


The Importance of Handwriting Experience on the Development of the Literate Brain

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Abstract

Handwriting experience can have significant effects on the ability of young children to recognize letters. Why handwriting has this facilitative effect and how this is accomplished were explored in a series of studies using overt behavioral measures and functional neuroimaging of the brain in 4- to 5-year-old children. My colleagues and I showed that early handwriting practice affects visual symbol recognition because it results in the production of variable visual forms that aid in symbol understanding. Further, the mechanisms that support this understanding lay in the communication between visual and motor systems in the brain: Handwriting serves to link visual processing with motor experience, facilitating subsequent letter recognition skills. These results are interpreted in the larger context of the facilitatory effect that learning through action has on perceptual capabilities.

Keywords

handwriting, development, brain, fMRI, letters

What we do with our bodies creates and constantly changes our knowledge of the world: Every eye movement, head turn, object held, or door opened is an action that creates new perceptual information. Self-generated actions performed within the context of our environment determine what we perceive and therefore what we process for subsequent behaviors. In this way, cognition is said to be “embodied” and more precisely “situated” in that it occurs in the context of a real-world environment. Further, the environment is a component of cognition: Our actions create our personal environment, which in turn changes our perceptions and cognition (for a review of theories of embodied cognition, see Shapiro, 2014). As such, the interactions among action-environment-perception form the brain systems that underlie our cognition. These brain changes emerge through a coupling of perceptual and motor systems such that our perceptions are intrinsically linked to our actions through brain networks. Because of these neural connections, our previous active experiences influence our current perceptions in important ways. By understanding how these systems become linked, we can better predict optimal learning conditions. The mechanism by which this coupling of brain systems occurs can be measured by research studies

that capitalize on brain imaging methods such as functional magnetic resonance imaging (fMRI). fMRI capitalizes on the blood-oxygen-level-dependent (BOLD) signal that is a direct reflection of neuronal activity.

Several fMRI studies have demonstrated that perceptual and motor systems become linked only when individuals learn through self-generated actions. For instance, in adults (e.g., Butler & James, 2013) and in young children (e.g., James & Swain, 2011), when the structures of novel objects are learned through self-generated action (either through indirect control—joysticks and mice—or through direct control—manually manipulating 3D objects), a network of brain activation is created that does not occur when individuals learn about the objects by watching others perform exactly the same behaviors. That is, by learning about objects through self-generated action, important connections in the brain are formed that have profound effects on our behavior.

During early development, self-generated actions serve to enhance a multitude of capabilities—for example,

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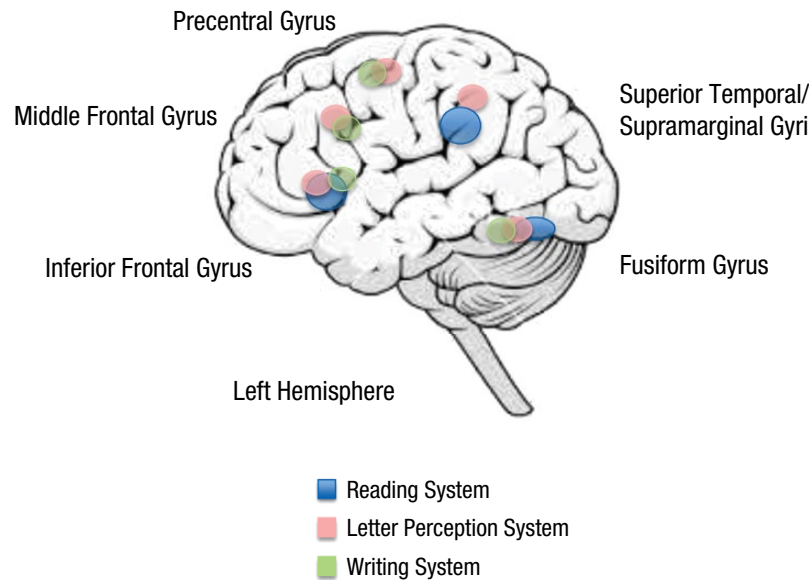


