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When Writing Impairs Reading: Letter Perception's Susceptibility to Motor Interference

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The effect of writing on the concurrent visual perception of letters was investigated in a series of studies using an interference paradigm. Participants drew shapes and letters while simultaneously visually identifying letters and shapes embedded in noise. Experiments 1–3 demonstrated that letter perception, but not the perception of shapes, was affected by motor interference. This suggests a strong link between the perception of letters and the neural substrates engaged during writing. The overlap both in category (letter vs. shape) and in the perceptual similarity of the features (straight vs. curvy) of the seen and drawn items determined the amount of interference. Experiment 4 demonstrated that intentional production of letters is not necessary for the interference to occur, because passive movement of the hand in the shape of letters also interfered with letter perception. When passive movements were used, however, only the category of the drawn items (letters vs. shapes), but not the perceptual similarity, had an influence, suggesting that motor representations for letters may selectively influence visual perception of letters through proprioceptive feedback, with an additional influence of perceptual similarity that depends on motor programs.

Keywords: action perception, letters, writing, motor interference

The observable output of the brain is action: People convey internal processes through speech, locomotion, limb and eye movements, and manipulation of the objects in their environment. These actions, in turn, allow sensory information to be gathered and processed to inform additional actions. In this sense, human behavior can be understood in terms of action–perception loops. Here, we consider how drawing, writing, and one's experience with writing may influence the visual perception of letters.

The idea that people's perception of the world is reliant on their motor interactions with their environment is not a new idea (e.g., W. James, 1890; Lotze, 1852) but one that has recently generated renewed interest, due in part to the theory of embodied cognition, that emphasizes the role of interactions with the environment as a crucial aspect of cognitive processes (Barsalou, 1999; Clark, 1998; Johnson, 1987; Wilson, 2002). In this framework, actions influence perception not only externally, by modifying the perceived world, but also internally: Executing a motor act, independent of its outcome, may affect perception through neural interactions (Wexler & van Boxtel, 2005). But how do the action and perception systems interact? Actions may be represented in terms of anticipatory codes of their (visual) consequences in the environment (W. James, 1890; Lotze, 1852). In addition, sensory events could engage action codes simply by virtue of the history of co-occurrences of the sensory and motor events (Hecht, Vogt, & Prinz, 2001; Prinz, 1997). Shared representations by the action and perception systems have been suggested in several theoretical frameworks, for example, *micro-affordances* shared by perception and action (Ellis & Tucker, 2001; Tucker & Ellis, 2001), the *direct mapping* hypothesis of actions and perception (Gallistel, 1990), *mental models* incorporating action and perceptual processes (Schwartz,1999), and the idea of forward internal models that can predict sensory consequences from efference copies of issued motor commands (Decety & Grezes, 1999; Miall et al., 2006). By virtue of the action and perception systems sharing representations in the brain, these hypotheses predict that under certain conditions, not only can perception affect action (a well-known phenomena), but motor learning and ongoing actions can affect visual perceptions.

The effects that actions have on perception can be divided into two types: effects observed when action and perception occur at the same time and effects that past actions (experience) may have on subsequent perceptions. Actions that are performed at the same time as visual perception may result in interference of one system with the other, as each tries to access the same representation, or common codes. This could lead to a decrement in performance in visual perception, action, or both due to competition. In contrast, experiences where action and perception are repeatedly paired may strengthen the common codes or representation and facilitate action and/or perceptual performance when they are not performed concurrently. Evidence for both of these situations has been demonstrated.

The influence of ongoing actions on visual perception has been studied using variations on interference paradigms. Musseler and Hommel (1997) showed that preparing to make a left-handed keypress interfered more with responding to a left-pointing arrow than a right-pointing arrow. It is interesting that this effect was only found when the interval between the action and the perception was very short. With considerably longer intervals, performance

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was facilitated when response hand and arrow direction matched. The authors interpreted these results as demonstrating a temporary blindness to stimuli that resembles the action, referred to as *action–effect blindness* (Musseler & Hommel, 1997). Action-induced perceptual impairment was also demonstrated in a similar paradigm using drawing as the action and size perception as the visual task: When a small curve was drawn, a similar line was perceived as being larger; when a large line was drawn, the test stimulus was seen as smaller (Schubo, Aschersleben, & Prinz, 2001). Hamilton, Wolpert, and Frith (2004) also showed that performing an action altered perception in an interfering manner: Holding a heavy weight biased people's judgments of a visually presented stimulus such that they estimated it to be lighter than it actually was. In a dual-task paradigm, Koch and Prinz (2005) demonstrated that visual encoding of a cue interfered with motor responses at very short intervals between stimulus and response but that as the interval was increased, the effect was diminished. Thus, the *contrast effect* or interference (Schütz-Bosbach & Prinz, 2007) should only occur when the percept and the action are co-occurring. If the two events are separated in time, then the activation of one may facilitate the other.

Facilitation or *priming* of action on perception and perception on action over a longer time frame has been documented. For instance, a large literature, going back at least as far as William James (W. James, 1890), suggests a crucial role for action in perceptual learning. This includes studies as diverse as research on perceptual learning with stimulus deprivation (Held & Hein, 1963), adaptation to visual distortions by optical lenses (Held, 1965; Held & Freedman, 1963), infant learning about binocular depth cues (E. J. Gibson, 1988), and the role of eye movements in adult perceptual learning (O'Reagan & Noe, 2001), as well as computational studies of the advantages of *active vision*—how an observer (human or robot) is able to understand a visual environment more effectively and efficiently by acting on it (e.g., Lungarella, Pegors, Bulwinkle, & Sporns, 2005; Lungarella & Sporns, 2005, 2006). In a similar vein, acting on novel objects during initial encounters can facilitate subsequent visual recognition of those objects (Harman, Humphrey, & Goodale, 1999; K. H. James, Humphrey, & Goodale, 2001; K. H. James et al., 2002). The perception of biological motion is also facilitated by prior performance of similar movements (Casile & Giese, 2006). In addition, participants can recognize an object faster if it is positioned in a manner congruent with how people typically act on the object (Tucker & Ellis, 2001). The degree or type of experience can determine to what extent action influences perception; for instance, the order of keypresses can influences tone perception, but only in skilled pianists (Repp & Knoblich, 2007).

Several neuroimaging studies have supported these behavioral findings: Motor systems are automatically engaged on visual perception of objects that have strong motor associations, such as tools, utensils, and letters (Chao & Martin, 2000; Gerlach, Law, Gade, & Paulson, 2002; Grezes & Decety, 2002; K. H. James & Gauthier, 2006; Longcamp, Anton, Roth, & Velay, 2003, 2005; Longcamp, Tanskanen, & Hari, 2006; Mecklinger, Gruenewald, Besson, & von Cramon, 2002). This activation does seem reliant on experience in some cases, as motor activation during the perception of notes was tied to expertise reading musical notation (Wong & Gauthier, 2008). Further, training individuals to practice writing novel, letterlike stimuli resulted in activation in letter-sensitive regions that was not apparent prior to extensive writing experience (K. H. James & Atwood, 2008). Children only develop a blood oxygen level dependent response to letters that is specific to the fusiform gyrus after a specific type of experience involving motor system involvement (K. H. James, in press).

Whether action and perception interactions translate to interference or facilitation often seems to depend on temporal contingencies. It is interesting that there is also documentation of facilitation of perception during concurrent motor behavior. This curious effect has been shown mostly for mental rotation tasks. For instance, mentally rotating complex figures presented visually was facilitated by motor rotation of a joystick in the same direction as the mental rotation, whereas movement in an incongruent direction slowed performance (Wexler, Kosslyn, & Berthoz, 1998). Mental rotation is also facilitated by manually rotating a block in the same direction, as a required mental rotation, and by pulling a string from a spool, causing it to rotate in a given direction (Schwartz & Holton, 2000). Presumably, the hand movement in these cases may help to solve the task, whereas in visual object recognition, hand movements may not play a role in the actual task of recognition. Facilitation has also been shown when perceiving body postures. In a dual-task paradigm, Reed and Farah (1995) demonstrated that perception of the body position of others was affected by one's own body position. More recently, Miall et al. (2006) showed that performed hand postures congruent with perceived hand postures facilitated performance in oddball detection tasks. Recognition of body parts and position may access a different neural system than object recognition. In fact, neuroimaging results suggest that body part perception does not overlap neurally with systems underlying object recognition (Downing, Jiang, Shuman, & Kanwisher, 2001). There is also strong evidence that mental rotation, orientation detection, and perception of biological motion (Grossman et al., 2000) are processed predominantly in the dorsal visual processing stream of the cortex (Gauthier et al., 2002; T. W. James & Gauthier, 2003; Valyear, Culham, Sharif, Westwood, & Goodale, 2006). In contrast, visual object recognition is predominantly a ventral visual stream function. It is possible that interference effects are due to dorsal stream processing during online control of action (Milner & Goodale, 1998) and during recognition tasks that involve the dorsal stream.

