An Alternative View of the Relation between Finger Gnosis and Math Ability: Redeployment of Finger Representations for the Representation of Number

Marcie Penner-Wilger (mpwilger@connect.carleton.ca)
Institute of Cognitive Science, Carleton University, Ottawa, ON K1S 5B6 Canada

Michael L. Anderson (michael.anderson@fandm.edu)
Department of Psychology, Franklin & Marshall College, Lancaster, PA 17604 USA
Institute for Advanced Computer Studies, University of Maryland, College Park, MD 20742 USA

Abstract

This paper elaborates a novel hypothesis regarding the observed predictive relation between finger gnosis and mathematical ability. In brief, we suggest that these two cognitive phenomena have overlapping neural substrates, as the result of the re-use ("redeployment") of part of the finger gnosis circuit for the purpose of representing number. We offer some background on the relation and current explanations for it; an outline of our alternate hypothesis; some evidence supporting redeployment over current views; and a plan for further research.

Keywords: finger gnosis; mathematics; redeployment; number representation; angular gyrus

Introduction: Finger Gnosis and Math

Finger gnosis, alternatively called finger recognition or finger localization, is the presence of an intact finger schema or "finger sense". A variety of neuropsychological tests have been designed to assess the presence of finger gnosis, or its absence—finger agnosia—in neuropsychological populations. In one common test (Baron, 2004), the examiner shields the participant's hand from view and lightly touches one or more fingers. The participant is asked to identify which fingers were touched. Finger gnosis tests have been used by neuropsychologists to provide an indication of parietal lobe damage, especially to the left angular gyrus (Gilandas et al., 1984). Finger agnosia is one of a constellation of symptoms in Gerstmann's syndrome, along with acalculia, agraphia, and left-right disorientation. Gerstmann (1940) identified finger agnosia or the loss of "finger sense" as the core deficit of the syndrome.

Perhaps surprisingly, recent research is demonstrating links between finger gnosis and mathematics ability in neuropsychologically-normal children. For instance, Fayol, Barrouillet and Marinthe (1998) discovered that a set of neuropsychological tests, including tests of finger gnosis, were the best longitudinal predictor of Grade 1 children's math scores. This finding was confirmed by Noël (2005), who demonstrated that children's finger gnosis scores predicted accuracy and fluency on a variety of mathematical tests, both concurrently in Grade 1 and longitudinally one year later. More recent results show that finger gnosis scores predict Grade 1 children's performance on *all* standard mathematical tests including number system knowledge and calculation (Penner-Wilger et al., 2007), and also predict Grade 1–5 children's performance on tasks assessing numerical representations including number-line estimation and magnitude comparison, concurrently (Penner-Wilger et al., 2008). Thus, the relation between finger gnosis and math in normal children is robust across means of assessing mathematics ability.

Current Views

Though a clear relation has been demonstrated between finger gnosis and math, what remains unclear is why such a relation exists. Here, we outline the two prevailing views, one functional and the other localizationist, and briefly review some of the evidence for these views.

Functionalist View

On the functionalist view, finger gnosis is related to math ability because fingers are used almost universally in the course of math development to represent quantities and perform counting and arithmetic procedures (Butterworth, 1999). Thus, the representations of fingers and of numbers become linked developmentally. According to this view, the comorbidity of finger agnosia and acalculia as well as the relation between finger gnosis and math in normally-developing children arise functionally, because the representation of numbers is not only co-located with, but also linked to, the representation of fingers. Importantly, on the functionalist view there is a direct causal link between finger gnosis and math ability and, moreover, this link is formed experientially in the course of normal development.

Localizationist View

On the localizationist view, finger gnosis is related to math ability because the two abilities are supported by neighboring brain regions in the parietal lobe (Dehaene et al., 2003). The comorbidity of finger agnosia and acalculia, as seen in Gerstmann's syndrome, is explained as arising from common vascularization to the associated parietal areas, with damage typically affecting both areas. The relation between finger gnosis and math in normally developing children is a reflection of the correlated developmental trajectories of neighboring brain regions. Consistent with the localizationist view, Simon et al. (2002) found regions in the intraparietal sulcus activated for calculation-only, calculation and language, manual tasks (i.e., pointing), and visuospatial tasks. Importantly, on the localizationist view, there is no *direct* causal link between finger gnosis and math ability.

