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The Devil's in the g-Tails: Deficient Letter-Shape Knowledge and Awareness Despite Massive Visual Experience

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Knowledge of letter shapes is central to reading. In experiments focusing primarily on a single letter shape—the "looptail" lowercase print *G*—we found surprising gaps in skilled readers' knowledge. In Experiment 1 most participants failed to recall the existence of looptail *g* when asked if *G* has two lowercase print forms, and almost none were able to write looptail *g* accurately. In Experiment 2 participants searched for *G*s in text with multiple looptail *g*s. Asked immediately thereafter to write the *g* form they had seen, half the participants produced an "opentail" *g* (the typical handwritten form), and only one wrote looptail *g* accurately. In Experiment 3 participants performed poorly in discriminating looptail *g* from distractors with important features mislocated or misoriented. These results have implications for understanding types of knowledge about letters, and how this knowledge is acquired. For example, our findings speak to hypotheses concerning the role of writing in learning letter shapes. More generally, our findings raise questions about the conditions under which massive exposure does, and does not, yield detailed, accurate, accessible knowledge. In this context we relate our findings to studies showing poor knowledge or memory for various types of stimuli despite extensive exposure.

Public Significance Statement

Knowledge about the shapes of letters is critical for reading. This study investigated skilled readers' letter-shape knowledge, focusing primarily on one specific letter form, the "looptail" form of lowercase G. Looptail g is extremely common in printed materials, but most people never learn to write it. We found that skilled readers were often unable to recall the existence of looptail g, and that their knowledge of the shape was usually incomplete or perhaps even inaccurate. These results contribute to our understanding of how letter shapes are learned (highlighting in particular the role that learning to write may play), and may also have implications for teaching of letters.

Keywords: handwriting, learning, letter recognition, memory, reading

Skilled readers of English have vast visual experience with the 26 letters of the alphabet. We learn to recognize letters in our earliest school years, if not before, and throughout our lives we are constantly processing visual letter stimuli. Letter recognition, a crucial component of reading (e.g., Pelli, Farell, & Moore, 2003), requires computation of the size, shape, location, and orientation of the visual features making up a stimulus letter, to generate a perceptual letter shape representation adequate for distinguishing visually similar letters (e.g., r/n, C/G). Readers must also have knowledge of letter shapes stored in memory, allowing recognition to be accomplished by matching the perceptual representation of a stimulus letter to a stored letter shape representation. Intuition suggests that knowledge of letter shapes is not only detailed and accurate, but also explicit and highly accessible. For example, if asked to call to mind the commonly encountered forms of a letter (e.g., b and B for the letter *B*), skilled readers would presumably not have any doubts about their ability to do so.

In the present article we question these seemingly straightforward assumptions about knowledge of letter shape. We report results showing surprising gaps in skilled readers' letter-shape knowledge, and in their ability to access this knowledge. Our results center on a very common form of lowercase print *g*, illustrated in the upper left portion of Figure 1, and referred to by typographers as looptail *g*. When people write a lowercase *g* in print (as opposed to cursive) format, they produce a form referred to as opentail *g* (Figure 1, upper right). However, in printed materials, including both adults' and children's books, the looptail form is dominant. We randomly sampled books from the shelves of several public libraries, selecting 100 books in each of three categories: (a) adult fiction and nonfiction, (b) children's picture books, and (c) children's chapter