Letters represent an interesting category with which to study questions of interactions between action and perception. Letters are read but rarely manipulated, although they are also written and perhaps nowadays even more often typed. Letter shapes do not afford an action the way a brush or hammer does (J. J. Gibson, 1979) without any learning. That is, the form of the letter does not, by itself, suggest how one should interact with it. Little work directly addresses whether objects without obvious affordances but with motor associations, gained during learning, activate the motor systems during visual perception (when there is no concurrent action). Recently, we have shown that simply perceiving letters engages motor areas involved in writing letters (K. H. James & Gauthier, 2006; see also Longcamp, Anton, et al., 2005). Similarly, learning to write novel letterlike forms results in activation of regions similar to those activated by letter perception, whereas learning these same forms without action results in activation common to other types of objects (K. H. James & Atwood, 2008). Behavioral evidence also supports the idea that motor experience with letters is stored and may be used during visual letter recognition. For instance, one's knowledge of the manner in which people write different strokes composing a letter affects its visual perception—one's motor experience with these abstract forms can change one's perceptions (Babcock & Freyd, 1988; Freyd, 1983; Kandel, Orliaguet, & Viviani, 2000; Knoblich, Seigerschmidt, Flach, & Prinz, 2002; Orliaguet, Kandel, & Bois, 1997; Tse & Cavanagh, 2000). Training children to write letters also facilitates letter recognition, more so than training them to type letters (Cunningham & Stanovich, 1990; Longcamp, Zerbato-Poudou, & Velay, 2005). Preschool children who practice printing letters show an increase in brain activity in the fusiform gyrus during letter perception, unlike children who practice saying letters instead of printing them, suggesting that motor training directly affects the visual representations of letters (K. H. James, in press). Such findings support the idea that information about actions with objects is stored with visual information or at least contributes to visual processing in some way.

In a similar way, recognition of movement is affected by past actions. Recognition of self-generated actions is very accurate, even long after the action has been produced, provided that velocity information is maintained in the reenactment (Knoblich & Prinz, 2001). Movement can facilitate letter recognition in cases where performance is not yet or no longer optimal. For instance, movement facilitates letter recognition in patients with pure alexia (a deficit in letter identification; Bartolomeo, Bachoud-Levi, Chokron, & Degos, 2002; Seki, Yajima, & Sugishita, 1995).

In the present study, we wished to address two issues regarding the effect of writing on letter perception. First, we asked whether concurrent motor behavior can affect visual processing of static forms and, if so, whether it is facilitatory or inhibitory. Although it is interesting that perceiving letters recruits motor areas associated with writing (K. H. James & Gauthier, 2006; Longcamp, Anton, et al., 2005, 2008) and that writing affects the ability to identify the movement produced during the formation of letters (Knoblich et al., 2002), it is unclear whether concurrent motor activity can interfere with the perception of static letters (the way letters are usually encountered). Second, we asked if actions interfere with visual processing in a manner that reflects motor experience: In what ways do the content of the perception and the action have to match? In other words, how specific is the interaction, if it exists? Does the execution of any concurrent movement affect visual perception of letters, or is interaction limited to letters similar in shape or even to the exact motor program associated with a letter? Writing is a highly practiced action in most adults and motor programs are precise enough for handwriting to have an individual signature, so there may be specific motor programs for writing different letters.

Experiment 1

In Experiment 1, we asked whether *any* concurrent hand movement affects visual perception of letters or whether the movement has to be very similar to the perceived form. Of course, it is possible that just any concurrent movement will affect letter perception. But the interaction could also be more specific, in at least two possible ways. In one case, any motor act that is similar to a visually perceived form could affect perception, even if the motor act does not share the same cognitive category (letter or shape) as the visual stimulus. For instance, drawing a square or drawing the letter *F* could equally interact with the visual perception of the letter *T* simply on the basis of shared features. An alternative is that only a motor act that shares the same category as the visual form interacts. In this case, drawing a letter *C* could interact more than a square would with the perception of an *H*, not because of its similarity in production but because it belongs to the same cognitive category, letters. The first possibility is more componential, assuming a linked relationship between visual and motor units that represent the same part of a shape, whereas the second possibility is more categorical, assuming segregation of the motor programs for writing letters from those for other shapes. Of course, these two options are not exclusive, such that it would be possible for only motor programs of similar letters (but not other shapes) to interact with letter perception.

Method

Participants. Thirty-five undergraduate students recruited from the Vanderbilt University undergraduate research pool were given partial course credit for their time. All participants provided informed consent and all reported normal or corrected-to-normal visual acuity. All subjects were right-handed and included 16 men (mean age = 20.2 years) and 19 women (mean age = 20.9 years).

Stimuli. The visual stimuli were six uppercase letters embedded in a 3-in. × 3-in. square of Gaussian noise presented on a gray background. The uppercase letters were constructed using the Sloan font (Pelli, Robson, & Wilkins, 1988) and were an average of 2.5 in. × 2.5 in. Participants viewed the letters from a distance of approximately 30 in. and thus the stimuli subtended a visual angle of approximately 4.8°. We included three straight letters, *H*, *N*, and *K*, and three curvy letters, *G*, *D*, and *U*. Letters were presented for 500 ms with a 1,000-ms interstimulus interval and were centered on the computer screen (see Figure 1 for examples of stimuli and design).

Apparatus. Stimuli were presented on an iMAC equipped with a CRT monitor, using RSVP software (Tarr & Williams, n.d.). Letters and shapes were drawn onto a Wacom Graphire digital writing pad (Wacom Technology Corporation, Vancouver, WA), positioned to the right of the participant. The apparatus for visual presentation was the same in all experiments, and the apparatus for movement execution was the same for Experiments 1–3.

Procedure. The general procedure for testing participants was the same in all experiments and involved four stages. First, participants performed a letter identification task to determine their 75% contrast threshold for stimulus identification. This was done using a two-up one-down staircase procedure with letters presented in the Sloan typeface and embedded in Gaussian noise with constant contrast. The 75% threshold was then estimated from a psychometric function fitted to the data. The mean contrast across participants was .055 (*SD* = .0075), but each individual's contrast threshold for each stimulus was used to determine the stimuli to be presented in the baseline letter identification task.

The next stage was a baseline letter identification task. The purpose of this task was to measure letter identification abilities in each individual that would later be compared with his or her performance in the dual task. The baseline letter identification task was administered using stimuli presented at four different contrasts: one log unit and one half-log unit above the individual participant's threshold for each stimulus, and one log unit and two

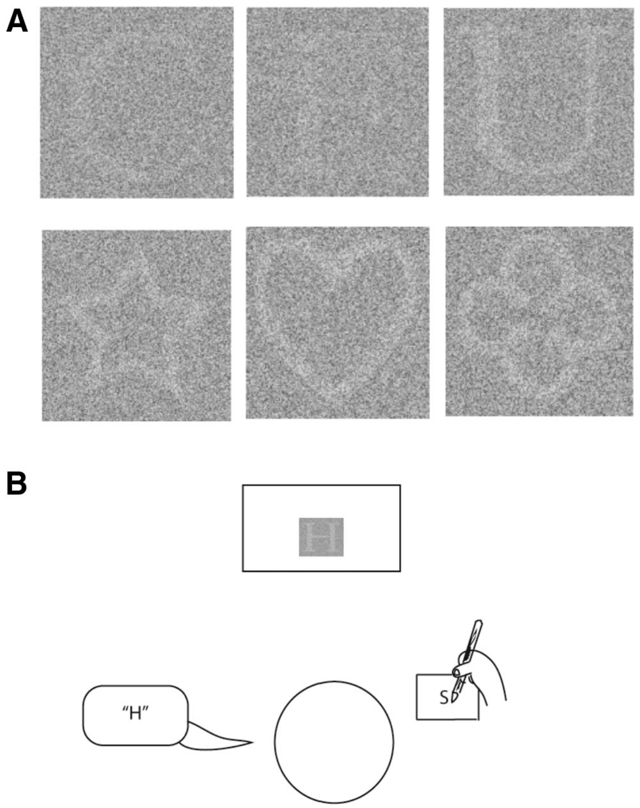

Figure 1. Examples of stimuli used in Experiments 1–4. A: The top row shows letters presented just above psychophysical threshold, whereas the bottom row shows shapes presented just above threshold. B: Schematic of interference paradigm: Participant looked at computer screen to identify letters or shapes verbally while writing letters or shapes concurrently.

log units below this threshold. A range of contrasts was used to provide a range of difficulty across trials and to prevent participants from becoming complacent. Contrasts were chosen such that accuracy was estimated to remain between 70–80%. Noise contrast was held constant across trials (root-mean-square = .5). Signal (letter) contrast was varied across trials, with the values based on each participant's 75% identification contrast threshold. Letters at different contrasts were presented in random order: The presentation of the stimuli in the baseline task was the same as in the dual task. During the baseline task, participants were asked to verbally identify visually presented letters embedded in noise. Accuracy of letter identification was recorded by an experimenter sitting behind the participant and later compared against performance in the dual task reported below. The experimenter who recorded the responses was blind to the specific predictions of the studies.