Empirical Support

Empirical support for each of these views has been mixed. The *functional* view predicts that facility in finger use (e.g., finger agility/fine-motor ability) should predict math ability as strongly as finger gnosis. Thus, children who can more easily use their fingers would form a stronger association between finger and number. Despite children's considerable variability in finger agility, this prediction is not borne out. In contrast to finger gnosis, finger agility is uncorrelated or only weakly correlated with all standard math tasks (Penner-Wilger et al., 2007). The *localizationalist* view predicts that, like finger gnosis, all co-located functions such as left-right orientation and graphia, should be equally well correlated with math ability. This prediction, however, is also not borne out. In contrast with finger gnosis, these co-located functions are uncorrelated or only weakly correlated with math ability (Noël, 2005).

Redeployment of Finger Representations

In Anderson and Penner-Wilger (2007) we briefly outlined an alternative view of the relation between fingers and math that used as its base the massive redeployment hypothesis of brain evolution (Anderson, 2007a). Here we further develop the redeployment view of the relation between fingers and number and outline some predictions and supporting evidence. Finally, we suggest further empirical work to test the redeployment view.

The Massive Redeployment Hypothesis

The massive redeployment hypothesis (MRH) is both a theory about the functional topography of the cortex, and an account of how it got that way. According to MRH, neural circuits evolved for one use are frequently *exapted* for later uses, while retaining their original functional role. That is, the process of cognitive evolution is analogous to component re-use in software engineering. Components originally developed to serve a specific purpose are frequently re-used in later software packages. The new software may serve a purpose very different from the software for which the component was originally designed, but may nevertheless require some of the same low-level computational functions (e.g., sorting). Thus, efficient development dictates re-use of existing components where possible. Note that in such re-use, the component just does whatever it does (e.g., sorts lists) for all the software packages into which it has been integrated, even if that computational function serves a very different high-level purpose in each individual case.

The end result of such re-use in the brain is a functional architecture such that brain areas are typically recruited to support many different functions across cognitive domains. Preliminary investigations—generally involving mining a large collection of brain imaging experiments—have uncovered evidence for four specific predictions made by MRH. First, any given brain area is typically redeployed in support of many cognitive functions, and such redeployment will not respect traditional domain boundaries (that is, brain areas are not domain-restricted entities). Second, differences in domain functions will be accounted for primarily by differences in the way brain areas cooperate with one another, rather than by differences in which brain areas are used in each domain. Third, more recently evolved cognitive functions will utilize more, and more widely scattered brain areas. And fourth, evolutionarily older brain areas will be deployed in more cognitive functions. See (Anderson 2007a; 2007b; 2007c; in press) for details of the methods and results.

Alternate Uses for the Finger Circuit

In line with the general findings of MRH, we propose that one of the neural circuits integrated into the functional complex supporting finger gnosis is *also* part of the functional complex supporting the representation of number. That is, one of the functional circuits originally evolved for finger representation has since been redeployed to support the representation of number and now serves both functions.

Note that one should expect redeployment only in cases where different functional complexes could plausibly benefit from incorporating the same low-level functional circuits. What are the possible functional overlaps in these two very different functional complexes? Consider from a computational perspective that one foundational element in any calculating circuit is a register for storing the number(s) to be manipulated. Such a register is typically implemented as a series of switches that can be independently activated. Likewise, at least one way to implement the ability to know whether and which fingers have been touched (and other aspects of a general "finger sense") would be with such a register of independent switches. Such a finger register—one part of the functional complex supporting finger gnosis—would be a candidate for redeployment in any later-developing complex with functional elements able to take advantage of a component with this abstract functional structure. Our suggestion is that the number representation complex did just that.

In order to properly understand this suggestion, it is crucial to make a distinction between the representation itself and the representation *consumer* (Millikan, 1984). The content of a representation depends both on the intrinsic properties of the representation (e.g., which switches are on, and which are off), but also on the details of the mechanism that treats the representation as having significance. For a simple example, consider the following representation: 1001. Depending on the context, and on the assumptions of the interpreter, that representation can be taken to have the same content as the English phrase "one thousand and one" or as the Arabic numeral 9.[1] It could conceivably also have alphabetic, numerological, or

[1] Hence the old joke: there are 10 kinds of people in the world: those that understand binary and those that don't.

iconographic content, or be an instruction set for a Turing machine. The point is: we are suggesting *only* that this particular representational resource may be shared between the finger-gnosis complex and the number-representation complex. The meaning of whatever representation was stored in that resource would depend on the representation consumer, and presumably would vary greatly depending on the needs of the functional complexes incorporating the resource. Indeed, even within each complex the specific content could change with context. For instance, switches could be interpreted as an ordered binary set in one context, (1001 = 9) but as a simple, non-ordered additive set in another (1001 = 2). Importantly, then, it is no part of our suggestion that the capacity of our number representation component is limited to (or is exactly) 2^{10}—the capacity of 10 ordered binary switches. Our capacity could be larger or smaller, depending on the details of the different representation consumers that have developed to work in concert with a register of the sort proposed.