Fig. 1. A schematic depiction of the visual-motor letter-processing systems. Although regions do not exactly overlap (because results are drawn from multiple studies), it is striking that despite multiple tasks and paradigms, substantial overlap is demonstrated.

hand-eye coordination (Needham, Barrett, & Peterman, 2002), depth perception, (Bertenthal & Campos, 1984), sound recognition (Pelphrey, Morris, & McCarthy, 2004), spatial understanding (Siegal & White, 1975), and even language development (e.g., Smith & Gasser, 2005). It may not be surprising then that our self-generated actions also have a significant effect on how we process letters. Nonetheless, historically, letter perception (a necessary precursor of reading) has been considered more of a passive behavior—that is, one that involves seeing the shapes of letters and hearing the sounds they represent. The potential importance of producing letters with the body, through handwriting, has generally not been considered as important. But what if—similar to learning about many other types of objects—learning about letters is facilitated by producing them? Then learning about written letters becomes an activity not only of seeing and hearing letters but also of producing them by hand.

A limited number of experimental studies have shown that, indeed, adults (James & Atwood, 2009; Longcamp et al., 2008) and children (Li & James, 2016; Longcamp, Zerbato-Poudou, & Velay, 2005) learn symbols better if they write them by hand during learning than through other forms of practice, including visual, auditory, and even typing. In addition, correlational work demonstrates that early handwriting can have significant effects on literacy skills in young children (for a review, see Hall, Simpson, Guo, & Wang, 2015). How handwriting facilitates symbol learning in terms of underlying mechanisms,

however, is a question that can be addressed only with brain-imaging studies.

Our hypothesis in a series of studies was that handwriting affects symbol learning by creating a network that includes both sensory (visual in this case) and motor brain systems. To investigate this idea, one must first outline the brain systems that underlie efficient letter processing, both in terms of handwriting (see Planton, Jucia, Roux, & Demonet, 2013, for a recent meta-analysis) and visual letter processing (see Martin, Schurz, Kronbichler, & Richlan, 2015, for a meta-analysis; see Fig. 1 for a schematic that summarizes the results). Many studies converge on a system that involves visual and motor brain systems that underlie both visual letter processing and handwriting. Letter processing in the literate individual involves the recruitment of the left fusiform gyrus in the ventral temporal lobe (a region associated with visual letter processing in general but also linguistic processing), the left superior temporal gyrus/inferior parietal lobule that often encompasses the angular gyrus (associated with language perception and writing), the inferior frontal gyrus (a region that responds during many tasks involving linguistic information and during general motoric sequencing), the left middle frontal gyrus (associated with writing), and the left dorsal precentral gyrus (the primary motor cortex/premotor cortex for direct motor control and writing). Visual letter processing and letter writing (without seeing a letter) was investigated in the same experiment comparing these systems within individuals and showed