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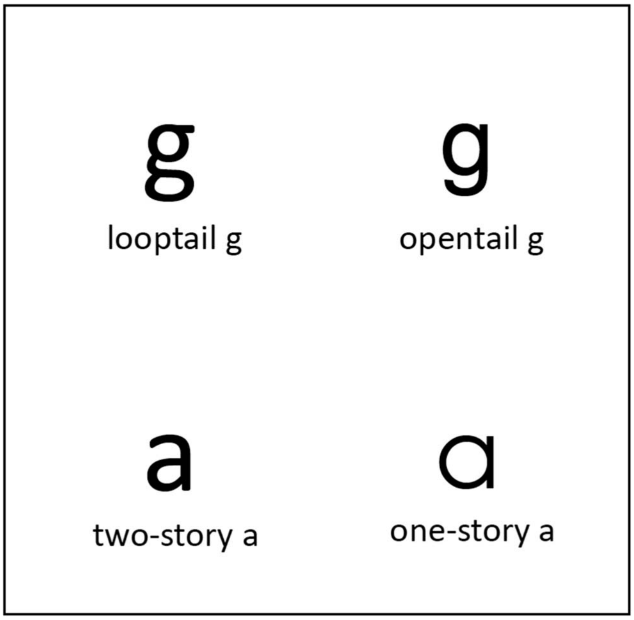

Figure 1. The looptail and opentail forms of lowercase print *g*, and the two-story and one-story forms of lowercase print *a*.

books (i.e., books for beginning and intermediate readers). For each book we tallied whether the lowercase *g*s were looptail or opentail *g*s. In all three categories, looptail *g* was far more common than opentail *g*, appearing in 74% of the children's picture books, 89% of the children's chapter books, and 97% of the books for adults.

In subsequent discussion we refer to looptail *g* and opentail *g* as *allographs* of the letter *G*—that is, distinct letter shapes corresponding to the same letter identity. *G* also has other allographs, including uppercase print *G* as well as upper and lower case cursive *G*s.

Like the letter *G*, the letter *A* has two lowercase print allographs, shown in the bottom half of Figure 1. One-story *a* is the typical handwritten form, but two-story *a* is overwhelmingly more frequent in printed materials. In our sampling of library books, two-story *a* appeared in 89% of the children's picture books, 96% of the children's chapter books, and 100% of the books for adults.

By the time they reach adulthood, literate individuals clearly have had massive experience in recognizing looptail *g*s and two-story *a*s. Nevertheless, we demonstrate in three experiments that skilled adult readers frequently fail on simple tasks probing knowledge of looptail *g*, and also evidence some—although considerably less—difficulty with two-story *a*. We discuss potential explanations for our results, and also explore the theoretical and potential educational implications within and beyond the domain of letters. In addition, we relate our results to previous findings (e.g., Nickerson & Adams, 1979; Jones, 1990; Rinck, 1999; Snyder, Ashitaka, Shimada, Ulrich, & Logan, 2014) showing limited knowledge despite extensive experience (e.g., knowledge about the facing direction of profiles on coins, or about the locations of keys on a keyboard).

Experiment 1

In this experiment we asked participants a series of questions about the forms of lowercase print letters, providing opportunities for the participants to report knowledge about looptail *g* and two-story *a*. For participants who failed to reveal knowledge of these allographs under general questioning, we asked progressively more pointed and leading questions.

Method

Participants. Thirty-eight undergraduate students at Johns Hopkins University (14 male, 24 female; mean age 19.5 years, range 18–22) participated in exchange for extra credit in courses. In this experiment, and in the subsequent experiments we report, English was the first language of instruction for all participants, and no participant had been diagnosed with dyslexia, dysgraphia, or other learning disability. Participants in all experiments gave informed consent in accordance with procedures approved by the Homewood Institutional Review Board at Johns Hopkins University. For all experiments, we had no firm basis for determining optimal sample sizes in advance, given the absence of previous research on the topic and the fact that our conclusions hinge upon largely qualitative patterns in the data, rather than requiring precise numerical estimates of population values. Accordingly, in each experiment we simply tested all of the participants we were able to recruit within a predetermined period of time (4 weeks for Experiment 1, and 2 weeks for Experiments 2 and 3).