On the redeployment view, finger gnosis is related to math ability because part of the functional complex for number representation overlaps with the functional complex for finger representation. Thus, finger and number share a common neural resource that supports both sorts of representation. The comorbidity of finger agnosia and acalculia as well as the relation between finger gnosis and math in normally-developing children arise from the shared neural circuit used for both representations.

The redeployment view of the relation between fingers and number is not a localizationist view. On the redeployment view, finger and number representations are not just neighboring neural functions on a correlated developmental trajectory; rather, they share a common neural substrate forming part of the neural complex supporting each function. Nor is the redeployment view a functional view. Importantly, on the redeployment view the connection between finger and number does *not* rest on the experienced use of the actual fingers to represent numerosities and perform arithmetic procedures, though it might suggest reasons we find it natural to use the fingers in this way (as well as natural ways to use the fingers; see *Evidence for Prediction 3*, below).

Before moving on to some supporting evidence for the view, we should pause here to admit that if one were modeling the finger gnosis complex in isolation it is unlikely that a register-like implementation for one of its components would leap out as the obvious choice. In fact, one of the important general implications of MRH is that one should *not* model functional complexes in isolation, but should consider what other complexes may also be using the same neural substrates. The effect of this change in methodology is often to suggest novel decompositions (and candidate implementations) of cognitive functions, of which the current hypothesis is one specific example. Of course, whether such speculations are fruitful (or *merely* novel) remains to be determined, both in this specific case, and as a general approach. But there is reason to be hopeful.

Evidence and Predictions

If the relation between finger gnosis and math arises because part of the neural circuit responsible for the representation of fingers has been redeployed in support of the representation of number then the following predictions should be borne out:

1) Brain regions associated with the representation of fingers should be activated during tasks requiring the representation of number.
2) Damage/disruption of the neural substrate should affect both finger gnosis and tasks requiring the representation of number.
3) There should be measurable interference between tasks involving finger gnosis and tasks involving number representation, insofar as these would be competing for the same neural resource.
4) Individuals *without* finger agnosia who could not or did not use their fingers to represent quantities during development, should nevertheless show activation in the finger circuit during tasks requiring the representation of number.

Evidence for Prediction 1

Brain regions associated with the representation of fingers are activated during tasks requiring the representation of number. Prediction one would differentiate redeployment from localization, given adequate precision; however it does not differentiate the redeployment view from the functional view, except in very young children. On both the functional and redeployment views the representation of fingers and numbers are linked, with the key difference being the experiential requirement in the functional view.

Zago et al. (2001) found activation of a finger-representation circuit in the left parietal lobe during adults' performance of basic arithmetic. Increased activation was observed in the premotor strip at the coordinates for finger representation during performance of single-digit multiplication compared to a digit reading condition. Andres, Seron, and Oliver (2007), using transcranial magntic stimulation over the left M1 hand area to measure changes in corticospinal excitability, found that hand motor circuits were activated during adults' number processing in a dot counting task. Both sets of authors speculated that the activation might represent a developmental trace consistent with the functional view. The findings, however, are equally consistent with the redeployment view that part of the circuit responsible for the representation of fingers was redeployed in the representation of number.

Across a variety of number and finger tasks, functional imaging studies have shown overlapping activation in parietal regions (see Andres, Seron, & Oliver, 2007). Thus, the finding that brain regions associated with the representation of number and fingers are co-activated is robust, consistent with the functional and redeployment views. It remains possible, however, that future increases in the accuracy of functional imaging will eventually produce evidence favoring the localizationist view.

Evidence for Prediction 2

Damage/disruption affects both finger gnosis and tasks requiring the representation of number. Prediction two is again inconsistent with the localizationist view, yet it does not differentiate between redeployment and functionalism. Studies where disruption was induced using either repetitive transcranial magnetic stimulation (rTMS) or direct cortical stimulation provide converging evidence that disruption in the left angular gyrus affects both finger gnosis and tasks requiring the representation of number.

Rusconi, Walsh, and Butterworth (2005) used rTMS applied to parietal sites to determine if there was a common neural substrate between number and fingers. In a series of experiments, they found that rTMS over the left angular gyrus disrupted both magnitude comparison and finger gnosis in adults. Roux et al. (2003) using direct cortical stimulation also found a site in the left angular gyrus that produced both acalculia and finger agnosia. Thus, consistent with the redeployment and functional views, stimulation of the left angular gyrus across methods has been found to disrupt finger gnosis along with number comparison and calculation.