After performing the baseline identification task, participants were trained in the writing task, the third stage. Participants were asked to draw certain pairs of shapes or letters in alternation on a digital writing pad with a stylus until writing was fluid and well practiced. This training, which took approximately 5 min, was performed for all letter and shape combinations used in the experimental session. In the final stage of testing, we began the experimental dual tasks in which participants verbally identified letters in noise while writing specific letter or shape combinations. The visual identification part of the dual task used the same procedure as the baseline letter identification task described above. In addition, participants had to simultaneously write or draw specified repeating sequences of letters or shapes. Participants were told that the letters and shapes that they wrote and drew were recorded and would be part of the analysis, although this was not the case. This deception ensured that the participants were motivated to write or draw the correct letters and shapes. Participants only had to identify letters visually, but they concurrently drew either letters or shapes. This procedure resulted in eight dual-task conditions, combinations of two visual conditions—see straight letters (H, N, K) and see curvy letters (D, G, U)—and four drawing conditions—straight letters (W, Y), curvy letters (S, C), straight shapes (square, rectangle), and curvy shapes (circle, oval). The order of these conditions was counterbalanced across participants.

Results and Discussion

We compared performance in each dual-task condition with performance in the baseline letter identification task, given these tasks only differed in terms of the writing–drawing component. For each participant and each stimulus, an interference index was computed using the difference in performance between the baseline and dual-task conditions. For instance, if performance was 85% in the baseline task and 80% in the dual task, the interference index would be 5. The interference index, therefore, reveals interference from the motor task and, more important, allows a comparison of the degree of interference produced by different motor conditions. All analyses are based on this interference index: A higher number indicates more interference from the concurrent motor task (raw percentage correct scores are recorded in the Appendix).

A 2 (writing category [letters or shapes]) × 2 (writing curvature [straight or curvy]) × 2 (seeing curvature [straight or curvy]) repeated-measures analysis of variance (ANOVA) revealed a main effect of writing category, $F(1, 34) = 11.7$, $p < .005$, as drawing letters ($M = 7.3$) caused greater interference than did drawing shapes ($M = 3.0$). A significant interaction was also obtained between writing curvature and seeing curvature, $F(1, 34) = 9.09$, $p < .005$. Drawing straight items interfered more with seeing straight letters than did drawing curvy items, and drawing curvy items interfered more with perceiving curvy letters than did drawing straight items (see Figure 2). There was also a trend toward a three-way interaction, $F(1, 34) = 2.7$, $p < .09$. This result, although not significant, suggests that the two-way interaction effect of congruency of the writing curvature and the seeing curvature (i.e., write straight and see straight or write curvy and see curvy) could be dependent on writing category, with stronger effects for writing letters than drawing shapes (see Figure 2). When single-sample t tests are performed comparing each interference value with 0 (no interference), all interference values when drawing letters are significant, $t(34) > 2.7$, $p < .00625$, Bonferroni corrected, but only drawing straight shapes interfered significantly with perceiving straight letters: No other values when drawing shapes were significant, $t(34) < 2.7$, *ns*.

The results of Experiment 1 suggest that motor activity interferes with letter perception. However, this result by itself is difficult to interpret because it may reflect a general dual-task cost

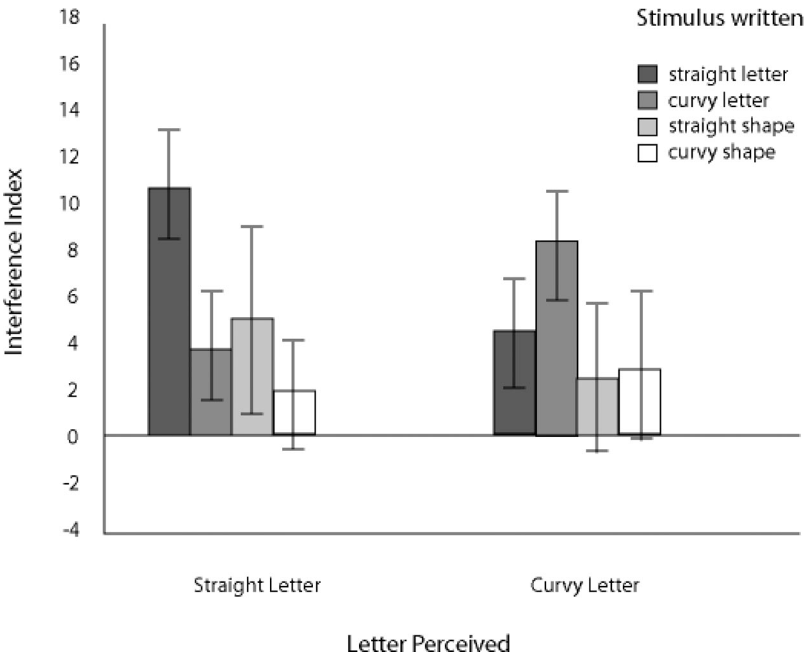

Figure 2. Amount of interference plotted as a function of letter seen in Experiment 1. Error bars represent 95% confidence intervals of the comparison with zero.

(Kahneman, 1973). More interesting is the modulation of this interference according to the nature of the visual and writing conditions. We found that writing letters interferes more with letter perception than does drawing shapes. This could reflect the categorical nature of motor programs for writing letters and their corresponding relationship to the visual representation of letters. Greater interference implies shared (Kahneman, 1973) or interconnected (Kinsbourne & Hicks, 1978) neural systems, supporting the notion that the visual representation of letters is not functionally independent from the motor representations engaged to write letters. However, because we did not have participants perceiving shapes, it is also possible that letters were somehow more taxing to write than shapes were and would have interfered with any perceptual task. But we found that similarity in the shape of the visual and drawn stimuli mattered. For both writing letters and drawing shapes, stimuli that were congruent (in terms of curvature) with the shape of the visual letters caused more interference. Finally, there was a trend toward this latter effect occurring more when participants wrote letters than when they drew shapes, but this could be due to a floor effect on the interference caused by shapes, which was lower overall than that caused by letters.

One interpretation of these findings is that the motor representations involved in writing letters interact with the visual representations engaged during letter perception. An alternate idea, however, is that participants may have subvocally rehearsed the items to draw, perhaps to keep track of where they were in the sequence of items to repeat. If so, interference may have occurred because of auditory rehearsal rather than from motor performance. Indeed, visual and auditory letter perception have been shown to interact in the brain (van Atteveldt, Formisano, Goebel, & Blomert, 2004). Although it seems unlikely that covert verbal rehearsal would happen more for letters than for shapes, we addressed this possibility in Experiment 2. In addition, the trend toward a three-way interaction was reexamined using a more detailed analysis of the effect of curvature on interference.

Experiment 2

There were three motivations for Experiment 2. First, we reduced the number of letters or shapes to draw to one at a time. We hoped that drawing only one letter or shape would reduce the need for covert rehearsal. Second, we changed the viewed stimuli to completely curvy or completely straight. That is, curvy letters were composed of only curved line segments and straight letters were composed of only straight-line segments. Third, we changed the stimuli that were drawn so that we had a continuum of curvature similarity among the drawn and perceived letters. Unfortunately, we do not have enough control over these properties of letters, given the limited set, to allow a perfect parametric manipulation.

Method

Participants. Participants were drawn from the undergraduate research pool at Vanderbilt University and received partial course credit for their time. Only right-handed individuals that reported normal or corrected-to-normal visual acuity participated. Of these participants, 18 were men (mean age = 20.2 years) and 17 were women (mean age = 19.9 years), resulting in 35 total participants.