Procedure. Participants, who were tested individually, were first told that letters can have multiple forms, even within the same case (upper or lower) and style (print or cursive). Uppercase print *J* was named as an example, and participants were asked if they could write the two forms. (Uppercase print *J* occurs either with or without a horizontal stroke at the top.) The majority of participants (27/38) were able to recall and produce both uppercase allographs of *J*. The remaining 11 participants were shown the two allographs. All 11 confirmed their familiarity with both forms, and indicated that they understood the notion of distinct forms of a letter.

Questions were then posed about lowercase print letters in a three-phase procedure:

1. Participants were asked whether they could think of any letters that had two distinct forms in lowercase print. Instructions stressed that we were looking for letter forms with clearly different shapes (like the two forms of *J*), and not minor font variations (e.g., serif vs. sans serif forms). Participants were also reminded that cursive and uppercase forms were not to be considered. For each letter named by the participant, he or she was asked to write the two forms. Participants who wrote a cursive letter as one of the forms were reminded that the question concerned print and not cursive forms, and were asked to try again to produce two distinct print forms of the letter. Cursive responses were not counted in scoring of results. (The same procedure was followed in subsequent phases when participants wrote cursive forms of letters.)

2. If either the letter *A* or the letter *G* was not named in phase 1, the experimenter read a list of letters (*B, G, N,*

Table 1
Number of Participants Who Acknowledged Existence of, and Were Able to Write, the Looptail g Allograph in Experiment 1

Phase of experiment	Number of participants[a]	Acknowledged two forms	Wrote correctly
1: Name letters with two forms	38	2	0
2: Does lowercase print *g* have two forms?	36	6	0
3: Told lowercase print *g* has two forms	30	12	1
Total	38	20	1

[a] Participants who reported knowledge of two lowercase print *g* forms in phase 1 or 2 were not tested in subsequent phases.

A, R) one by one, and participants were asked to say for each letter whether it had multiple forms in lowercase print (the correct answer being "yes" only for *G* and *A*). For each "yes" response, participants were asked to write the two forms. For participants who had named one of the letters *A* and *G* in phase 1, that letter was omitted from the list in phase 2.

3. Participants who responded "no" in phase 2 to *A*, *G*, or both were told that the letter has two forms, and were asked to write the two forms.

Finally, all participants—regardless of their responses in the preceding phases—were shown both forms of lowercase print *a* and both forms of lowercase print *g*. For each letter they were asked whether they recognized both forms, and whether they had seen both before. In addition, participants were asked whether they had ever written two-story *a* or looptail *g* prior to the experiment.

Results

Tables 1 and 2 present the principal results from the three main phases of the experiment. We first discuss the findings for *G*, and then turn to *A*.

Lowercase print g. In phase 1, participants were asked to name letters that have two forms in lowercase print, and to write both forms of these letters. Only 2 of the 38 participants (5%) named the letter *G*, and neither wrote the looptail g accurately.[1] Figure 2 presents examples of participants' attempts at writing looptail *g* in the various phases of the experiment.

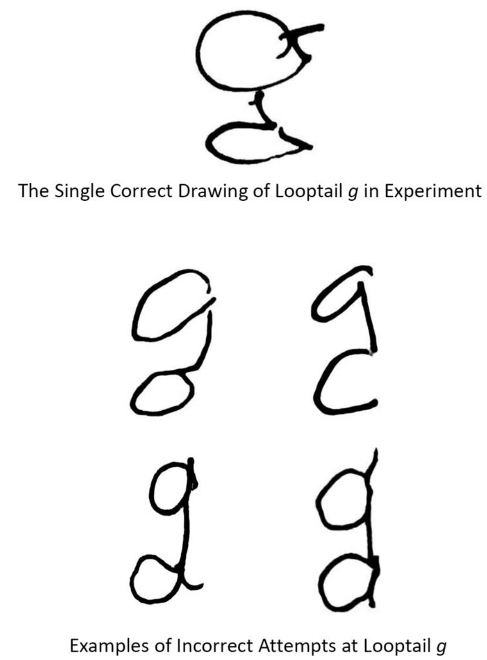

Figure 2. The single correct production of looptail g in Experiment 1, and four examples of incorrect attempts. Note that in the incorrect examples the tail is misplaced, and most of the incorrect examples are also missing the 'ear.' In the single written response we (generously) scored as correct, the overall shape is acceptable, although the lower loop is drawn counterclockwise rather than following a clockwise path as in well-formed looptail *g*s (see Figure 1).