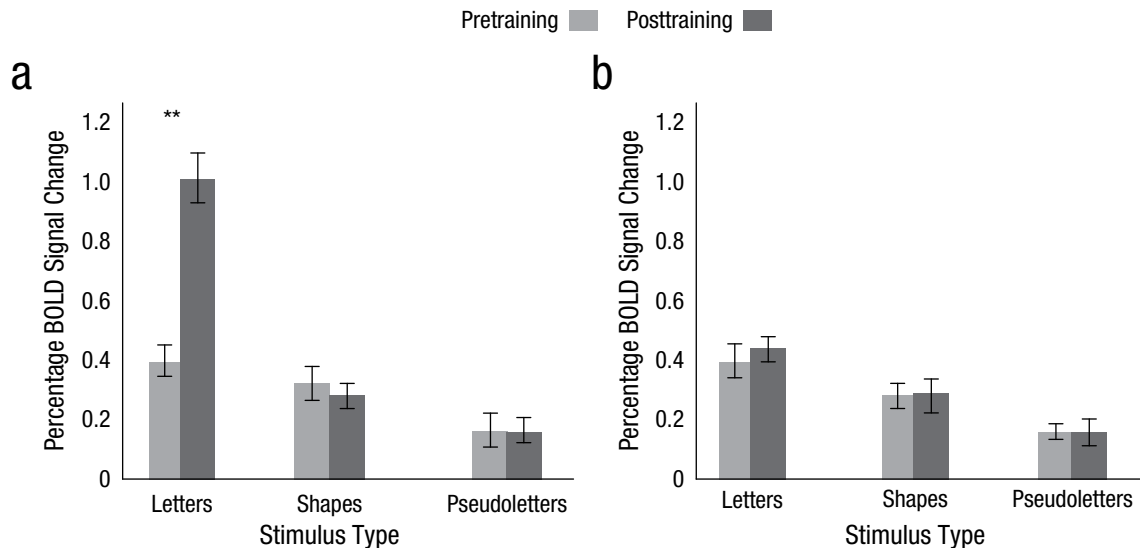


Fig. 2. Percentage of blood-oxygen-level-dependent (BOLD) signal change in the left posterior fusiform region of interest (results from James, 2010). Results are shown before and after (a) handwriting training and (b) visual-only training for each of three stimulus types. Error bars represent standard errors of the mean. The asterisks represent a significant difference between training sessions (** $p < .01$).

substantial overlap between letter perception and letter production; the network outlined above was recruited in both cases (James & Gauthier, 2006; see Fig. 1).

However, this work in adults demonstrates only that there is a dedicated network for proficient letter processing but not whether the self-generated actions involved with handwriting serve to create the connection among perceptual (fusiform gyrus and parietal cortex) and motor (the regions in the parietal and frontal cortices) systems. To address this question, we need to advance into the world of developmental neuroimaging to determine how networks are built in the brain given different types of experiences—those with and without self-generated actions.

Prior to age 4, most children are not able to name all the letters of the alphabet, much less write them by hand. By conducting studies on this population, we can discover (a) whether experience printing letters by hand creates the perceptual-motor brain network that underlies letter identification and (b) what kind of manual production is important for creating these brain networks. To answer these questions, we developed methods that use state-of-the-art neuroimaging methods to observe brain changes in young, 4-year-old children as they learn about letters and words. Our primary question in this work was whether writing letters by hand creates the perceptual-motor brain networks that underlie proficient letter recognition.

We first addressed this question by training 4-year-old children to learn their letters in two ways: either through hearing and saying letter names (see-and-say

method) or through printing those same letters (James, 2010). The first condition, the see-and-say method, is one that is most commonly used when teaching preschool children letters, the assumption being that producing the letters by hand is too difficult at this age. The participants underwent fMRI scanning before and after 4 weeks of training with letters either through the see-and-say method or through printing those same letters (without saying them). Before training, there was no letter-specific activation in the brain. That is, the brains of these children responded the same way to both letters and simple shapes (such as triangles and squares). Only after the printing training did the visual regions that later become specialized in the literate individual for letter recognition become active (see Fig. 2). This finding was the initial evidence supporting the idea that printing letters by hand actually formed neural specialization for letters and perhaps paved the way to creating the brain systems that were used for subsequent reading.

A similar paradigm compared learning letters through the see-and-say method, printing, typing on a keyboard, or tracing (James & Engelhardt, 2012). The question in this case was whether printing letters by hand had a different effect on the formation of brain systems underlying letter perception than typing letters and tracing letters. The tracing condition was included in this design to test whether self-generated handwriting, through copying a form, resulted in different brain activity during letter perception than the situation where a complex action is still present (tracing) but without the need to