Stimuli. The visual stimuli were generated and presented as in Experiment 1 but included only the uppercase letters *H*, *F*, *I*, *C*, *O*, and *U*. Contrast thresholds were collected using the same procedure as was used in Experiment 1. Mean contrast across participants was similar to that in Experiment 1 ($M = .060$, $SD = .009$).

The items to draw included the letters *S*, *V*, lowercase *t*, and the number *8*, as well as a circle, a triangle, a cross, and an infinity sign. We used these stimuli for the following reasons: Seeing the letter *O* and drawing a circle resulted in the same shapes that had different labels and belonged to different categories (letter and shape). In addition, the letter *t* and the Christian cross were also the same shape but again belonged to different categories. These contrasts allowed us to better determine whether interference is due to feature or category similarity. We also now had a continuum of similarity: The letter *t* and the cross are more similar to the viewed letters *H*, *F*, and *I* (all composed of horizontal and vertical segments), whereas the written letter *V* and a triangle are not as similar (diagonals). These contrasts allow a comparison of similarity within the same category of straight shapes.

Results and Discussion

We again performed a 2 (writing category [letters or shapes]) × 2 (writing curvature [straight or curvy]) × 2 (seeing curvature [straight or curvy]) repeated-measures ANOVA on the interference index. Results from this analysis revealed that writing letters ($M = 9.6$) interfered more with letter perception than did drawing shapes ($M = 6.8$), $F(1, 34) = 10.52$ $p < .005$ (see Figure 3). However, a significant two-way interaction was again obtained, $F(1, 34) = 43.2$, $p < .001$: Congruent curvature between the perceived and the drawn stimuli led to more interference relative to incongruent curvature. The three-way interaction was also significant, $F(1, 34) = 4.8$, $p < .05$. For both writing letters and drawing shapes, feature congruency had a significant effect on interference. However, the effect was more pronounced during letter writing than shape drawing (see Figure 3). Single-sample *t* tests revealed that all drawing conditions in this experiment significantly interfered with letter perception, $ts(34) > 2.7$, $p < .00625$, Bonferroni corrected.

Three planned comparisons were conducted, all involving selected items. The purpose of the first contrast was to determine if writing or drawing the same form produced different effects when the instructions placed that form in different writing categories. Specifically, we contrasted the conditions in which participants wrote a *t* versus drew a cross. Results demonstrated that writing a *t* ($M = 8.1$) interfered more with letter perception than did drawing a cross ($M = 3.1$), $t(33) = 3.11$, $p < .001$.

The purpose of the second contrast was to investigate whether there was a graded effect of similarity between the written and perceived stimuli. To do this, we compared the interference index across writing or drawing the four straight items while seeing the letters *F*, *H*, and *I*. As depicted in Figure 4, all conditions interfered with straight letter perception more than chance (for all conditions different from 0, baseline $p < .00625$, Bonferroni corrected). Furthermore, writing a *t* interfered the most with straight letter perception, followed by a cross, a *V*, and a triangle, although the cross and *V* did not differ significantly from one another (for all comparisons, $p < .00625$, Bonferroni corrected). Therefore, perception of the straight letters was interfered with to different degrees, depending on whether the drawn stimulus was a letter and depending on degree of curvature. These results suggest additive effects of feature and category similarity. The featural and categorical effects may depend on different resources, according to Sternberg's (2001) additive factors logic, with all the associated caveats.

The third contrast of interest was comparing the amount of interference on the perception of the letter *O* when drawing a circle in comparison to other curvy-shaped stimuli. Drawing a circle

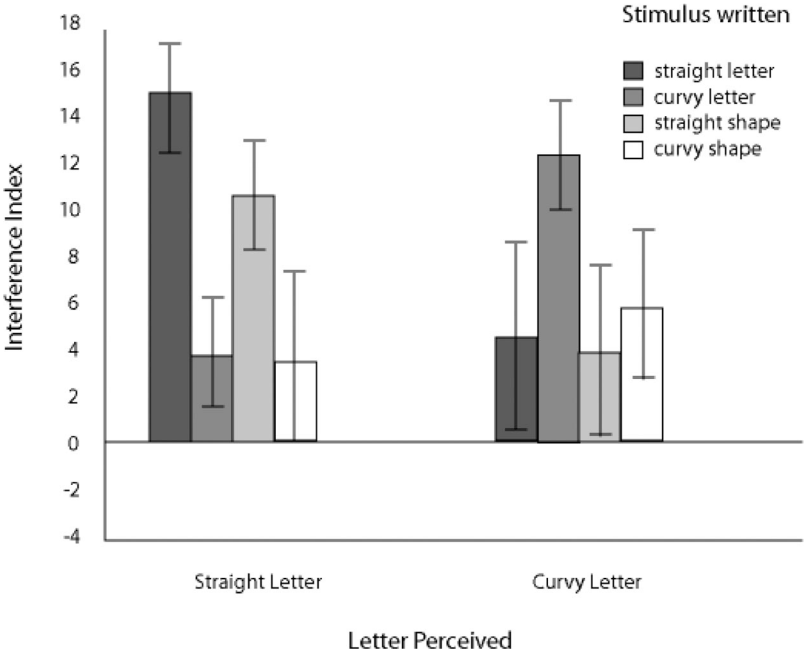

Figure 3. Amount of interference plotted as a function of letter seen in Experiment 2. Error bars represent 95% confidence intervals of the comparison with zero.

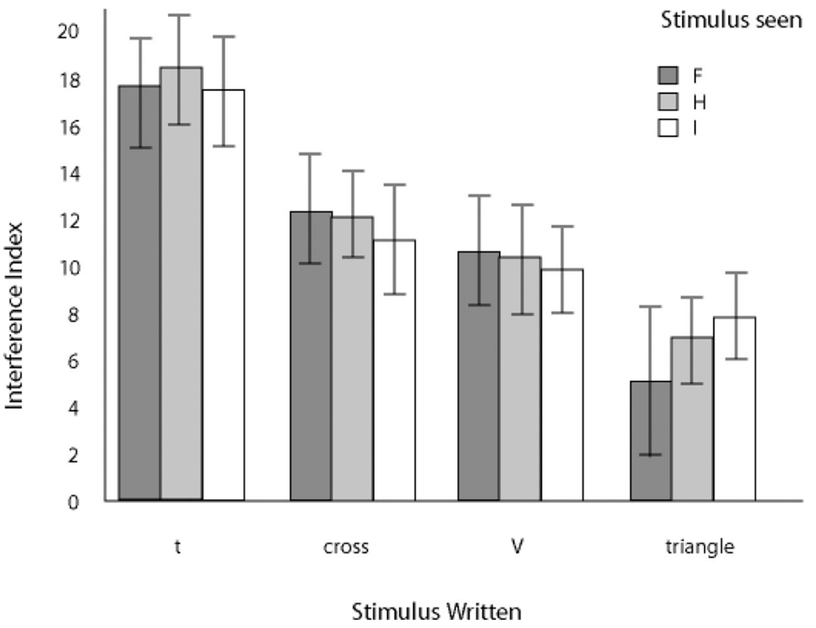

Figure 4. Amount of interference of writing on straight letter perception in Experiment 2. Note here that the *x*-axis depicts the stimulus written. All stimuli written interfered significantly with stimuli seen, but the amount differed depending on category and curvature. Error bars represent 95% confidence intervals of the comparison with zero.

interfered much less ($M = 1.0$) with perception than did any of the other drawing conditions. In fact, this amount of interference was not significantly greater than 0. Drawing the other curvy shape (∞) led to more interference with *O* perception ($M = 12$), as did writing curvy alphanumerics (mean for *8* = 11 and mean for *S* = 11.3). The curvy shape and alphanumerics did not differ from one another, $ts(33) < 1.2$, *ns*. Although this is based on a single case, it suggests that when the drawn item is exactly the same shape as the perceived item, little interference occurs. This was an unexpected result, but past research suggests that a certain amount of motor priming can occur when drawn and perceived stimuli are the same (Craighero, Fadiga, Rizzolatti, & Umiltà, 1998). In this study, drawing a circle did not facilitate the recognition of *O*, but unlike the other stimuli, it did not interfere, either. It is unclear whether this results from two opposite influences. This was not the focus of our study but could be an interesting avenue for future work.

