies have found an association between finger representation, finger-use, and enumeration, there is debate about how fingers instantiate numerical knowledge. As noted earlier some claim that the properties of number are acquired through habitual hand/finger counting practice (Di Luca et al., 2006; Domahs et al., 2008, 2010; Sato and Lalain, 2008). Others claim that hand/finger representations facilitate mapping numerical concepts onto a pre-existing spatial, mental number line. Whatever side one takes in this debate, our findings suggest that the development of finger representation *per se* cannot be ignored, nor can the relationship between finger gnosia and the use of fingers as computational tools.

FUTURE RESEARCH

The performance profiles identified herein suggest developmental trajectories for finger representation and finger-use in arithmetic problem solving. We suggest that a longitudinal analysis of young children's finger gnosia and finger-use in enumeration would help to establish a development model of the relationship between the two components. Indeed, developmental changes in the relationship between spatial ability, finger gnosia, and arithmetic performance would help identify the precise contribution of each component to the acquisition of number knowledge. Furthermore, we need to better understand the developmental interrelationship between early learning environments and the emergence of cognitive representations (Sameroff, 2010). In the present study, we showed that finger representation ability changed between 5- and 7-years. However, we are unable to say why this change occurred. It is possible that calculation practices may facilitate finger representation, which in turn may facilitate more sophisticated calculation practices.

Improving finger gnosia is assumed to mediate the spatial representations that support numerical development. Further research that investigates finger gnosia training would help determine whether spatial representations of number can be targeted directly. This is consistent with Lonnemann et al.'s (2008) suggestion that visuo-spatial strategies may assist number processing when they coincide with spatial representations.

CONCLUSION

We investigated the developmental role fingers play in the acquisition of computation abilities, in particular, whether non-motoric finger gnosia predicts finger-use in computation. We show for the first time that non-motoric finger gnosia is a good measure of motoric finger-use in simple addition. Moreover, we also show that both finger gnosia (possibly, the spatial properties of finger/hand arrangements) and spatial working memory independently predict finger-use in computation. This suggests that different kinds of spatial processes support the development of numerical cognition. It is also evident that general cognitive measures (processing speed and non-verbal reasoning in the present context) do not predict arithmetic competence, at least in young children.

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Unimanual SNARC effect: hand matters

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A structural representation of the hand embedding information about the identity and relative position of fingers is necessary to counting routines. It may also support associations between numbers and allocentric spatial codes that predictably interact with other known numerical spatial representations, such as the mental number line (MNL). In this study, 48 Western participants whose typical counting routine proceeded from thumb-to-little on both hands performed magnitude and parity binary judgments. Response keys were pressed either with the right index and middle fingers or with the left index and middle fingers in separate blocks. 24 participants responded with either hands in prone posture (i.e., palm down) and 24 participants responded with either hands in supine (i.e., palm up) posture. When hands were in prone posture, the counting direction of the left hand conflicted with the direction of the left–right MNL, whereas the counting direction of the right hand was consistent with it. When hands were in supine posture, the opposite was true. If systematic associations existed between relative number magnitude and an allocentric spatial representation of the finger series within each hand, as predicted on the basis of counting habits, interactions would be expected between hand posture and a unimanual version of the spatial–numerical association of response codes (SNARC) effect. Data revealed that with hands in prone posture a unimanual SNARC effect was present for the right hand, and with hands in supine posture a unimanual SNARC effect was present for the left hand. We propose that a posture-invariant body structural representation of the finger series provides a relevant frame of reference, a within-hand directional vector, that is associated to simple number processing. Such frame of reference can significantly interact with stimulus–response correspondence effects, like the SNARC, that have been typically attributed to the mapping of numbers on a left-to-right mental line.

Keywords: spatial–numerical association of response codes, numbers, fingers, unimanual SNARC, parity, magnitude

INTRODUCTION

The relation between spatial and numerical cognition was first assumed by Galton (1880) at the end of the nineteenth century. Taking into account introspective reports he proposed that magnitude information might be analogically arranged through the location of numbers along a spatial axis oriented from left to right. The concept of a mental number line (MNL), where smaller numbers occupy leftward locations and larger numbers rightward locations, later found consistent evidence in the spatial–numerical association of response codes (SNARC) effect. The effect was first named by Dehaene et al. (1993), in a seminal study where participants were asked to decide if a centrally presented number was even or odd by pressing one of two lateralized keys. They reported that large numbers were responded to faster with the right than with the left key and small numbers were responded to faster with the left than with the right key. Such preferential mapping effect (see, e.g., Kornblum et al., 1990) between the magnitude of a target number and the location of a correct response in external space would thus corroborate the idea of the existence of a mental representation linking numbers to space. Even if magnitude information is irrelevant to the task of parity judgment, the display and subsequent processing of an Arabic number was thus assumed to obligatorily activate its numerical magnitude code (i.e., cardinality; see, e.g., Santens and Gevers, 2008; Fitousi et al., 2009 for more recent proposals with a different emphasis). The SNARC effect is nowadays an established finding (see Fischer, 2006, for reservations) and it has been consistently found across different tasks, materials, response modalities, and populations (Fias and Fischer, 2005; Wood et al., 2008).

Dehaene et al. (1993) found that the SNARC effect does not reverse in left handed individuals or when participants are asked to respond with their hands crossed (but see Wood et al., 2006a). They found weaker SNARC effects in subjects who were originally educated in a right to left writing system, such as Iranian immigrants; and the longer their Iranian participants had dealt with a left-to-right writing system (i.e., the longer they had been living in France), the more likely they were to show the typical Western SNARC effect. Later on Zebian (2005) provided more direct evidence, by showing a significant reverse SNARC effect in monoliterate Arabic readers. These findings are interesting as they highlight the possibility that the association between number and space is the byproduct of educational factors rather than some biologically determined connection (see also Núñez, 2011). Other sources have pointed to finger counting habits, in alternative or in addition to reading direction, as a crucial component of the mental representation of number from which spatial attributes could originate (e.g., Butterworth, 1999; Fias and Fischer, 2005; Rusconi et al., 2005; Fischer and Brugger, 2011). In many cultures the use of fingers develops spontaneously in childhood, and tends to precede the use of more abstract numerical codes (Butterworth, 1999). Accordingly, influences from finger representations and counting habits have been recently shown both in children and in adult numerical cognition (see, e.g., Noël, 2005; Di Luca et al., 2006, 2010; Di Luca and Pesenti, 2010; Domahs et al., 2008, 2010; Di Luca and Pesenti, 2011). Finger counting habits appear to influence also the SNARC effect as measured in a parity judgment task with bimanual responses (Fischer, 2008). Fischer (2008) suggests that a systematic relation exists between the hand one starts counting with and the strength of the preferential mapping of numbers on bimanual lateralized responses. More precisely, the SNARC effect is weaker in right-starters compared to left-starters because their counting routine consistently associates smaller numbers to their right hand and larger numbers to their left hand, in contrast with the MNL-based correspondence effect (Fischer, 2008). Predominance of a counting- over a MNL-based representation was reported by Di Luca et al. (2006), who directly tested number–finger associations. They asked participants to respond to Arabic digits by pressing 1 of 10 keys with all 10 fingers and with their hands in prone and in supine posture. Consistent with their participants being right-starters, performance was better when small numbers were associated to the right hand and large numbers to the left hand (with modulations). Such advantage was present in either postures and top performance was achieved when the specific number-to-finger mapping was also congruent with the prototypical direction of counting within a hand, which therefore can be said to influence the way numerical information is projected into physical space via hand motor outputs (see also Sato et al., 2007 for neurophysiological evidence). In conclusion, part of the available evidence suggests that finger counting habits modulate the association between numbers and space as measured via manual responses.