Evidence for Prediction 3

There should be measurable interference between tasks involving finger gnosis and tasks involving number representation, insofar as these would be competing for the same neural resource. The predictions here are somewhat subtle and surprising. If two tasks are using the same representational resource, they will interfere with one another *only* when the representation as it stands in the resource is *inaccurate* when read by the representation consumers in one or both domains. The obvious way to cause such a situation is to inject noise into the system. For instance, electrical stimulation of the fingers (but not of various locations on the forearm) might impact performance on mathematical tasks, if the stimulation caused the register to contain activation that represented a number *different* from the one stored there by the mathematical complex.

Finding such electrical-stimulation based interference would not be accounted for by the localizationist view, but is once again likely to be consistent with the functional view. Once the finger and number representations become linked, there would be every reason to suppose that tasks utilizing one would interfere with tasks utilizing the other. Note this does suggest the possibility of a *developmental* interference test. For the functionalist, there should be a time before the intertwining has occurred, and thus a time before one would expect interference. Unfortunately, the *failure* to find a pre-interference period would not be strong evidence against the functionalist, as there are always multiple possible explanations for the lack of an effect. Likewise, the *discovery* of a pre-interference period wouldn't necessarily be strong evidence against the redeployment view, since even genetically determined cognitive structures and relationships unfold over time. Thus, any evidence along these lines is unlikely to be definitive, however interesting and suggestive.

That's the story for electrical stimulations producing inaccurate representations. But if by chance a finger stimulus produced activation *consistent* with the standing number representation, there would be no interference. This is relevant because counting on the fingers, during which process one successively touches fingers, is a real-world instance of a finger stimulation task that by design produces representations in the shared register that can provide accurate information to consumers in both complexes. This realization suggests a further implication. Although the details of the procedure one can use to count on one's fingers—which fingers are touched in which order with what meaning—are theoretically arbitrary, the set of such procedures that can produce representations that would be accurate in both domains would be constrained by the representation consumers in both domains; not every procedure will produce representations compatible with the available consumers. Thus, on the redeployment view, there should exist a set of *self-interfering* finger-based counting procedures. The complementary implication is that there should be a set of procedures that are more natural and/or easier to acquire, insofar as they produce representations consistent with existing consumers.

Discovering self-interfering counting procedures would seem to count against both the localizationist view and the functionalist view. If the intertwining of representations is the result of experience, then there need be no *a priori* limit on the nature of the procedure that would cause the intertwining; and no consistent procedure that produced intertwining could be self-interfering. Likewise with the complementary implication: if *any* such procedure could be learned, then there is no specific theoretical reason that one should be easier than another.

Of course, in the event of any such discoveries, the functionalist would have available many plausible extra-theoretical elaborations (e.g., the measurable performance deficiencies of different procedures, or limits on which are easily learnable, could be the result of body mechanics, competing social conventions, and the like), and the advantage of redeployment on this issue might be limited to an explanatory parsimony. Moreover, the prediction is complicated by the difficult question of whether, and how easily, one can train arbitrary representation consumers in the numerical domain to work with finger-based counting procedures. So perhaps even evidence along these lines is unlikely to be definitive.

Still, it seems an intriguing line of research that could push both models in new directions. For instance, the discovery of a counting procedure that didn't just reduce performance, but resulted in systematic errors consistent with the mismatch between the procedure and the inferred properties of a representation consumer, could be strong evidence for the redeployment view.

In general, which outcomes in interference experiments would, and would not, be consistent with the functionalist view depend in part on the nature and timeline of the hypothesized intertwining of representations that occurs during development. The strongest interpretation of intertwining is that number representations and the finger sense become inextricably linked, even coming to share the same neural resources. If this is the hypothesis, then perhaps redeployment and functionalism cannot be distinguished based on interference studies, since they posit the same underlying neural relationship, and differ only with respect to the account of how that relationship came about. However, there are weaker versions of intertwining that are consistent with the original model. For instance, one might expect that number representations would come to depend on the finger sense, but not the reverse. Such a model might be somewhat more plausible developmentally speaking, as although it may be typical to use the fingers whenever one is doing mathematics, it would certainly be atypical to think of mathematics whenever one is using the fingers. At the very least, the various possibilities to be entertained in designing interference experiments suggest the need for a clarification of the functionalist model.

Evidence for Prediction 4

Individuals *without* finger agnosia who could not or did not use their fingers to represent quantities during development, will nevertheless show activation in the finger circuit during tasks requiring the representation of number. Prediction four is the key difference in distinguishing the redeployment view from the functional view. Special populations may play a crucial role in testing this prediction.