The results of Experiment 2 support and extend those of Experiment 1. Again, interference depended on similarity of curvature, and this time the effect was significantly larger for drawn alphanumeric characters. Both our omnibus ANOVA and planned comparisons suggest additive effects of overlap in item category (more interference of drawn alphanumeric characters than from shapes on letter perception) and of the similarity of the items. In addition, items that are exactly the same in shape may not interfere with perception, but items composed of the same features in a different combination do interfere.

Although this experiment was partially aimed at reducing the effects of covert verbal rehearsal, it does not rule out this possibility entirely. However, we assume that having participants draw just one letter or shape eliminated the need to rehearse the items to support performance (to help participants keep track of which item to write next). In addition, because interference primarily occurred for writing over drawing shapes, this verbal rehearsal would need to be more important for letters. It is possible that subvocalization of letter names specifically occurs automatically, a phenomenon not inconsistent with the general multimodal framework in which this work is inscribed. However, it is unlikely that verbal responses would mediate the effect of similarity in curvature that we observed.

We originally hypothesized that letter perception would be influenced by writing letters more than by drawing shapes because of our extensive experience writing letters. Experiments 1 and 2 confirm this hypothesis, but they do not address the possibility that writing letters could also interfere more than drawing shapes with perception of any other objects. To address this issue, we compared letter perception with shape perception in Experiment 3.

Experiment 3

In Experiment 3, we asked participants to perceive not only letters in noise but also shapes in noise. Participants' individual contrast thresholds were collected separately for letters in noise and shapes in noise and stimuli were generated on the basis of these separate thresholds. We hypothesized that the effects seen in Experiments 1 and 2 with letter stimuli would not surface with shapes. We attributed our motor interference results to participants' extensive experience with writing letters. Although people do draw shapes, this motor experience is not nearly as extensive as with letters, thus shape perception should be less sensitive to motor interference than letter perception.

Method

Participants. Participants were drawn from the undergraduate research pool at Vanderbilt University and received partial course credit for their time. Only right-handed individuals with normal or corrected-to-normal visual acuity participated. Of these participants, 18 were men (mean age = 19.9 years) and 17 were women (mean age = 20.1 years), resulting in 35 total participants. All participants provided written informed consent.

Stimuli. The letters that were viewed and the letters and shapes that were drawn in Experiment 2 were also used in Experiment 3. In addition, we included six shapes embedded in noise for visual identification: star, hexagon, square, heart, clover, and circle, resulting in three straight and three curvy shapes.

Procedure. The procedure was the same as in the previous experiments with the exception that we acquired a second set of contrast thresholds for the shapes in noise, used as the extra baseline identification task for shapes in noise, and added shape perception dual-task blocks. Collecting thresholds for shapes as well as letters allowed us to match visual identification difficulty for letter and shape identification by presenting shapes at a higher contrast than letters. Mean contrast across participants for letters was similar to the contrast found in Experiments 1 and 2 (M = .058, SD = .0091). Mean contrast across participants for shapes was higher than for letters (M = .174, SD = .0194). However, similar to letters, the contrast thresholds did not differ among the individual shapes. Participants first completed the threshold task for letters and shapes, then completed the baseline letter and shape identification tasks, followed by the dual-task portion for letter and shape perception.

Results and Discussion

We first performed a 2 (seeing category [letters or shapes]) × 2 (writing category [letters or shapes]) × 2 (writing curvature [straight or curvy]) × 2 (seeing curvature [straight or curvy]) factorial ANOVA on the interference index. There was a main effect of seeing category, $F(1, 34) = 108.9$, $p < .0001$: That is, interference on letter perception (M = 7.25) was greater than interference on shape perception (M = 1.6). There was also a main effect of stimulus drawn, $F(1, 34) = 14.4$, $p < .001$, as writing letters interfered more with perception (M = 5.8) than did drawing shapes (M = 2.7; see Figure 5).

The expected three-way interaction between perceived stimulus category and drawn stimulus category was significant, $F(1, 34) = 56.8$, $p < .0001$. To further investigate this effect, we ran separate two-way ANOVAs on letter and shape perception. In letter perception, there was a significant main effect of writing letters versus drawing shapes, $F(1, 34) = 13.9$, $p < .001$, as writing letters interfered more with letter perception (M = 10.4) than did drawing shapes (M = 4.1). In contrast, during shape perception, there was no main effect of the writing–drawing condition, $F(1, 34) = .34$, *ns*. Writing letters interfered more with letter perception than did drawing shapes, whereas writing letters or shapes had no effect on shape perception.

We also obtained a four-way interaction including all factors, $F(1, 34) = 38.15$, $p < .0001$. In general, our four-way interaction reflected the finding that during letter perception (see Figure 5A), congruency effects emerged as in the previous two experiments. When participants viewed a straight letter, there was more interference from writing straight letters, but when participants viewed curvy letters, there was more interference from writing curvy letters. This also held true for drawing curvy shapes during curvy letter perception, which interfered more than did drawing straight shapes. Drawing straight shapes resulted in no interference with straight letter perception, however, $t(34) = 0.77$, *ns*. The data from shape perception (see Figure 5B) revealed only one significant interference score: When participants wrote letters, curvy shape perception was affected, $t(34) = 3.05$, $p < .05$.

Additional planned contrasts similar to those in Experiment 2 were performed. We again compared the amount of interference that resulted from drawing stimuli that differed from the seen stimuli (see Figure 6). Letters interfered more overall, but *t*s and *V*s did not differ from one another, $t(34) = 3.2$, *ns*; within the drawing shapes category, crosses interfered more than did triangles, $t(34) = 2.0$, $p < .05$. There was again greater interference from writing a *t* (M = 12.1) on letter perception than drawing a cross (M = 3.5), $t(34) = 2.4$, $p < .01$. Certainly in this experiment, writing straight letters interfered more with straight letter perception than did drawing shapes. Drawing shapes that were similar to the perceived letter (the cross), however, did interfere more with perception than did drawing dissimilar shapes (the triangle).

As in Experiment 2, we found very little interference from drawing a circle on perception of the letter *O* (M = .45, not significantly different from 0), but again, more interference from drawing other curvy shapes (M = 6.4) and the most interference from drawing curvy alphanumerics (mean for *8* = 10.2; mean for *S* = 11.3). It is interesting that a significant difference existed between drawing curvy shapes and drawing the letter *S*, $t(34) = 2.5$, $p < .01$, a reflection of the higher interference of writing letters than drawing shapes on letter perception. When we look at interference effects on the perception of the circle, we see no significant interactions from either drawing shapes or writing letters, $ts(34) < 2.7$, *ns*.

Results from Experiment 3 confirm and extend our previous findings. The primary result of interest that emerges from Experiment 3, however, is that although we see significant interference of motor tasks on letter perception, motor interference is very low during shape perception. This allows us to reject the possibility that results in Experiments 1 and 2 were due to the act of drawing letters simply being more difficult than the act of drawing shapes. This supports the idea that motor interference that is observed on letter perception may depend on people's extensive experience of writing letters. Although letters are not the only visual stimuli with motor associations (e.g., tools, utensils, and musical instruments), they are more strongly associated with practiced movements than are many common shapes, such as stars or hearts.

The category-specific pattern of interference obtained here suggests that letter perception and letter writing engage overlapping (or at the least interacting) neural systems, consistent with prior functional magnetic resonance imaging work (K. H. James & Gauthier, 2006; see also Longcamp, Anton, et al., 2005, 2006) and with frameworks that hypothesize shared representations (Prinz, 1997). In contrast, shape perception and shape drawing may be more independent from one another: The content of these two