On the other hand, Dehaene et al. (1993) obtained a significant SNARC effect also with an incongruent hand-to-response key mapping, that is having participants respond with their hands crossed. They thus concluded that the SNARC effect is not driven by the association between number magnitude and any lateralized effectors but it rather depends on response location. Wood et al. (2006a) later failed to replicate Dehaene et al.'s (1993) result, as the SNARC effect disappeared when their participants responded with their hands crossed. Fischer (2006) suggested that, although it is true that several spatial frames of reference may exist that either conflict with or boost each other, it is also possible that one single number to space association (which does not necessarily reflect any long-term representation) is strategically instantiated by working memory, depending on contingent task requirements and settings. In agreement with Fischer's (2006) proposal, Bächtold et al. (1998) have shown that the classical (and supposedly MNL-related) SNARC effect can be easily "overwritten" by a reverse SNARC effect when asking participants to perform simple tasks with numbers while imagining them as hours on a clock face (whereby small numbers are on the right hand side, large numbers on the left hand side). Thus different long-term associated frames of reference and/or working memory strategic representations can contribute to the resulting behavioral SNARC effect. Finally, Wood et al. (2006b) convincingly argued that the presence (absence) of a SNARC effect in their study may not only reflect the activation (or lack of activation) of the MNL but it may also represent the end result of an interaction between different, and at times conflicting, spatial frames of reference evoked by numbers. More recently, Gevers et al. (2010) have also advanced the proposal that different mechanisms (categorical vs. coordinate spatial reference frames) may be at the origin of "endogenous" SNARC effects as detected in parity vs. magnitude judgment tasks. The proposal is especially interesting, considered that it would see these mechanisms naturally mapped on different macro-anatomical substrates (e.g., left vs. right hemisphere; Kosslyn, 2006; Gevers et al., 2010) and thus predict a specific role for the language dominant hemisphere in the SNARC effect from parity judgment and for the non-dominant hemisphere in the SNARC effect from magnitude judgment tasks (Gevers et al., 2010; see, e.g., Rusconi et al., 2011a, for consistent neuro-functional evidence).

Data from left-sided visuo-spatial neglect patients and studies with transcranial magnetic stimulation (TMS) applied on the right (non-dominant) hemisphere of healthy participants (e.g., Zorzi et al., 2002; Oliveri et al., 2004; Doricchi et al., 2005; Göbel et al., 2006; see Sandrini and Rusconi, 2009; Umiltà et al., 2009; Sandrini et al., 2011 for related reviews) reported a systematic bias toward larger numbers in numerical bisection tasks analogous to the bias that is produced by actual or virtual lesions to the right hemisphere in physical space processing. Neglect patients have also been reported to show a rightward bias in binary-choice magnitude judgment tasks on Arabic digits (Vuilleumier et al., 2004) but an intact SNARC effect in parity judgments (Priftis et al., 2006), and TMS on the right anterior hemisphere eliminates the SNARC effect in magnitude judgments but not in parity judgments (Rusconi et al., 2011a,b).

While the right hemisphere is generally considered dominant for space processing, the left hemisphere has been historically recognized as dominant for the skilled use of hands and their coordination (Liepmann, 1905; Binkofski et al., 1999). It has also been indicated as the site of body-related schemas (Kinsbourne and Warrington, 1962; Sirigu et al., 1991; Guariglia et al., 2002), in addition to hosting a language-related categorical space reference system (Kosslyn, 2006). Furthermore, left hemisphere lesions often produce spurious (i.e., either incomplete or with additional deficits) and sometimes pure Gerstmann's syndrome, a cluster of neuropsychological symptoms characterized by left–right confusion, agraphia, acalculia, and finger agnosia (Gerstmann, 1940; see Rusconi et al., 2010 for a recent review). Likewise, TMS studies have identified contiguous neural substrates with causal effects on numerical processing, finger gnosis, and categorical left–right discrimination (Rusconi et al., 2005; Hirnstein et al., 2011). If there is any cross-talk between a supposed embodied spatial reference frame and the SNARC effect, it thus appears more likely to occur by virtue of left hemisphere fronto-parietal networks.

Building on neuropsychological insights (e.g., Gerstmann, 1940; Kinsbourne and Warrington, 1962) and on current knowledge of somatosensory stimulus processing we have recently identified an abstract structural representation of the hand and fingers that is posture-invariant (Rusconi et al., 2009). Such body structural representation would constitute a very basic form of self-awareness, and is thought to embed long-term information about the identity and the relative position of fingers rather than their current position in egocentric space (which would instead be continuously updated via proprioceptive input and be functional to action systems). As counting consists of an overlearnt sequence of movements that is essentially rooted in the invariant structure of the hand, the fixed order of fingers and their identity (e.g., Butterworth, 1999) we hypothesize the existence of a long-term association between small digits and the internal structure of the hand (i.e., the relative position of fingers) that, in addition to the side of the starting hand (Fischer, 2008), may influence the behavioral effects of number–space associations in a predictable way. The issue of a relation between hands and number has been so far tackled from two complementary perspectives: an action-related and a representational perspective (Sandrini and Rusconi, 2009). As the possible mechanism linking counting routines to the MNL is still underspecified and far from definitively established (Fischer, 2008), we propose that the posture-invariant body structural representation referred above may provide a relevant frame of reference (a within-hand directional vector) involved in the cross-talk between numbers, bodily representations, and the MNL.