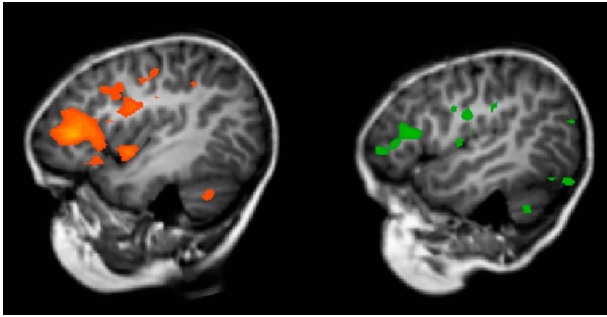


Fig. 3. Blood-oxygen-level-dependent (BOLD) activation differences during letter perception as a function of learning condition in the average of 12, preliterate, 4- to 5-year-old children. Red in the left image depicts significantly greater activation during letter perception if the letters were learned through writing vs. through typing. Green in the right image depicts significantly greater activation during letter perception if the letters were learned through writing vs. through tracing. Statistical maps are thresholded at $p < .0001$ for this group analysis.

self-generate the letters' form. Again, the results were obvious: Only after printing training did the brains of the children recruit the letter recognition network that is observed in adults (see Fig. 3). This finding is important in establishing that it was not just any self-generated action that led to the formation of the system that underlies letter recognition but that the action required was specific—in this case, simply pressing a key or even tracing a letter was not effective.

Thus, two studies demonstrate that learning letters through printing creates the network of activation that is known to underlie letter processing in adults but that learning through typing or tracing did not recruit this network to the same extent.

To follow up on this finding, we then conducted an analysis that specifically targeted how the perceptual and motor systems become functionally connected in the brain (Vinci-Booher, James, & James, 2016). It was possible that the network of activation that is seen during letter perception in the James and Engelhardt (2012) experiment may be simply a coactivation due to the paradigm itself and may not reflect a functional connection among regions—that is, a connection that reflects communication among regions. We therefore used functional connectivity analyses in the follow-up experiment, a method that is used to determine whether brain regions communicate for a given purpose. This technique requires setting a “seed” region of interest, in this case the left fusiform gyrus, and determining, across the entire brain, regions that are functionally connected to this seed region. Our analyses revealed that, indeed, the visual regions that are active during letter perception (the fusiform gyrus) become functionally connected to motor regions only as a result of handwriting experience (Fig. 4).

Interestingly, the studies outlined above showed not only that typing a letter did not recruit the letter perception network but, more surprising, that tracing did not either. If self-generated action was key, then why would typing and tracing not result in the same activation as handwriting? We addressed this question in part by directly comparing the effects of free-hand copying with tracing on symbol knowledge. Because of the well-known phenomenon that we learn things better if we see many, variable examples than if we see a single example repeated (e.g., Gibson & Gibson, 1955), we hypothesized that copying letters resulted in variable examples of a given letter, whereas tracing did not (see Fig. 5).

For instance, learning variable instances of a named category (such as the object “duck”) results in a more sophisticated understanding of the category. When toddlers learn the word “duck,” they are referring to the rubber duck in the bath *and* the duck in the pond at the park *and* the fluffy duck in his book *and* ducks flying in the sky. This variability leads to a better knowledge of what the word *duck* represents compared to seeing multiple instances of the same duck in the bathtub (e.g., Gentner & Namy, 1999). We hypothesized that learning letters may follow the same idea: The more instances of the letter “A” that a child encounters leads to a better understanding of the category of items that belong to the name “A.” Furthermore, they infer that handwriting may be a viable route for this type of learning to occur. The reason for this is simple: When young children print letters through copying, the results are messy and highly variable (see Fig. 5). In contrast, when they trace letters, the results are the same: a nonvariable production of the letter. We surmised that the variable productions that occur with handwriting may be important for learning letters.

We tested this idea by having 5-year-old children learn symbols of the Greek alphabet. They learned the symbols through seeing typed examples, copying typed examples, tracing typed examples, seeing handwritten examples, copying symbols freehand (handwriting), or crucially tracing handwritten examples (Li & James, 2016).