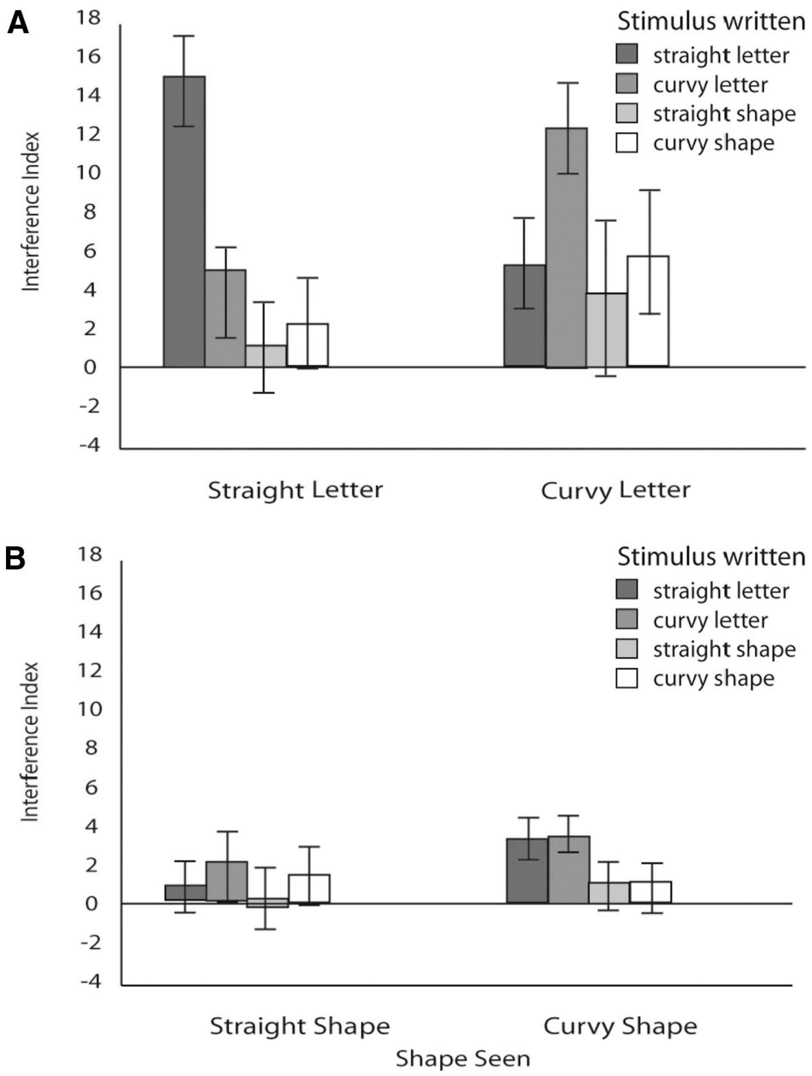

Figure 5. A: Amount of interference plotted as a function of letter seen in Experiment 3. B: Amount of interference plotted as a function of shape seen in Experiment 3. Error bars represent 95% confidence intervals of the comparison with zero.

types of stimuli may be sufficiently different as to not overlap (Prinz, 1997). But it should be noted that drawing shapes interfered more with letter perception than writing letters interfered with shape perception. Thus, what may be critical for this asymmetry is not so much the motor programs engaged during drawing, as they may be equally required when people draw shapes and write letters, but the fact that motor areas may be engaged automatically by letter perception (K. H. James & Gauthier, 2006) but not by drawing shapes.

In the next study, we addressed to what extent the intent or motor program that is recruited to write a letter interferes with perception or whether information from the hand movement itself, such as proprioceptive information, is sufficient to interfere with letter perception. The fact that we obtained categorical effects (relatively dissimilar alphanumeric characters causing more interference than equally dissimilar shapes) suggests that at least part of the effects we observed may occur at a more abstract level. Nonetheless, across all three experiments, we found robust effects of similarity of the features, and it is possible that this reflects bottom-up mechanisms (muscle fatigue or proprioception) rather than top-down mechanisms (motor programming). In Experiment 4, we investigated this idea.

Experiment 4

To investigate whether results of Experiments 1–3 were due to top-down versus bottom-up mechanisms, we devised a task where the motor component of the experiment was either active or passive. This experiment also further addresses the issue of silent verbal rehearsal of letters. In the passive condition, participants were unaware of the identity of the movements they were producing, and even if they recognized them, there was no need for them to rehearse the identity of the letters or shapes that were being written. Intentional motor acts differ from unintentional motor acts

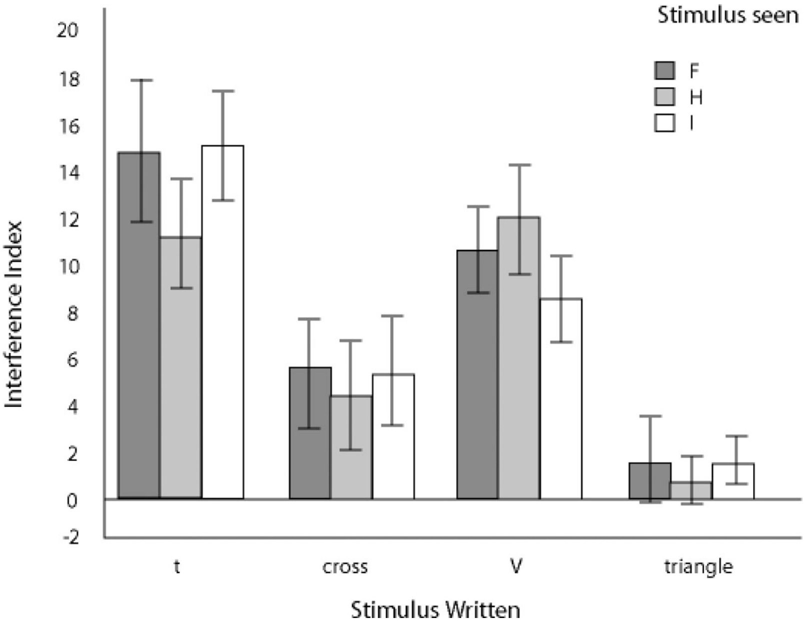

Figure 6. Amount of interference of writing on straight letter perception in Experiment 3. Error bars represent 95% confidence intervals of the comparison with zero.

in many ways, and although both result in proprioceptive feedback, there is evidence that this feedback differs depending on intentionality (Paillard & Brouchon, 1968). For instance, in our passive condition, there should be no sense of authorship, in that the participants know that their hand is moving but the movement is not intentional. According to some researchers, this unintentional movement will result in a different type of binding with the outcome of the action (Haggard, Aschersleban, Gehrke, & Prinz, 2002) and does not require prediction of action or awareness of outcome. Evidence suggests that the sensory consequences of one's own actions are identified and attenuated (Blakemore, Wolpert, & Frith, 2000), which would distinguish one's active and passive conditions. Thus, forward model theories propose that the brain predicts the next sensory state on the basis of its current state and active motor commands (e.g., Wolpert, Ghahramani, & Jordan, 1995). Because no writing motor command is issued in our passive condition, forward prediction should not be engaged. Thus, according to this model, passive movement should not interfere with perception in this task.

Separating intentional (active) and unintentional (passive) movements during our dual task may help to determine at what level the visual–motor interferences occur. One interesting possibility we addressed in this design is that different types of interference may have different causes. In previous experiments, we observed that interference obeyed a categorical boundary: Writing a letter with a different identity than the letter on the screen could interfere with its perception, but drawing a shape did not, even when it was similar to the letter on the screen. Motor programs are likely to be categorical, whereas proprioception should be domain general. Thus, in the passive condition, bottom-up proprioceptive information may be expected prior to a category assignment and therefore might equally interfere on the perception of letters and shapes. In contrast, categorical interference based on whether the item is a letter or shape may be more top-down, and we would predict categorical interference only when letter writing is intentional, as in our prior experiments. Featural interference, however, may be independent of category assignment and we therefore expected this type of interference under both conditions.

Method

Participants. Participants were again drawn from the undergraduate research pool at Vanderbilt University and received partial course credit for their time. Only right-handed individuals with normal or corrected-to-normal visual acuity participated. Of these participants, 12 were men (mean age = 21.2 years) and 12 were women (mean age = 20.9 years), resulting in 24 total participants. The participants provided written informed consent and were randomly assigned to one of two groups: active motor movement or passive motor movement.

Stimuli. The perceived and drawn stimuli were the same as those used in Experiment 3.