In the present study we thus address the relation between number, mental space, and finger representations by investigating whether the intrinsic directionality of the finger schema, which may lie behind the widespread use of "anatomical" counting routines (see Lindemann et al., 2011), will exert any measurable effects in unimanual parity and magnitude judgment tasks – that is simple numerical tasks that are known to reliably produce spatial stimulus–response (S–R) correspondence effects with bimanual response (Umiltà and Nicoletti, 1990; Wood et al., 2008) but to the best of our knowledge have never been systematically studied in unimanual version and with posture manipulation (one notable exception being Leuthard et al., 2005, who thoroughly investigated clock-related SNARC effects for different postures of the dominant hand, in a person's front and back space). In certain experimental and clinical settings, however, bimanual responses are best avoided, impractical, or impossible (e.g., some TMS experiments, studies with hemineglect or hemiplegic patients), and the possibility to probe number–space associations by measuring the SNARC effect with unimanual responses should not be given for granted.

In order to minimize potential carry over effects in the mapping of stimuli to responses from one posture to the other and mental rotation strategies (see, e.g., Leuthard et al., 2005) we manipulated hand posture between rather than within participants. Since the mechanisms of implicit and explicit access to number magnitude may be supported by different neuro-functional networks or even by different hemispheres (see, e.g., Priftis et al., 2006; Gevers et al., 2010; Rusconi et al., 2011a), all of our participants engaged both in a number magnitude judgment and in a parity judgment task for exploratory reasons. In particular we were interested in detecting whether hand posture may affect the SNARC effect in a different way, when probed in the context of a number parity or a number magnitude judgment task. We thus measured unimanual SNARC effects from either hands in two different postures and with two classical numerical tasks. Typically, the SNARC effect emerges in settings requiring bimanual key-press responses, with response keys aligned along the horizontal dimension and therefore being defined one as left key and the other as right key (Dehaene et al., 1993). Although the right hand typically operates the right response key, and the left hand operates the left response key, Dehaene et al. (1993) manipulated also the hand-to-key assignment in their seminal study and reported that the SNARC effect follows the laterality of response keys rather than that of the response effectors (but see Wood et al., 2006a). Later studies adopted a unimanual response version of the same task, to produce an equivalent measure of the SNARC effect for left hemispatial neglect patients who could only respond with their ipsilesional effector (i.e., the right hand only; e.g., Priftis et al., 2006). Rather than operating a left and a right response key with their left and right hands, participants operated a left and a right response key with a left and a right finger of their right hand (see Leuthard et al., 2005 for extensive background information and rationale of the unimanual variant). In the current study we will maintain the typical definition of the SNARC effect, as a preferential association of small numbers to a left response key and large numbers to a right response key. When present, the SNARC effect will be signaled by a significant interaction between number magnitude and response side (e.g., Bächtold et al., 1998), and by a negative linear regression slope for the difference between right and left response latencies having number (1–9, 5 excluded) as a regressor (e.g., Fias et al., 1996).

Unlike the usual SNARC effect, unimanual SNARC is characterized by the preferential mapping of numerical stimuli to lateralized responses operated by different fingers of the same hand rather than homologous fingers on different hands. Our participants showed anatomical finger counting routines whereby, within each hand, counting starts from the thumb and ends with the little finger, thus invariably associating small numbers (in relative terms) to the thumb and large numbers to the little finger. We thus predicted instances of conflict between the direction of an active hand spatial framework and the MNL, while processing single-digit numbers. A responding right hand in prone posture will see the two frames of reference aligned, a responding right hand in supine posture will see the two frames run in opposite directions. A responding left hand in prone posture will have its intrinsic hand direction misaligned with the MNL, whereas its supination will have them aligned (see **Figure 1**). If the MNL dominates over the within-hand reference frame in a unimanual context, the SNARC effect when present should remain unaffected by posture manipulations. If the hand reference frame dominates over the MNL, the SNARC effect should be significant in either aligned posture and of reverse sign in the posture with a misalignment between hand direction and MNL. If both frames of reference contribute about equally to the mapping of numbers onto response space, then it is possible that the SNARC effect is significant when they are aligned and reduced or eliminated when they are misaligned. With this manipulation it is thus possible to investigate the influence of multiple competing

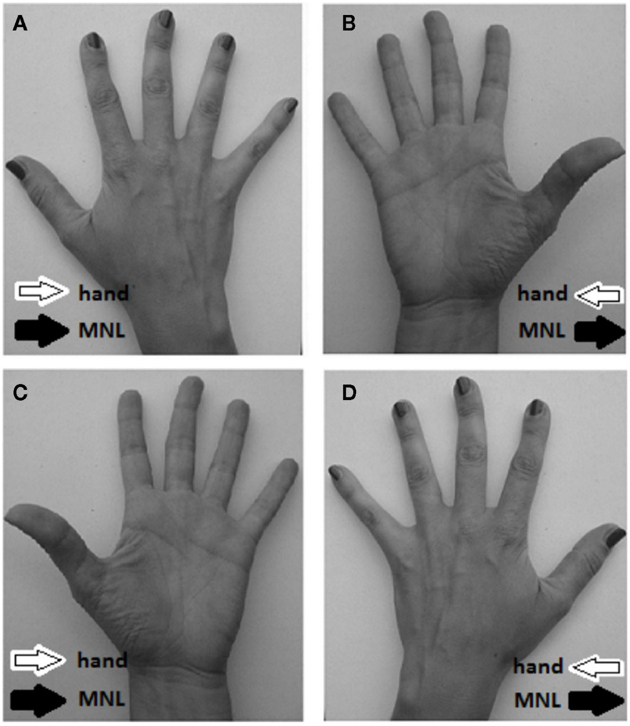

FIGURE 1 | Schematic showing the study main rationale. (A,B) Show a right hand in prone and supine posture respectively. **(C,D)** Show a left hand in prone and supine posture respectively. In **(A,C)**, within-hand counting direction (white arrow) is aligned with the mental number line direction (MNL, black arrow); in **(B,D)**, within-hand counting direction is misaligned with the direction of the mental number line. When unimanual responses are required with index and middle fingers, a regular SNARC effect should be present in condition **(A,C)**, whereas its presence in condition **(B,D)** may depend on the relative weight of the within-hand counting direction and the mental number line spatial frame.