This latter condition allowed them to learn variable instances (similar to handwriting) but through tracing instead of through free-hand copying—which equates other factors that may differ between tracing and copying. Results demonstrated that in all the conditions where children learned variable instances of the symbols (the symbols in handwritten form), their categorization ability was enhanced (see Fig. 6). That is, tracing and visually studying handwritten symbols resulted in the same categorization accuracy as copying them. These results suggested that the reason why

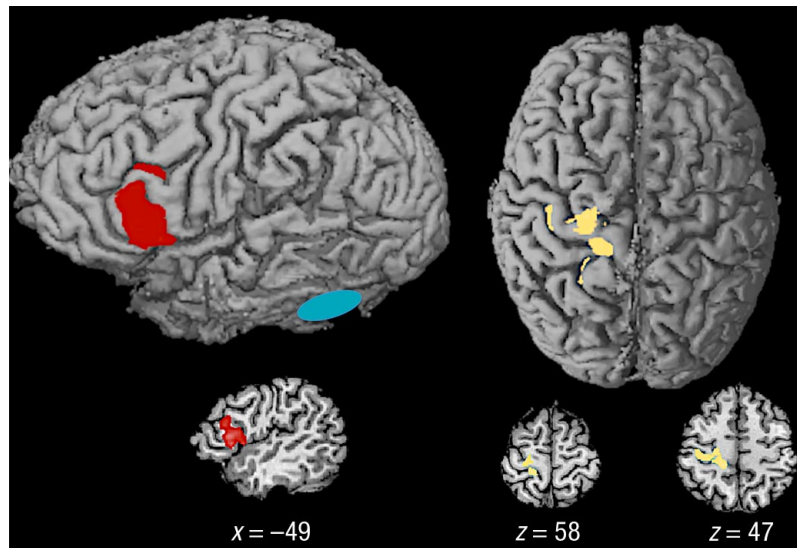


Fig. 4. Effects of functional connectivity analyses from Vinci-Booher, James, and James (2016). Functional connections between the left fusiform gyrus (LFG) seed region (in aqua) and frontal regions are shown in red and yellow. The red area is the left inferior frontal gyrus, which shows functional connectivity with LFG when observers perceived letters trained through handwriting compared to shapes trained through drawing. In yellow is the dorsal sensorimotor area, including the left primary motor and somatosensory cortices, which was functionally connected to the LFG when observers perceived letters learned through handwriting compared to letters learned through typing. Talairach coordinates are provided. The left hemisphere is on the left of the image.

handwriting creates a perceptual-motor network and facilitates letter learning is because it allows the learner to produce and perceive variation in their learning.

This last study begs the question of whether or not handwriting, as a self-generated action, is really necessary for letter learning and for creating the perceptual-motor network that underlies letter perception and reading. This issue was addressed in a study that required 6-year-old children to learn a new script—letters written in cursive—either through self-production or through seeing an experimenter produce those same letters in a variable manner (Kersey & James, 2013). Note that in both conditions the children are, again, perceiving handwritten forms. We then scanned the children using fMRI to determine whether the letters written in the unfamiliar script recruited the same perceptual motor system regardless of whether they were learned through self-production or through passive viewing. The results from this study demonstrated that only when the letters were self-produced did seeing them subsequently recruit the perceptual-motor network. Learning the letters, even if they were variable in form, did not result in recruiting the reading network unless the letters were self-produced. Therefore, although simply viewing variable instances of letters results in higher categorization ability than seeing

nonvariable examples (as in Li & James, 2016), only self-production of letters during learning results in recruiting the brain network that underlies letter recognition during simple letter perception. In short, for a preliterate individual, learning letters through handwriting leads to the recruitment of the letter processing network in the brain, but the reason why handwriting is



Fig. 5. Examples of 4-year-olds' tracing (top row) and copying (middle and bottom rows) of letters (Li & James, 2016). Middle row is the same child producing the letter three times; bottom row is three different 4-year-olds producing the same letter.