In phase 2, the 36 participants who failed to name *G* in phase 1 were asked about a series of letters, including *G*, and asked to indicate for each letter whether the letter had two forms in lowercase print. Only 6 of the 36 participants stated that *G* has two lowercase print forms, and none of these participants produced looptail *g* accurately when asked to write both forms.

In the third phase, the 30 participants who had thus far failed to demonstrate knowledge that *G* has two lowercase print forms were informed of this fact, and asked to write the two forms. Even after being told directly that *G* has two distinct forms in lowercase print, 18 of the 30 participants were unable to recall having seen more than one form of lowercase print *g*, and so could not attempt to write the looptail *g*. The remaining 12 participants acknowledged having some recollection of two lowercase print *g* forms, and made an attempt at writing looptail *g*. However, only 1 of the 12 participants wrote a looptail *g* that could be considered correct.

Table 2
Number of Participants Who Acknowledged Existence of, and Were Able to Write, the Two-Story a Allograph in Experiment 1

Phase of experiment	Number of participants[a]	Acknowledged two forms	Wrote correctly
1: Name letters with two forms	38	22	22
2: Does lowercase print *a* have two forms?	16	5	4
3: Told lowercase print *a* has two forms	11	3	3
Total	38	30	29

[a] Participants who reported knowledge of two lowercase print *a* forms in phase 1 or 2 were not tested in subsequent phases.

[1] Attempts at writing looptail *g* were scored incorrect if any of the major features of the shape were missing, malformed, or misplaced. Specifically, we scored for: (a) a closed upper loop; (b) a lower loop, either closed or open to the left; (c) a line connecting the loops, either straight or curved counterclockwise from top to bottom, and attached to the lower half of the upper loop anywhere except the far right side; and (d) a straight or curved 'ear' attached to the upper right quadrant of the upper loop.

The other 11 participants produced responses that resembled looptail *g*, but were incorrect on one or more of the major features.

These results may be summarized succinctly: Despite being questioned repeatedly, and despite being informed directly that *G* has two lowercase print forms, nearly half of the participants (18/38) failed to reveal any knowledge of the looptail *g* allograph, and only 1 of the 38 participants was able to write looptail *g* correctly.

When shown the two lowercase *g* allographs at the end of the experiment, all 38 participants recognized, and acknowledged having seen, the looptail *g* (and also, of course, the opentail *g*). However, none of the participants reported attempts at writing looptail *g* prior to the present experiment.

Lowercase print a. Performance was better, although not perfect, for the letter *A* (see Table 2). When asked in phase 1 to name letters with two lowercase print forms, 22 of the 38 participants (58%) named *A*, and all of these participants wrote both the one-story and two-story allographs correctly. In phase 2, the 16 participants who failed to name *A* in phase 1 were specifically asked if A has two lowercase print forms. Five responded yes, and 4 of the 5 wrote both forms correctly; the remaining participant erred in writing the two-story allograph. In the third phase, the 11 participants who had not yet demonstrated knowledge of two-story *a* were told that *A* has two forms in lowercase print. Three of these participants then acknowledged familiarity with two forms, and succeeded in writing both. By the end of phase 3, 30 of the 38 participants (79%) had demonstrated knowledge of two-story *a*, whereas 8 (21%) had not, despite repeated opportunities to do so.