spatial representations in numerical cognition. An alternative view could maintain that the absence of an effect in the misaligned condition indicates the absence of any spatial frames of reference (see, e.g., Fischer, 2006; but see Wood et al., 2006b). This position however, based on a view of the SNARC effect as byproduct of working memory strategies, would require the *ad hoc* assumptions that posture but not responding hand in one group (right hand in supine posture) and responding hand but not posture (left hand in prone posture) in the other group make the use of MNL too taxing or task-inefficient, while being instead useful when responding with the left hand in prone posture or with the right hand in supine posture. Following previous studies (e.g., Leuthard et al., 2005; Wood et al., 2006b), we will propose that the coexistence of two conflicting frames of reference may be indicated by the lack of an overall SNARC effect in the misaligned condition due to increased variability in the leading frame of reference between participants rather than to the reciprocal neutralization of coexisting frames within individuals. If this was true, two comparable groups having significant but opposite SNARC effects should be found in the misaligned condition. Absence of both frames of reference in the misaligned condition would instead be signaled by the lack of an overall SNARC effect in concomitance with low inter-individual variability in the SNARC effect (expected to be close to null for most of the participants, with occasional deviations due to random error; Wood et al., 2006b). In the aligned condition, variability of the SNARC effect would depend in any case on random error plus inter-individual differences in the overall strength of number–space associations, with most of the participants showing a SNARC effect in one direction.

MATERIALS AND METHODS

PARTICIPANTS

Forty-eight healthy participants (26 females; 45 right-handed) took part in the investigation, all of whom were naïve to its purpose and were born and educated in a Western country (left-to-right reading direction). They had a mean age of 26 (SD = 5) years. The study was approved by the ethical committee for experiments on humans at the University of Trento and participants gave informed written consent before taking part in the experiment. Two independent groups were formed by random assignment of participants. One of the groups (11 females, 22 right-handed, mean age = 25, SD = 4) responded with either hands in prone posture, the other (14 females, 23 right-handed, mean age = 27, SD = 5) responded with either hands in supine posture. To avoid priming or carry-over effects in the experimental session, only at the end of the task participants were asked to show the experimenter how they count with their fingers when both their hands are free. Most participants (44 out of 48, more precisely 22 in each group) reported using the conventional Italian and French counting sequence starting from the right thumb, except for four participants who were reportedly left-starters. All of them, however, counted the smallest number on the thumb and the largest on the little finger of the opposite hand, and therefore switched from one hand to the other by following an "anatomical" (as opposed to "spatial") sequence (see, e.g., Lindemann et al., 2011).

APPARATUS, STIMULI, AND PROCEDURE

On each trial, participants fixated the center of a computer display where a white digit (range: 1–9, 5 excluded; font and size: Arial 48 Bold) subtending horizontally about 1.2° and vertically about 1.9° of visual angle was shown on black background for 1,300 ms (see **Figure 2**). In one of the two tasks, digits were to be classified as smaller/larger than 5, in the other digits were to be classified as even/odd. In the prone posture condition, participants kept their hands with their palms down throughout the experiment. While the responding hand was placed on the keyboard, the non-responding hand was resting comfortably on the ipsilateral knee. For half the trials participant responded with their right hand by pressing a left key with their index finger and a right key with their middle finger (see **Figure 3A**), and for the other half with their left hand by pressing a left key with their middle finger and a right key with their index finger. Response keys were aligned on participants' vertical meridian, with the left key (corresponding to V on a QWERTY keyboard) in left hemispace and the right key (corresponding to N) in right hemispace. In the supine posture condition, participants kept their hands with their palms up throughout the experiment. While the responding hand was placed on the keyboard, the non-responding hand was resting comfortably on the

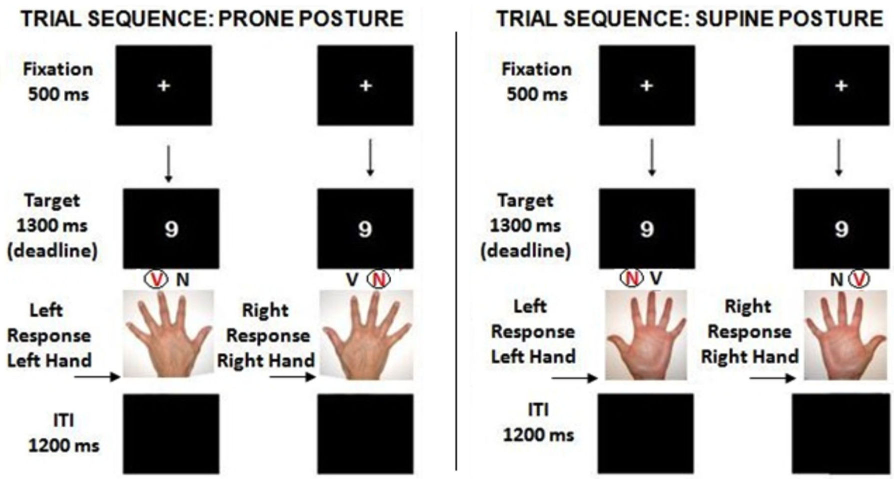

FIGURE 2 | On each trial, participants fixated the centre of a display where a digit (1–9, 5 excluded) appeared for 1,300 ms. In half the blocks, digits were classified as smaller/larger than five in the other half as even/odd. Participants responded with either their right index and middle finger or their left index and middle finger, and the experiment was divided in two main parts according to which hand was used to respond. Since nine is large in the experimental range, the right-side key is compatible with a left-to-right representation of the numbers 1–9, and the left-side key is incompatible.

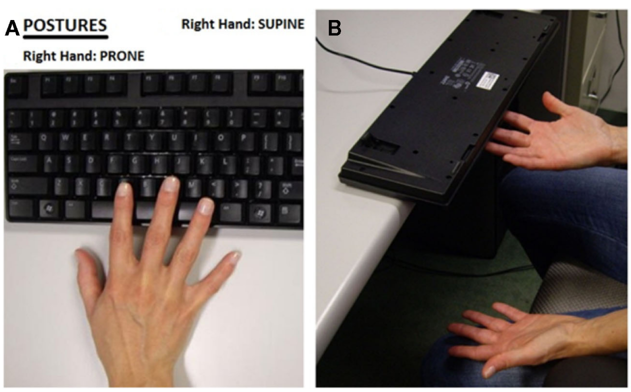

FIGURE 3 | (A) In the prone posture, participants' fingers (index and middle of the same hand) were placed on the V and N keys of an upright QWERTY keyboard. The response keys were centered on the participant's vertical meridian while the other hand rested comfortably on the ipsilateral knee in the same posture as the responding hand. **(B)** In the supine posture, participants' fingers (index and middle of the same hand) were placed on the V and N keys of a reverse QWERTY keyboard that was firmly attached to the table with its two bottom rows of keys (including V and N) protruding from the edge. As in the prone posture condition, the non-responding hand rested comfortably on the ipsilateral knee in the same posture as the responding hand.

ipsilateral knee. For half the trials participants responded with their right hand by pressing a left key with their middle finger and a right key with their index finger (see **Figure 3B**), and for the other half with their left hand by pressing a left key with their index finger and a right key with their middle finger. Response keys were aligned on participants' vertical meridian, with the left key (corresponding to N, as the keyboard was reversed) in left hemispace and the right key (corresponding to V, as the keyboard was reversed) in right hemispace. In either postures they were instructed to keep their non-responding hand comfortably resting on their ipsilateral knee in the same posture as their responding hand (e.g., see **Figure 3B**). Their compliance was visually monitored by the experimenter throughout the entire session.