Apparatus. To enable us to compare active versus passive writing and drawing, we constructed an apparatus that allowed an experimenter to move a participant's hand without requiring any knowledge or effort on the part of the participant (Figure 7). The experimenter wore one part of the apparatus while the other part was attached to the participant's hand and wrist. A curtain separated the experimenter from the participant so that the participant could not see what the experimenter was doing. In the passive condition, the experimenter moved his or her portion of the apparatus and the participant's hand thus moved in the same manner. The experimenter either wrote letters or drew shapes depending on the experimental block. In the active condition, the participants still wore the yoked apparatus, but the experimenter did not. However, the apparatus was weighted such that

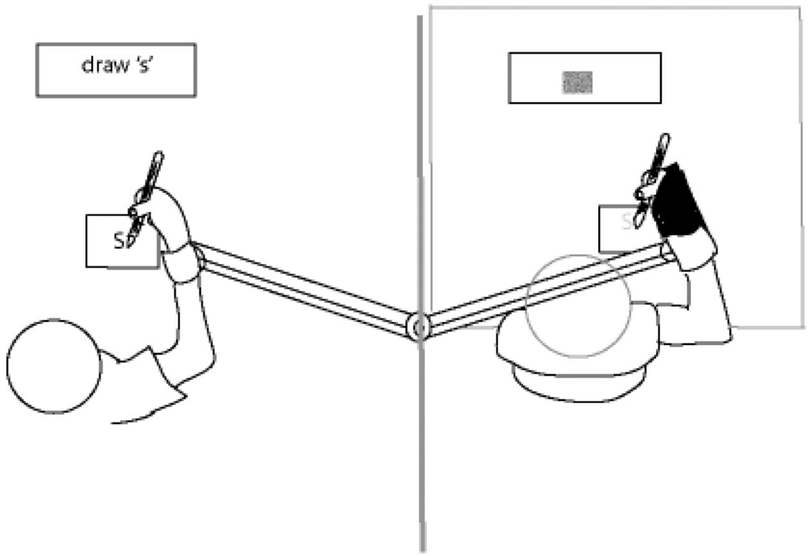

Figure 7. Schematic of the apparatus used in Experiment 4. The experimenter (left) and the participant (right) were separated by a black curtain. The experimenter wrote or drew the stimulus presented to her, which moved the yoking apparatus, moving the participant's hand in the same manner. The participant's hand was placed into a neoprene glove and rested on a small platform, allowing them to relax the hand completely. During the passive condition, the participants relaxed their hand, such that it was moved only by the experimenter. In the active condition, the participants moved their own hand.

the resistance on the participant's hand and arm in both conditions was similar.

Procedure. After initial threshold determination and baseline letter and shape identification tasks (as in previous experiments, mean contrast thresholds for letters—M = .054, SD = .008—and shapes—M = .172, SD = .0192—did not differ between Experiments 3 and 4), the experimenter explained how the yoking apparatus worked. The active and passive conditions were run as a between-participants factor. Both sets of participants were trained in drawing and writing stimuli with the yoking apparatus. The stimuli used during training were different from those used for the actual experiment. Thus, the only difference between groups was that in the active group, participants were told what to write or draw and were required to do so during testing (similar to previous experiments). However, in the passive group, participants were told to try to disregard that their hand was being moved remotely by the experimenter and to simply concentrate on the letter and shape identification task. Participants reported that after an initial familiarization with the apparatus, they were able to disregard their hand movements successfully. Verbal responses were recorded in both conditions by a second experimenter seated in the testing room.

Results and Discussion

We performed a 2 (writing condition [active or passive]) × 2 (seeing category [letters or shapes]) × 2 (writing category [letters or shapes]) × 2 (writing curvature [straight or curvy]) × 2 (seeing curvature [straight or curvy]) mixed-model factorial ANOVA with the write condition (active or passive) run as a between-subjects factor. All other factors were within participant.

Results from this ANOVA revealed significant main effects of seeing category (letters or shapes), $F(1, 24) = 58.2$, $p < .0001$, and writing category, $F(1, 24) = 3.9$, $p < .05$. There were no main effects of the curvature dimension and, it is interesting to note, there was no significant main effect of the writing condition (active $M = 2.3$; passive $M = 1.9$) on perception.

Also interesting, although not expected, was that writing condition (active or passive) and writing category (letters or shapes) interacted. Although drawing letters interfered more with perception (active $M = 2.8$; passive $M = 2.8$) than did drawing shapes (active $M = 1.8$; passive $M = 0.99$), $F(1, 24) = 3.9$, $p < .05$, only drawing letters was sensitive to the writing condition, with more interference in the active condition. As expected, there was an interaction between seeing letters or shapes and drawing letters or shapes, $F(1, 24) = 23.3$, $p < .0001$. When letters were identified, there was more interference from writing letters ($M = 5.7$) than from drawing shapes ($M = 2.4$), but when shapes were perceived, there was no interference from letter writing ($M = -0.13$) or from drawing shapes ($M = 0.39$). This result replicates findings from Experiment 3. A five-way interaction between all of our factors, $F(1, 24) = 5.2$, $p < .03$, also surfaced, but because there was clearly no interference from writing when shapes were viewed (as evidenced in the four-way interaction above), we ran an additional four-factor ANOVA (writing condition [active or passive] × writing category [letters or shapes] × writing curvature [curvy or straight] × seeing curvature [curvy or straight]), excluding the shape perception condition. As depicted in Figure 8, the overall interference in this experiment was less than that in Experiments 2 and 3 but quite similar to that in Experiment 1. The variability in the amount of interference may stem from a combination of slightly lower baseline measures in this experiment than in Exper-

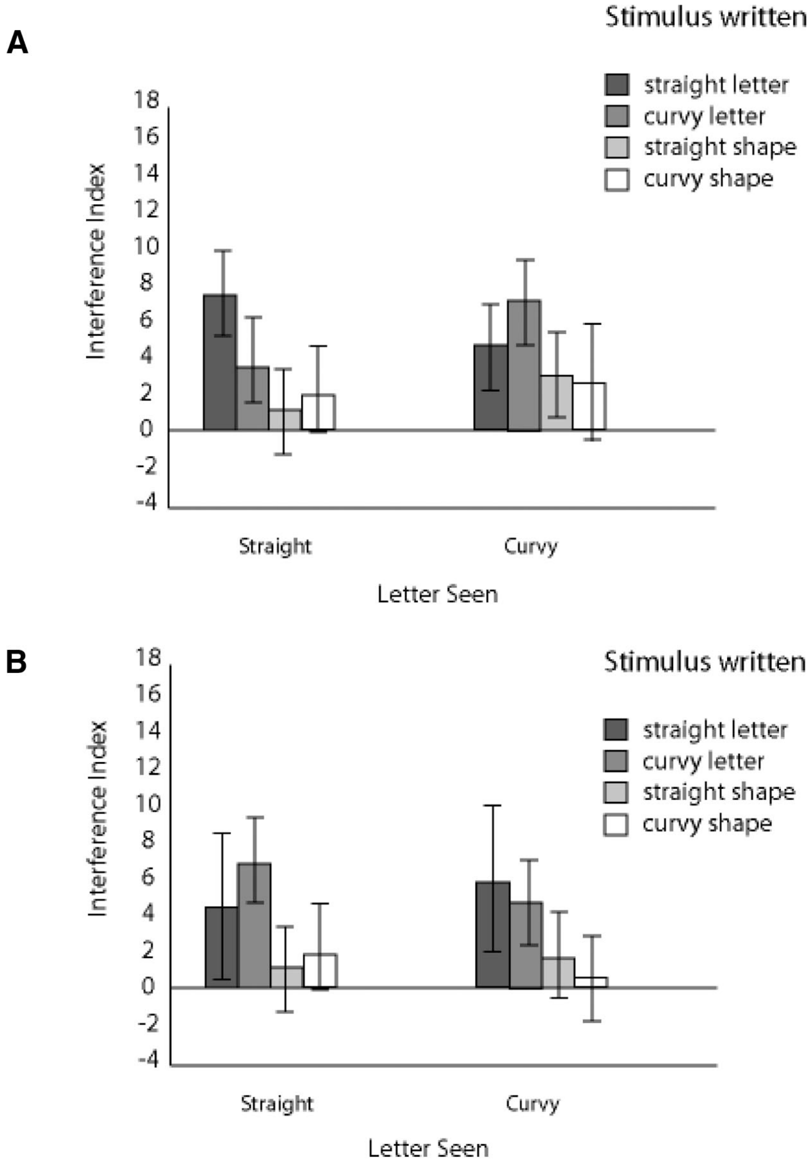

Figure 8. A: Amount of interference plotted as a function of letter seen in the active condition in Experiment 4. B: Amount of interference plotted as a function of letter seen in the passive condition in Experiment 4. Error bars represent 95% confidence intervals of the comparison with zero.

iments 2 and 3 together with slightly better performance in the letter-writing dual tasks (see the Appendix). Critically, the pattern of interference obtained in the active condition is the same as in all of our other experiments.

The results of this ANOVA revealed only one main effect, that of writing category, letters or shapes, $F(1, 48) = 20.4$, $p < .0001$. In addition, the only significant interaction was a three-way interaction between writing category, writing curvature, and seeing curvature, $F(1, 48) = 4.4$, $p < .05$. A two-way ANOVA revealed no effect of writing category on shape perception, $F(1, 34) = 0.69$, *ns*, unlike the effect on letter perception, $F(1, 34) = 7.9$, $p < .05$. Figure 8 depicts this effect: There was much less interference on letter perception for both groups when shapes were drawn than when letters were written.