At the end of the experiment all the participants recognized both lowercase *a* allographs, and 24 (63%) reported writing the two-story form sometime prior to the experiment. Recall and writing of two-story *a* during the experiment was slightly better for participants who reported writing the two-story form previously than for those who reported no prior experience in writing the allograph. For example, 67% of the prior-writing participants but only 43% of the no-prior-writing participants reported in phase 1 that *A* has two lowercase print forms. However, none of the differences between the two participant subgroups approached significance.[2]

Discussion

As a framework for interpreting the results, we illustrate in Figure 3 a set of basic assumptions about knowledge of letters, and the use of this knowledge in various letter processing tasks (e.g., Caramazza & Hillis, 1990; Grainger, Rey, & Dufau, 2008; Schubert & McCloskey, 2013). We assume that literate individuals have several types of knowledge about letters, linked to an abstract, amodal representation of the letter's identity (e.g., Friedman, 1980; Rapp & Caramazza, 1997; Rothlein & Rapp, 2014). First, readers have stored knowledge about the shapes of the various allographs of a letter. Figure 3 illustrates the two lowercase print allographs of *G* (opentail and looptail); uppercase and cursive allographs are omitted to avoid cluttering the figure. The allograph representations play a critical role in visual letter recognition. When a letter stimulus is presented, the corresponding allograph representation is activated, leading in turn to activation of the abstract letter identity (e.g., Grainger et al., 2008; Schubert & McCloskey, 2013).

Also associated with the letter identity representation is the letter name (e.g., /ʤi/ for the letter *G*). A spoken letter name will activate the stored letter name representation, leading to activation of the letter identity representation (e.g., Schubert & McCloskey, 2015). For letter forms an individual has learned to write, the abstract letter identity is also linked to a stored *graphic motor plan* that specifies a sequence of writing strokes for producing the appropriate shape (e.g., Ellis, 1982, 1988; Margolin, 1984; van Galen, 1991). In writing, abstract identity representations for to-be-written letters are activated, leading in turn to activation of graphic motor plans, and ultimately to production of writing movements.

In the case of looptail *g*, we assume that stored knowledge will usually not include a graphic motor plan, because very few individuals have learned to write this allograph. Similarly, individuals who have not learned to write two-story *a* would not have a stored graphic motor plan for the two-story allograph. The absence of a previously learned graphic motor plan does not necessarily mean, however, that a character cannot be written. We assume that a graphic motor plan can be generated online from stored knowledge of a character's shape—that is, from the stored allograph representation. For example, a person who is familiar with the shape of two-story *a*, but has never written it, could presumably generate and execute a graphic motor plan for writing the character. The plan might not be highly efficient, but should suffice to produce the shape accurately. Of course, writing via online generation of a motor plan can succeed only given sufficiently detailed and accurate knowledge of the character shape, and the ability to access that knowledge for purposes of creating the motor plan.

These assumptions provide a basis for interpreting the results from Experiment 1. Consider first the results for the letter *G*. When shown a looptail *g* at the end of the experiment, all participants indicated that they were familiar with the allograph, and recognized it as a *G*. Furthermore, we can reasonably assume that all of the participants were able to recognize (i.e., identify as *G*s) the looptail *g*s they encountered in their everyday reading. These observations imply that for all participants, knowledge of the letter *G* included a looptail *g* allograph representation, and that all participants, upon encountering a looptail *g*, were able to activate the looptail allograph representation, leading in turn to activation of the {G} letter identity representation.

Nevertheless, two results from Experiment 1 point to gaps in participants' knowledge about looptail *g*, and/or their ability to activate and use this knowledge. The first result concerns failure to recall the existence of the looptail *g* allograph. Only 2 of the 38 participants mentioned *G* when asked to list letters with two lowercase print forms; and even after being told that lowercase print *g* has two forms, almost half of the participants were unable to recall having seen a form other than opentail *g*.