Each main task (magnitude or parity judgment) included four blocks presented in ABBA order: two blocks with a S–R mapping (block-type A, e.g., "respond to small – or odd – with the left key, to large – or even – with the right key") and two with the alternative mapping (i.e., block-type B, "respond to large – or even – with the left key, to small – or odd – with the right key"). For this reason, subjects were instructed to carefully read the instructions preceding each block and containing precise indications about the required S–R mapping. In order to avoid confounding the effects of interest with switching/remapping costs, the first eight trials of each block were considered as practice and excluded from subsequent analyses (see Rusconi et al., 2011a, for a similar procedure).

A 800-ms visual feedback ("Error" in case of incorrect or "Too Slow" in case of missing response) or blank screen (in case of correct response) followed, and was then replaced by another 1,200 ms blank screen before the start of a new trial. Since the experimental set comprised numbers ranging from 1 to 9, numbers from 1 to 4 were considered small and numbers from 6 to 9 were considered large in either task (Dehaene et al., 1993). We therefore expected, in the baseline, to find an advantage for left key responses to 1–4 and for right key responses to 6–9. The experiment was divided in two parts: one in which participants responded with index and middle fingers of their left hand, and one in which they responded with index and middle fingers of their right hand. Order of parts was counterbalanced between participants. Order of tasks was kept constant for each participant both within and between sessions. Half participants responded with their hands in a prone posture, half with their hands in a supine posture. In total, the experiment comprised 384 experimental and 128 practice trials and was completed in a single session. Each cell of the design response hand (left, right) × task (magnitude, parity) × magnitude (small, large) × response key (left, right) contained 24 observations per each individual.

DATA ANALYSIS

Response latency (mean RTs) and accuracy (arcsin-transformed percentages of correct responses) were entered in an exploratory mixed design ANOVA having one between participant factor (hand posture) with two levels and four within participant factors (responding hand, task, number magnitude, and response side) having two levels each (see below). Follow-up F- or t-tests were then carried out to disambiguate interactions. Whenever left unspecified, all of the reported follow-up tests remain significant with a family-wise Bonferroni-corrected threshold equal to 0.05/(number of comparisons in a cluster). The presence of a significant SNARC effect was then investigated more specifically by performing directional t-tests on individual β weights, as obtained from linear regressions on the RT differences between right and left responses for each target number (Lorch and Myers, 1990), in the critical posture by response hand combination for either tasks. Proportion of participants showing negative β weights are also provided for conditions in which the SNARC effect was significant, as well as the proportion of participants whose β values were higher when MNL and hand-related frames of reference were misaligned. Finally, proportions of participants having negative vs. positive βs are reported for the aligned and the misaligned condition across experiments. Relevant measures of effect size are provided throughout (Rosenthal, 1991; Field, 2007).

RESULTS

Total error rate averaged 3.9% and both latency and accuracy data were analyzed. A mixed design 2 × 2 × 2 × 2 × 2 ANOVA having hand posture (prone, supine) as between subject factor and response hand (left, right), task (magnitude, parity), magnitude (small, large), and response key (left, right) as within subject factors was performed on mean reaction times (RTs) for correct responses. Significant main effects of task [$F_{(1,46)} = 126.11$, MSE = 4300; $P < 0.001$, $\eta^2 = 0.73$], magnitude comparison being 53 ms faster than parity judgment (magnitude: $M = 512$, SE = 8; parity: $M = 565$, SE = 8), and magnitude [$F_{(1,46)} = 14.65$, MSE = 788; $P < 0.001$, $\eta^2 = 0.24$], smaller numbers being responded to 8 ms faster than larger numbers (small: $M = 534$, SE = 8; large: $M = 542$, SE = 8) were found. The significant two-way interaction between hand and response key [$F_{(1,46)} = 21.28$, MSE = 2091; $P < 0.001$] indicated that left-side responses were faster than right-side responses with the left hand (left: $M = 531$ ms, SE = 9; right: $M = 544$ ms, SE = 9), and viceversa for the right hand (left: $M = 548$ ms, SE = 9; right: $M = 531$ ms, SE = 7) [$T_{(46)} = 3.23$, $P = 0.0023$, $r = 0.43$; and $T_{(46)} = 3.68$, $P = 0.0006$, $r = 0.48$, respectively]. A two-way interaction between magnitude and response key [$F_{(1,46)} = 11.81$, MSE = 1665; $P < 0.002$, $\eta^2 = 0.20$] was also present showing a 10.5-ms SNARC effect, further qualified by the four-way interaction between posture, hand, magnitude, and response key [$F_{(1,46)} = 7.06$, MSE = 1368; $P < 0.02$, $\eta^2 = 0.13$]. With a prone posture, a 16.5-ms SNARC effect was present and significant when responses were given with the right hand [$F_{(1,46)} = 8.93$, $P < 0.005$, $r = 0.40$] but not when they were given with the left hand (1.5 ms; $F < 1$; see **Figure 4A**). With a supine posture, a 18.5-ms SNARC effect was present and significant when responses were given with the left hand ($F_{(1,46)} = 9.82$, $P < 0.004$, $r = 0.42$) but not when they were given with the right hand (4.5 ms; $F < 1$; see **Figure 4C**). Finally, a significant three-way interaction was also found between task, magnitude, and response key [$F_{(1,46)} = 6.480$, MSE = 1029; $P < 0.02$; $\eta^2 = 0.12$] pointing to the presence of a fully significant SNARC effect in the parity task [16 ms; $F_{(1,46)} = 20.84$, $P < 0.0001$, $r = 0.56$] which fell instead far from significance in the magnitude task [4 ms; $F_{(1,46)} = 1.131$, $P > 0.10$].