If the relation between fingers and number is a functional one, then the ability to functionally use ones' fingers to represent numerosities and perform counting and arithmetic procedures would be a crucial element in the development of numeracy. We have already found that finger gnosis in an unselected population of children is more highly correlated with numeracy and calculation skills than is finger agility. This finding is apparently at odds with the functional view, but is consistent with the redeployment view that the connection between fingers and number does not rest on the experiential use of fingers to represent number.

Children with Spina Bifida have both finger agnosia and poor finger agility co-morbid with significant mathematical difficulties (Bannister & Tew, 1991; Barnes, Smith-Chant, & Landry, 2005). This finding has been taken as evidence for a functional role of fingers in mathematical development, as children with Spina Bifida would have difficulty using their fingers to form a functional/developmental link with number. However, as this population also has disrupted finger gnosis, the finding is likewise consistent with the redeployment view.

In contrast, children with developmental coordination disorder (DCD) have poor finger agility, but most have preserved finger gnosis (Cermak & Larson, 2001; Hamilton, 2002). Thus, children with DCD are ideally suited as a population with which to test the redeployment view against the functional view. Approximately 6% of children meet the criteria for DCD outlined in the DSM-IV. On the redeployment view, we predict that children with DCD and preserved finger gnosis will show activation in the finger circuit (left angular gyrus) during tasks requiring the representation of number such as magnitude comparison. We are currently designing an imaging experiment to test this prediction in a population of children with DCD.

As a first indication of support for the redeployment view, DCD is not generally comorbid with mathematical difficulties (Cermak & Larson, 2001). Thus, despite motor problems limiting the ability to use the fingers to represent numerosities, the representation of number appears unaffected in children with DCD. This finding is consistent with the redeployment view, but on its face presents difficulties for the functional view. On the redeployment view, children with DCD might be expected to show some deficits with arithmetic, given a functional role of the fingers in the development of counting and arithmetic *procedures*, but such deficits would not be expected to impact numerical *representation*. On the functional view, the use of fingers is crucial for the development of *both* numerical representations and arithmetic procedures. Hence, on the functional view children with DCD would be expected to show widespread math disabilities as seen in children with Spina Bifida.

Summary of Available Evidence

In summary, two of the four predictions (1 & 2) that arise from the redeployment view are well supported by empirical evidence, and there is suggestive evidence for the fourth. The third remains to be investigated. The two supported predictions are inconsistent with the localizationist view that finger gnosis is related to math ability because the two abilities are supported by neighboring brain regions. However, support for the redeployment view could not be distinguished from that for the functional view on the basis of evidence for predictions one and two (and possibly not on the basis of any evidence for three). Thus, support for prediction four would be the crucial evidence to conclude that the relation between fingers and number is not functional. We provided evidence consistent with prediction four and outlined further empirical tests of the redeployment view.

Conclusion

This paper elaborated a novel hypothesis regarding the observed predictive relation between finger gnosis and mathematical ability. In brief, we suggested that these two cognitive capacities have overlapping neural substrates, as the result of the re-use ("redeployment") of part of the finger gnosis circuit for the purpose of representing number. We offered some background on the relation and current explanations for it; an outline of our alternate hypothesis; some evidence supporting redeployment over current views; and a plan for further research.

It is important to reiterate that on the redeployment view, the neural circuitry shared between finger gnosis and number representation forms only one part of the functional complex necessary for number representation. In MRH, existing neural circuits are redeployed for new purposes and combined to support new capacities. Along with the neural circuit shared with finger gnosis, additional neural circuits (with additional abstract functional capacities) are expected to combine in support of the capacity for number representation.

One capacity expected to play a role in the representation of number is *subitizing*, an evolutionarily-primary ability to distinguish the numerosities of small sets quickly without counting, with supporting neural circuitry in the horizontal segment of the intraparietal sulcus (Dehaene & Cohen, 2007). It may be that the functional capacity redeployed from finger representation forms the digital representation of number (how many), whereas the functional capacity redeployed in subitizing forms the analog representation of number (how much).

Despite some overlap between our view and Dehaene and Cohen's Neuronal Recycling Hypothesis, it is worth noting a significant difference: they posit that neural circuits originally evolved for subitizing were re-used in the course of *cultural* development for a sufficiently similar function in arithmetic, possibly to the decrement of the original function (Dehaene & Cohen, 2007). In contrast, MRH posits that neural circuits originally evolved for one use were re-used in the course of *evolution* for the exact same function in another use, with *no decrement* of the original function.

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