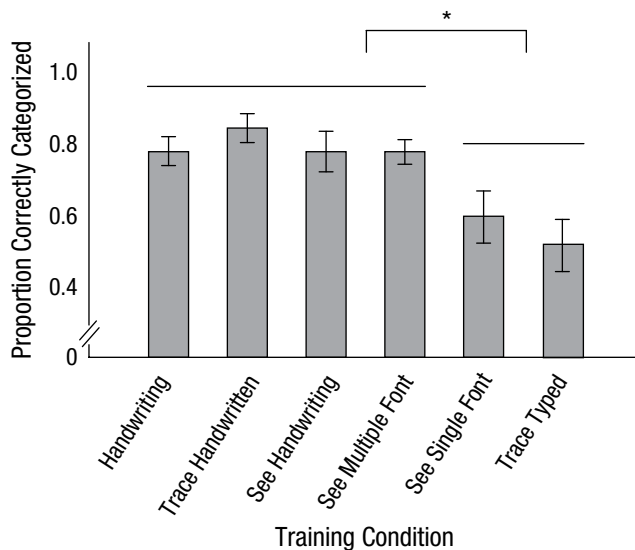


Fig. 6. Proportion of correct categorization of Greek symbols across training conditions (results from Li & James, 2016). All conditions that allowed learning of handwritten (variable) examples resulted in higher accuracy than conditions in which repeated single examples were learned (no variability). The test symbols to sort were presented in both typed and written formats, and there was no difference in sorting accuracy for the two types of test symbols. Error bars represent standard error of the mean. The asterisk indicates a significant difference between conditions ($p < .05$).

affective in enhancing letter knowledge is because it results in the self-production of variable forms. Our actions in the world produce many instances of a stimulus that we then perceive, and it is this production of the variable instances that results in an enhancement in cognitive ability—in this case, categorization.

What do these studies tell us about the importance of handwriting for letter learning? First, that handwriting and letter perception recruit the same network of activation in the literate brain, but before people become literate, handwriting serves to recruit this same network, implying that handwriting experience plays a crucial role in the formation of the brain network that underlies letter recognition. Further, we showed that perhaps the crucial aspect of handwriting for the development of this network is the variability in form that results from early handwriting in the young child. These findings have numerous important implications for literacy development. First, and obviously, handwriting (printing in the case of young children) is important for letter understanding and therefore for literacy development. Second, it does not matter how well a child prints his or her letters; in fact, it may be better if the child produces a lot of different versions of the same letter. Third, for children who have difficulty printing letters, viewing and tracing variable instances of a given letter may be very helpful for their letter categorization—an

early step in letter learning—and subsequent literacy development.

Importantly, the outlined research addresses an important point in cognitive neuroscience: Often behavioral data measured by overt responses and neuroimaging data measured by BOLD signal can have different outcomes. There are well-documented reasons for this, including (a) that brain changes predate and can predict behavioral changes (e.g., Black, Myers, & Hoeft, 2015); (b) that BOLD data reflect the source of a behavior rather than the outcome of manual or verbal responses and, thus, circumvent effects of the motor response per se; (c) that the same overt response can happen as a result of the recruitment of different brain systems (the dual route model of reading is an example of this; e.g., Jobard, Crivello, & Tzourio-Mazoyer, 2003); and (d) that the BOLD signal is more powerful statistically than an overt response given the higher number of observations used in the analyses. In addition, this body of work demonstrates that behavioral measures may show that certain types of learning are more effective than others, but when measuring brain activation patterns, the results may lend different insights into how the learning occurs. Therefore, we benefit from using multiple methods to better understand how learning happens. Theoretically, this research demonstrates that the motor system creates variability (through handwriting in this case) in our perceptual world that enhances behavioral performance and serves to link brain systems into functional networks.

Recommended Readings

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invaluable source for understanding the various types and instantiations of theories of embodied cognition.

Declaration of Conflicting Interests

The author(s) declared that there were no conflicts of interest with respect to the authorship or the publication of this article.

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