The difficulty participants evidenced in recalling looptail *g* suggests that they frequently failed to activate the looptail *g* allograph representation from the abstract letter identity. Consider,

[2] Tests for differences between participants who had and had not previously written two-story *a* had adequate power for detecting medium effect sizes. For example, the analysis of the phase 1 result mentioned in the text had the power to detect an effect size of 0.5 with a likelihood of 87%.

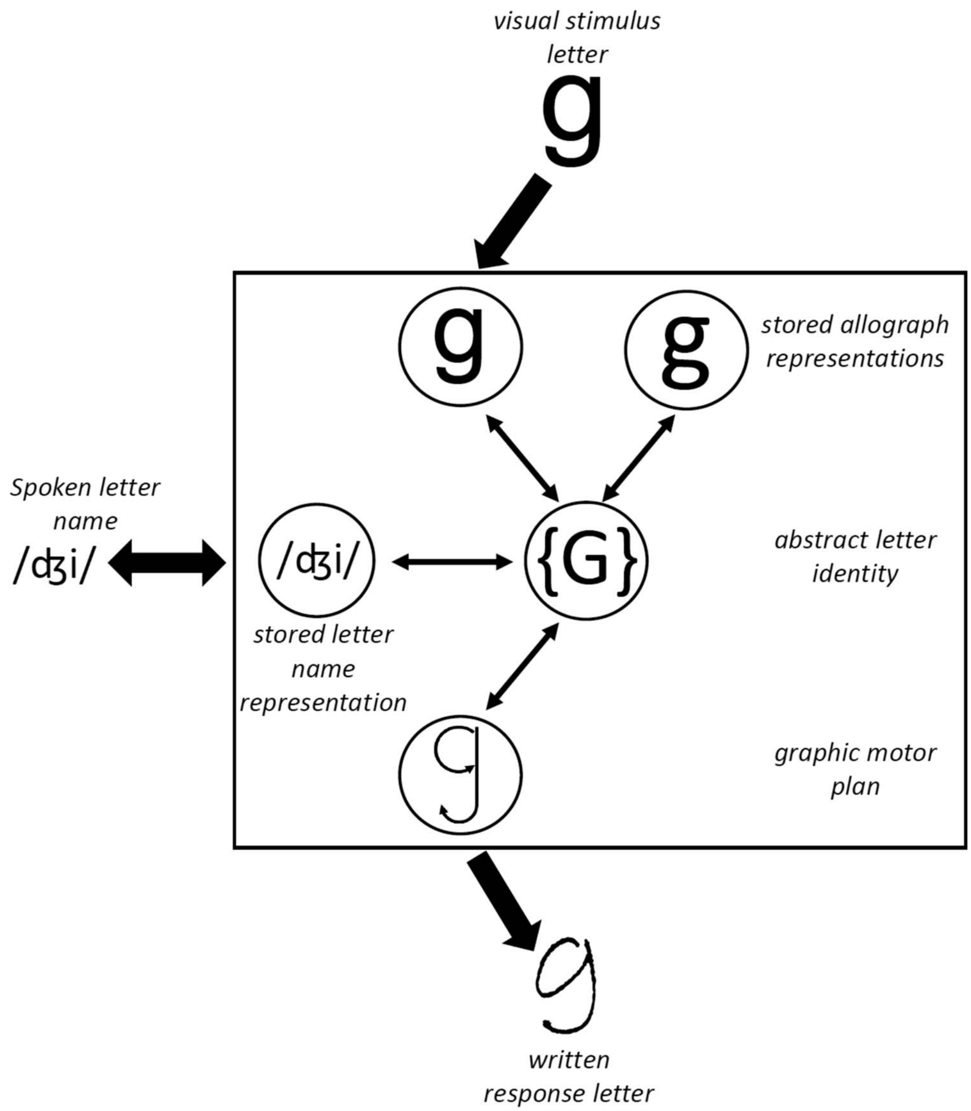

Figure 3. Schematic illustrating the various forms of stored knowledge about letters, and the use of this knowledge in letter recognition and writing.

for example, phase 2 of the experiment, in which participants were asked whether *G* has two lowercase print forms. We assume that the spoken letter name /ʤi/ activated the abstract letter identity {G}, leading to activation of the opentail *g* allograph representation (see Figure 3). Apparently, however, the looptail *g* allograph representation was often not activated, with the result that participants often failed to recall that lowercase print *g* takes more than one form. The frequent activation failures suggest that, even for skilled readers, the link from the {G} letter identity representation to the looptail *g* allograph representation is often weak.