The same design 2 × 2 × 2 × 2 × 2 ANOVA performed on arcsin-transformed proportions of accurate responses detected a significant main effect of task [$F_{(1,46)} = 55.92$, MSE = 0.026; $P < 0.001$, $\eta^2 = 0.55$], magnitude comparison being more accurate than parity judgment ($M = 1.48$, SE = 0.01 and $M = 1.39$, SE = 0.01, respectively). Moreover, a significant two-way interaction between magnitude and response key [$F_{(1,46)} = 10.42$, MSE = 0.021, $P < 0.003$; $\eta^2 = 0.18$] indicating a regular SNARC effect was qualified by a four-way interaction between posture, hand, magnitude, and response key [$F_{(1,46)} = 6.77$, $P < 0.02$; $\eta^2 = 0.13$]. Consistently with the latency analysis, the SNARC effect was present and significant when responses were given with the right hand [$F_{(1,46)} = 7.43$, $P < 0.009$, $r = 0.37$] but not when they were given with the left hand in a prone posture ($F < 1$; see **Figure 4B**). The SNARC effect was present and significant when responses were given with the left hand [$F_{(1,46)} = 9.71$, $P < 0.004$, $r = 0.42$] but not when they were given with the right hand in a supine posture ($F < 1$; see **Figure 4D**).

The significant interactions between magnitude and response, for participants responding with their right hand in prone posture and participants responding with their left hand in supine posture, signals the presence of a classical SNARC effect. Differential RTs (or dRTs; RTs of right responses minus RTs of left responses) were thus computed for all target numbers in each of the critical experimental conditions for every participant: if a classical SNARC effect was present, it should be possible to fit dRTs with a line having negative slope (i.e., modeling faster left responses to smaller numbers and faster right responses for large numbers). Directional single-sample t-tests on individual regression slopes (see Lorch and Myers, 1990; Fias et al., 1996) showed that β weights were significantly smaller than zero [prone posture, right hand: magnitude comparison, $T_{(23)} = 2.72$, $P = 0.006$, $r = 0.49$; $M = -0.25$, SE = 0.10; parity judgment: $T_{(23)} = 4.01$, $P = 0.006$, $r = 0.64$, $M = -0.30$, SE = 0.07; supine posture, left hand: magnitude comparison, $T_{(23)} = 1.80$, $P = 0.042$, $r = 0.35$; $M = -0.18$, SE = 0.10; parity comparison, $T_{(23)} = 4.54$, $P < 0.0001$, $r = 0.71$; $M = -0.35$, SE = 0.08]. Finally, in the presence of a significant SNARC effect, 17 out of 24 participants had negative β weights in the magnitude task and 18/24 in the parity task for the prone posture condition. In the presence of a significant SNARC effect, 15/24 had negative β weights in the magnitude task, and 19/24 in the parity task, for the supine posture condition. Overall, the experimental manipulation within participants (i.e., misalignment of the spatial frames of reference by changing the responding hand) caused a significant increase in the β weights, by pushing them toward 0, of 0.21

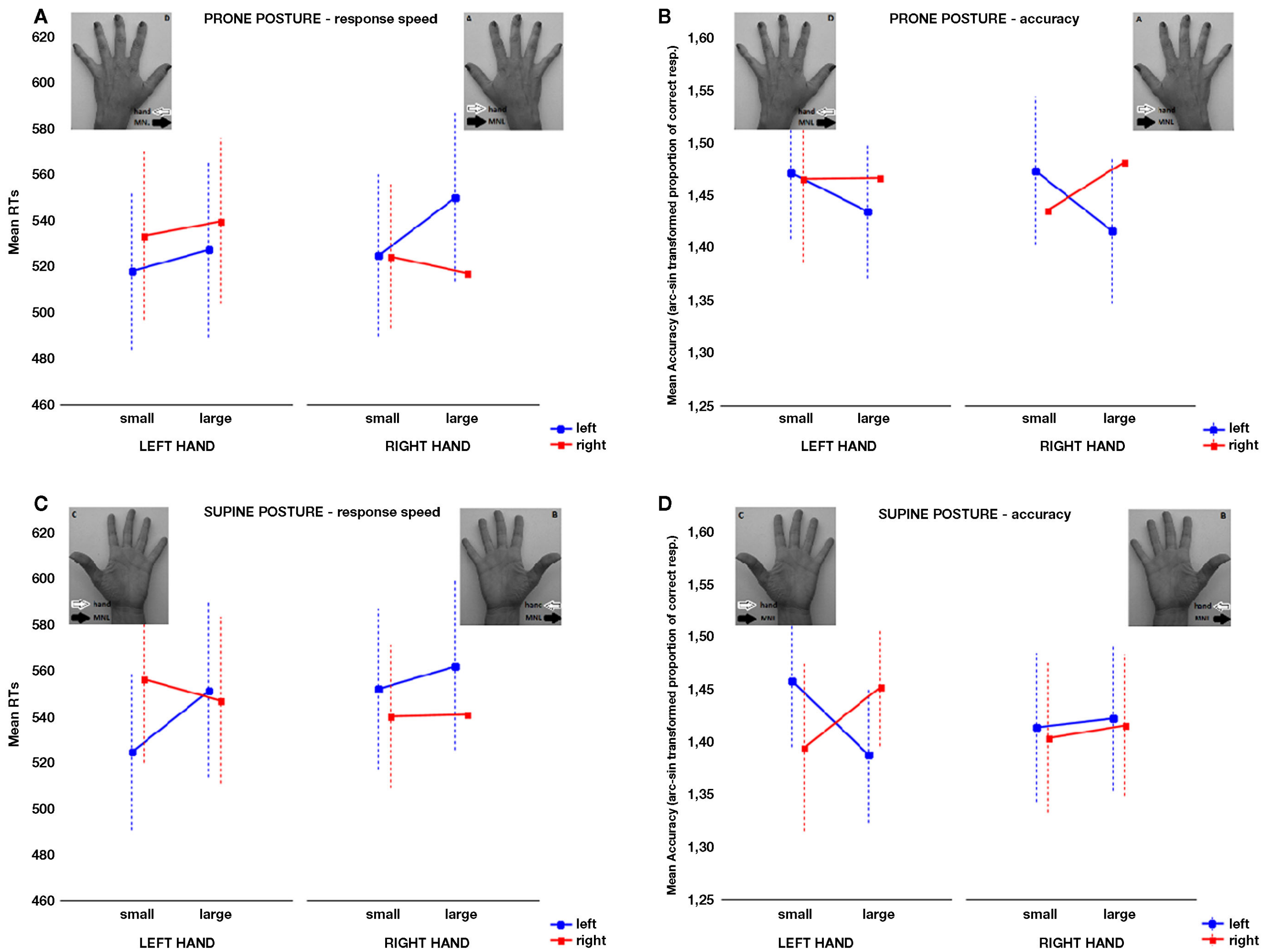

FIGURE 4 | The four-way interaction between posture, responding hand, magnitude, and response key on mean RTs is depicted. Vertical bars denote 95% confidence intervals. **(A,B)** When participants kept their hands in a prone posture, the SNARC effect was significant for the right hand only (and likely driven by the difference between left and right key for large numbers). **(C,D)** When participants kept their hands in a supine posture, the SNARC effect was significant for the left hand only (and likely driven by the difference between left and right key for small numbers).