The active and passive conditions were similar in that they both produced significant interference from letter writing but little, if any, interference from shape drawing. This could happen if in the passive condition, participants recognized what their hand was made to draw or write or at least recognized it was more or less similar to writing letters. It is interesting that this effect does not have to occur very rapidly, because in our design it is impossible to tell if interference on perception comes from the simultaneously performed action or from previously performed actions. Depending on the temporal dynamics of the effect in the active condition, for instance, if the proprioceptive feedback is categorized and then interferes, then the same effect could occur in the passive condition. Our experiment does not allow us to determine the temporal dynamics of the interference or to determine the specific locus of the interference common to both the passive and the active conditions. The fact that some interference can be obtained at all during the passive condition is interesting and argues against strategic factors being in cause. Nonetheless, the active versus passive manipulation is most informative when it comes to the differences obtained in these conditions, to which we turn to next.

The active condition showed a robust congruency effect. Writing straight letters interfered more with perception of straight letters than did writing curvy letters, $t(24) = 3.2$, $p < .01$, and writing curvy letters interfered more with the perception of curvy letter than did writing straight letters, $t(24) = 2.0$, $p < .05$ (see Figure 8A). But when participants were identifying shapes, there was little interference from the concurrent motor task. In the passive condition (see Figure 8B), however, the congruency effect was absent. Writing straight or curvy letters did not differ in their interference effect on straight letter perception, $t(24) = 0.5$, *ns*, nor did they differentially affect curvy letter perception, $t(24) = 0.34$, *ns*. In sum, in the active condition, both categorical and featural similarity governed interference, whereas in the passive condition, there was only a categorical influence. These results were unexpected but are informative. First, they suggest that the categorical and featural effects have distinct origins and, second, it suggests that some aspect of intentional writing movements underlie the featural effect. We note that it is possible that the lack of a featural effect in the passive condition could be due to proprioceptive noise added by the apparatus and could render the specific features less distinctive.

An additional conclusion emerges from this experiment: Verbal rehearsal of the letters is probably not contributing to the interference effects we observed. This conclusion is based on the assumption that in the passive condition, participants were not rehearsing the letters because they did not know what the items were. Although participants reported not knowing what they were writing, it is still possible that they did know and were unaware of some degree of verbal rehearsal in this condition. This account seems relatively implausible, as it requires unconscious verbal rehearsal of items whose identity the participants claim not to know under conditions where rehearsal would not be beneficial to performance. In addition, when we analyzed the types of errors that participants committed, they were never an intrusion from the written stimulus, which would be expected if the participants were verbally rehearsing the written letters. Errors were almost all from visually similar letters (i.e., 90%), many of which were in the stimulus set (e.g., *F* for *H* and *U* for *O*; i.e., 80% of the 90%). The remaining 10% of errors were from other, visually dissimilar letters.

General Discussion

In a series of studies, we have begun to characterize how action interacts with perception during object recognition. Here, we looked at recognition of objects with which people have extensive experience. Further, this experience is multisensory and sensorimotor: Letters are seen, written, typed, read, and heard. We found that writing interferes with letter perception in an interfering manner: Letter perception was worse during concurrent writing. We also found that writing did not interfere with shape perception: Therefore, the interference effect was stimulus specific. We assume here that this specificity is due to people's experience writing letters. Interference was modulated both by stimulus category and by perceptual similarity, and these two contributions were dissociated in Experiment 4. The categorical effect was obtained in both active and passive conditions, while interference was constrained by featural similarity only in the active condition. Our finding of category-specific interference in a passive condition where no motor commands were required suggests a potential role of proprioception in our effects. The role of proprioceptive feedback on movement execution is controversial (Pipereit, Bock, & Vercher, 2006), as motor movements can be performed without sensory feedback (Christensen et al., 2007). However, proprioceptive feedback is generally compared with motor commands after a movement, to verify the quality of execution. Whether the proprioceptive feedback in our passive condition may have reactivated previously stored motor commands is unknown, but this leaves open the possibility that interference arose from motor stages even in the passive condition. Although prior functional magnetic resonance imaging work reported motor areas engaged during letter perception (K. H. James & Gauthier, 2006; Longcamp, Anton, et al., 2005, 2006), the studies were motivated by a search for motor–visual interactions and did not target the distributed network of cortical and subcortical areas that has been involved in proprioception (Kavounoudias, Roll, & Roll, 1998). The present findings would motivate further investigation in disentangling the respective influences of motor commands and proprioception in the perception of letters.

Our results add to the growing body of literature on the intimate relationship among the visual and motor systems reflected by action–perception interactions. Here, we find evidence consistent with the idea that motor activity occurring during letter perception (K. H. James & Gauthier, 2006) is not epiphenomenal but has a functional role in the visual perception of letters. This relationship between writing and letter perception appears to depend on experience, as we find little evidence for the same link between shape perception and drawing. Unlike many stimuli used in other studies, such as tools or kitchen utensils (Chao & Martin, 2000; Grezes & Decety, 2002), letters do not, in themselves, suggest a specific motor act. The relationship between a movement and the visual perception of a letter is learned through extensive experience. Previous work has shown that writing practice can facilitate later visual recognition (Bartolomeo et al., 2002; Longcamp, Anton, et al., 2005), and here we unravel the opposite side of the equation: The systems are so closely linked that they can interfere with one another if the movement and the perception do not exactly match.

It has been shown that people's knowledge of how letters are written influences the way in which the letters are perceived (e.g., Freyd, 1983; Knoblich, 2008; Knoblich et al., 2002; Orliaguet et al., 1997; Tse & Cavanagh, 2000). Our results suggest that the relationship between writing and reading goes beyond stored knowledge and can have an online influence. This is consistent with the idea of a multimodal representation for letters, reminiscent of Barsalou's theory of perceptual symbol systems (Barsalou, Simmons, Barbey, & Wilson, 2003). Our result can also be interpreted in light of the *common-coding* hypothesis. In this framework, event codes and action codes share the same representation, allowing for interference (Prinz, 1997). Here, we further specify in what ways the action and the percept must resemble each other to access the same representation and produce interference. Previous work has documented that interference can occur when action is produced concurrently with perception. We show that the magnitude of the interaction between action and perception depends on (a) whether the stimuli are from an overlearned category, (b) whether the stimuli share perceptual features, and (c) whether the movements are intentional.

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Appendix

Mean and Standard Deviations of All Raw Scores in the Experiments

			Write condition							
	Baseline		Straight letters		Curvy letters		Straight shapes		Curvy shapes	
See condition	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Experiment 1										
Straight letters	77.7	2.2	67.5	2.5	73.7	2.0	74.1	2.8	75.9	2.2
Curvy letters	75	3.0	71.6	2.4	67.8	2.0	73.4	2.7	72.7	2.2
Experiment 2										
Straight letters	78.7	3.2	63.2	3.5	74.7	2.1	68.1	2.2	74.9	2.3
Curvy letters	77	2.4	73.4	2.7	65.8	1.9	74.4	2.0	71.3	2.6
Experiment 3										
Straight letters	76.7	2.2	60.7	2.5	72.7	2.0	75.1	1.9	74.8	2.1
Curvy letters	75	2.1	70.2	2.0	63.5	2.2	72.4	2.2	69.3	3.1
Straight shapes	75.0	2.0	74.0	1.6	73.0	2.7	75.3	2.9	73.5	2.9
Curvy shapes	75.4	2.1	72.5	2.0	72.2	2.5	74.6	2.7	74.3	2.4
Experiment 4										
Active										
Straight letters	74.7	2.7	67.2	2.1	71.3	2.6	73.8	2.4	72.4	2.6
Curvy letters	74.0	2.8	70.2	2.3	67.5	2.8	71.4	2.5	72.1	2.7
Straight shapes	74.2	2.5	74.2	1.6	74.5	2.2	74.3	2.0	74.9	2.7
Curvy shapes	73.9	2.4	74.0	2.2	73.2	2.3	73.1	2.0	73.0	2.1
Passive										
Straight letters			70.7	2.9	68.7	2.0	73.1	2.9	73.8	2.5
Curvy letters			69.2	2.6	70.5	2.3	72.4	2.5	73.3	2.1
Straight shapes			74.0	2.6	74.5	2.3	74.1	1.3	74.6	1.7
Curvy shapes			74.3	1.9	73.2	2.1	73.5	1.5	73.2	2.1

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