units [$T_{(47)} = 3.27$, $P = 0.001$, $r = 0.43$; $M = -0.21$, SE $= 0.06$], with two-thirds of the participants (i.e., 32 out of 48) showing a change in the expected direction [$\chi^2_{(1)} = 5.33$, $P = 0.021$]. Finally, two separate groups of participants could be identified based on the sign of individual β weights in the misaligned condition across experiments, showing opposite SNARC effects of large size in each group [negative: $N = 27$, $M = -0.31$, SE $= 0.04$, $T_{(26)} = 8.29$, $P < 0.0001$, $r = 0.85$; positive: $N = 21$, $M = 0.26$, SE $= 0.04$, single-sample $T_{(20)} = 6.62$, $P < 0.0001$, $r = 0.83$]. In the aligned condition, the proportion of participants having negative vs. positive βs appeared much more unbalanced in favor of negative βs; effect sizes were in the large range for either group [negative: $N = 39$, $M = -0.38$, SE $= 0.04$, single-sample $T_{(38)} = 10.05$, $P < 0.0001$, $r = 0.85$; positive: $N = 9$, $M = 0.19$, SE $= 0.04$, single-sample $T_{(8)} = 4.46$, $P < 0.01$, $r = 0.84$]. A McNemar's test for dichotomous variables in paired samples detected a significant difference between the misaligned and the aligned conditions ($P = 0.017$).

DISCUSSION

In this study, we have used a unimanual version of the SNARC effect to test for the possible presence of an hand-related allocentric frame of reference (see, e.g., Kinsbourne and Warrington, 1962; Rusconi et al., 2009) that may be evoked by number processing. The directional vector of such representation was predicted to run from thumb-to-little based on our participants' counting habits. By introducing conflict between the hand-related and MNL-related vectors, we predicted opposite modulations of the SNARC effect for the two hands, depending on their posture. More precisely, when the right hand is pronated (see **Figure 1A**) or the left hand is supinated (see **Figure 1C**), the direction of either hand is aligned with the direction of the MNL as their thumb-to-little axis runs from left-to-right. When the right hand is supinated (as in **Figure 1B**) or the left hand is pronated (as in **Figure 1D**), the direction of either hand is opposite to the direction of the MNL because their thumb-to-little axis run from right to left. In the former cases, a regular SNARC effect was found, in the latter cases no SNARC effect was found. Unimanual SNARC effects where thus obtained from both hands. However, for each hand the SNARC effect was found in just one of the tested postures. We showed that our manipulation acts at a group level by increasing inter-individual variability in the misaligned condition, rather than by neutralizing individual SNARC effects in the misaligned condition. This is more compatible with the coexistence, in the misaligned condition, of two vectors having similar force but opposing direction, of which only one takes the lead and influence individual performance, rather than with the absence of any frames of reference. A much less clearcut, because found in the RTs ANOVA only and the smallest in size, finding was the different reliability of the unimanual SNARC effect in parity judgment and the unimanual SNARC effect in magnitude judgment. Task, however, was not involved in any significant interactions with posture and response hand.

The above results prompt interesting speculations about the cognitive mechanisms underlying interactions between numerical magnitude and representational space. First of all, they make it implausible that the unimanual SNARC effect originates in a long-term MNL that is indiscriminately activated by number magnitude processing, because the SNARC effect was involved in an interaction with response hand and hand posture. Had it been the byproduct of MNL processing, the SNARC effect might have interacted with task but in the opposite direction than the one we reported here (i.e., stronger SNARC effect when number magnitude is relevant to the task). The fact that unimanual SNARC effects, when present, were particularly strong in the parity judgment task, seem to corroborate the idea that a within-hand frame of reference, if present, may be more active in concomitance with the activation of categorical spatial representations from the dominant hemisphere (provided that Gevers et al., 2010 perspective about the origin of the SNARC effect in parity judgments is tenable; see Introduction). On the other hand, if the SNARC was solely determined by finger identity, a reverse SNARC effect would have been found for either hand in the misaligned condition (i.e., right hand in the supine posture, **Figure 1B**, and left hand in prone posture, **Figure 1D**) since the assignment of finger to response key was reversed. The fact that this systematic association (index-small and middle-large) was not present in the aligned conditions at the group level, suggests that a fully embodied model of the mental number-space is unsatisfactory as well.

Our data could be best accommodated by assuming that, in unimanual two-choice tasks involving numbers, at least two pre-existing frames of reference may simultaneously influence performance. In particular, with a supine posture, the thumb-to-little preferential mapping of the right hand could have competed with the left–right oriented response vector deriving from the MNL. Viceversa, with a prone posture the thumb-to-little preferential mapping of the left hand could have competed with the left–right oriented response vector from the MNL. Since the non-responding hand was always kept in the same posture as the responding hand, it is unlikely that our results could be explained by conflict between active vs. inactive hand frames of reference, because this was kept constant across all conditions. Alternatively, one should postulate that a group of participants was strategically evoking a number spatial representation when responding with their right hand but not with their left hand in a prone posture, and another group was strategically evoking a numerical spatial representation when responding with their left hand but not with their right hand in supine position, which would not be theoretically parsimonious. The concomitant presence of two frames of reference fits better than the absence of any frames of reference in the misaligned condition with the proportion of participants showing negative vs. positive β weights and the detection of large and significant but reverse SNARC effects (see also Leuthard et al., 2005; Wood et al., 2006b for similar arguments).

A few other studies had previously introduced postural manipulations in simple numerical tasks (e.g., Leuthard et al., 2005; Di Luca et al., 2006; Brozzoli et al., 2008). Brozzoli et al. (2008), for example, had their participants perform a tactile detection task by foot pedal responses. The tactile stimulus could be delivered either on their right thumb or on their right little finger following the appearance of a digit on a computer display. Participants performed the test with their right hand both in supine and in prone posture, and results indicated faster detection whenever a stimulus was delivered to the left-side after the appearance of a small than a large digit and viceversa with a right-side stimulus, irrespective of hand posture. Thus Brozzoli et al. (2008) rightly concluded that Arabic digits may evoke an extrapersonal spatial frame of reference that remains active and influences behavior even when attention is focused on the hand and on tactile stimuli to individual fingers. However, Brozzoli et al.'s set-up required no motor response selection stage as the spatial effects of number magnitude processing were measured in simple reaction times. No competition between MNL and hand-related frames of reference could be detected, if their interaction becomes manifest only when a response selection stage is involved. Foot responses, moreover, may be relatively unaffected from correspondence effects arising from hand-structural representations (it would be probably different if responses required toes differentiation; see, e.g., Tucha et al., 1997). Finally, the task did not require fine finger discrimination and only the most external fingers (thumb and little), which are usually told apart even in the presence of an acquired deficit in the structural representation of the hand (see, e.g., Kinsbourne and Warrington, 1962) received stimulation. In our study, on the contrary, participants were to continuously discriminate and select between two internal fingers (index and middle) and we employed a more demanding two-choice task. Note that a study requiring discrimination between all the 10 fingers (Di Luca et al., 2006; see below) reported a striking predominance of hand-related counting associations over MNL-related associations, that is diametrically opposite to Brozzoli et al.'s conclusions.

Systematic posture manipulations for the dominant hand were adopted by Leuthard et al. (2005), who investigated spatial S–R compatibility effects in a unimanual two-choice task. Their participants had to imagine numbers as they appear on a clock face, and were to answer whether a centrally presented number came earlier or later than six o'clock. With similar instructions but bimanual responses, participants typically present a reverse SNARC effect (i.e., a spatial S–R compatibility effect consistent with the clock representation having smaller numbers on its right hand side, larger numbers on its left hand side; Bächtold et al., 1998). By originally adopting a unimanual response modality, with keys operated by the index and ring fingers of the dominant hand, Leuthard et al. (2005) reported a similar effect. Moreover, the typical reverse SNARC effect was found to follow the relative position of response keys rather than finger identity (i.e., the preferential association between finger and side of the clock interacted with posture) when participants responded in peripersonal front space (i.e., in a condition very similar to ours, except they had the same participants doing both postures and with their dominant hand only). An opposite effect of posture was found instead when participants responded with their right hand in back space. In that condition, a reverse SNARC effect was present for the supine posture only whereas it was absent for the prone posture. Absence was due to increasing variability in mental imagery strategies between participants rather than elimination of any S–R effects at the individual level. In other words, the pattern of results that we found here for right hand responses look very similar to the pattern of results that Leuthard et al. (2005) found with responses in back space. Notably, that was also the condition in which participants were left free to choose their own frame of reference (i.e., they could choose to imagine a clock in front space or a clock in back space) and lack of a reliable S–R correspondence effect in the group analysis was not taken as evidence for the absence of any spatial frames of reference. Since Leuthard et al.'s participants were actively engaged in a mental imagery task, those claims could be verified against individual strategy self-reports. Thus, unlike in our present study, a spatial frame of reference was intentionally used by participants throughout the experimental session. A task-relevant allocentric spatial representation might thus have been superimposed and given precedence over other pre-existing frames of reference (either MNL or hand-related), and consequently have overridden their potential effects (see also Bächtold et al., 1998).

Our results appear consistent with the interplay between finger counting habits and MNL-related effects as reported by Fischer (2008), who showed a reliable SNARC effect for left-starters (associating small numbers with left space via counting routines, similarly to the MNL) and a weaker SNARC effect for right-starters (associating small numbers with right space via counting routines, opposite to the MNL) with bimanual responses. Whether the direction of counting routines may exert a causal influence on the direction of MNL, however, is still an open question and not a simple one to solve. Here we adopted a complementary approach by zooming in on the within-hand directional vector that may be identical for either hand, rather than focusing on the between hands counting sequence. We reported reliable unimanual SNARC effects within either the dominant or the non-dominant hand of a group of participants that was mainly composed by right-starters (results did not change when the same analyses were performed without the four left-starters who participated in our study) and, based on Fischer (2008), would therefore be expected to show relatively weak bimanual SNARC effects. The interaction between SNARC, hand and posture, and the pattern of inter-individual variability here described suggest that counting may affect number to space mappings at multiple levels and all possible frames of reference should be taken into account when attempting to model the possible effects counting routines on MNL representations.

Like Fischer's (2008) study, our study is in partial agreement with Di Luca et al.'s (2006), as for the supremacy of finger counting routines over MNL in numerical cognition. Di Luca et al.'s (2006) participants were are asked to respond to Arabic digits by pressing a key with one of their 10 fingers. Performance was significantly faster when the mapping of digits to fingers matched individual finger counting habits rather than MNL. Hand posture, moreover, did not modulate the finger–digit correspondence effect. Unlike in Leuthard et al. (2005) and Brozzoli et al. (2008), however, here the association between number and finger identity is largely unaffected by a change in the spatial position, and not viceversa. We could however speculate that, since Di Luca et al. (2006) employed a bimanual response modality where discrimination between the 10 fingers was necessary to the task, the counting-based frame of reference as opposed to the MNL-based frame was highly emphasized by the task. Our set-up, like Leuthard et al.'s, still required finger discrimination, however only two response alternatives were provided and two fingers (or their homologous on the other hand) were actively engaged throughout the session. Emphasis was thus not so heavily posed on the finger series and other available mental frames of references may have been activated with equal strength.

In conclusion, with the current study we provide novel evidence against a uni-dimensional model of number–space associations. In particular we propose that a posture-invariant structural representation of the hand should be taken in consideration, in addition to the side of the hand where counting starts, when investigating the relation between individual counting routines and the MNL. In addition to the distinction of concepts such as bodily left and right, finger gnosis can reliably predict numerical abilities in developmental age (Noël, 2005). Typical counting routines integrate both abilities (e.g., Butterworth, 1999). Such combination of functions and their habitual use to manipulate and represent numerosities may be rooted in and facilitated by the contiguity of left parietal circuits in which they reside (see, e.g., Rusconi et al., 2005, 2010). Left-lateralized embodied representations, however, although important, may be only one of the cross-domain support systems that are available to the adult number processing system. Visuo-spatial representations from a right-lateralized attentional system may also play an equally important role in number processing (see Sandrini et al., 2011 for a review on relevant studies). Clarifying how these separate but interacting systems can influence basic number processing will enable us to better understand both potentiality and limitations of human numerical cognition, as well as to identify new rehabilitative and educational paths toward facilitation and improvement in number skills.

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