The second result bearing on knowledge of looptail *g* is the failure of nearly all participants to write looptail *g* accurately. None of our participants reported having attempted to write looptail *g* prior to the experiment, implying that none had a stored graphic motor plan for this allograph. Consequently, attempts to write looptail *g* presumably required using the stored allograph representation to create a graphic motor plan online.

The 18 participants who consistently failed to recall the existence of looptail *g* apparently never activated the looptail allograph representation, and so were of course unable to write the looptail *g*. The more interesting results come from the 20 participants who evidenced awareness of two lowercase print *g* forms. Why did 19 of these 20 participants fail to produce an accurate written rendition of looptail *g*? One possibility is that despite reporting some recollection of two lowercase print *g* allographs, the participants did not in fact activate any specific knowledge about looptail *g*. Perhaps, for instance, they simply had some vague sense that they had seen a lowercase *g* form other than opentail *g*. However, all of the incorrect written responses clearly bore some resemblance to looptail *g* (see examples in Figure 2), implying that the responses were based at least in part on stored knowledge about the looptail allograph.

The erroneous written responses could conceivably have resulted from incomplete activation of the looptail *g* allograph representation, or difficulty in translating the rather complex looptail shape into a graphic motor plan. However, another possibility is that despite their ability to recognize looptail *g*s in reading, many if not most skilled readers lack detailed and accurate knowledge of the allograph's shape. Perhaps, for instance, the allograph representation typically specifies little more than two loops, one above the other, with a connecting line somewhere in between. This sort of underspecified shape representation might be adequate for distinguishing looptail *g*s from other letters in the course of reading, but is not sufficient to support accurate writing of the allograph.

In 16 of the 19 incorrect attempts at writing looptail *g*, the line connecting the upper and lower loops was placed on the far right side of the letter (see examples in Figure 2). This result could conceivably reflect systematic inaccuracy in many participants' looptail allograph representations. However, the finding is also consistent with an underspecified representation of the sort suggested above. Given an allograph representation that failed to specify the precise location of the connecting line, participants may have opted to place it in the same location as the descending vertical stroke in opentail *g*.

Thus far we have assumed that participants' responses concerning forms of letters and, in the case of looptail *g*, their attempts to write letters, were mediated by the same stored allograph representations that underlie letter recognition in reading. However, another possibility is that the allograph representations are not accessible to awareness, and cannot be used to answer questions about letter shapes, or to create graphic motor plans for writing letters. If this were the case, the results of Experiment 1 would not speak to the letter knowledge that mediates reading, but instead to some other type(s) of knowledge about letters. We address this possibility in Experiment 3, with a visual letter recognition task that more straightforwardly probes the allograph representations implicated in reading.

Consider finally the results for two-story *a* in Experiment 1. In each phase of the experiment some participants failed to recall the existence of two-story *a*, suggesting that they failed to activate the two-story allograph representation. However, these failures were far less frequent than for looptail *g*. By the end of phase 2, for example, 27 participants had reported knowledge of two lowercase print forms for the letter *A*, but only 8 had done so for the letter *G*, $\chi^2(1, N = 76) = 19.12$, $p < .001$. Furthermore, 29 of the 30 participants who attempted to write two-story *a* rendered the character accurately, whereas only 1 of the 20 participants who tried to write looptail *g* produced an acceptable rendition, $\chi^2(1, N = 50) = 42.01$, $p < .001$. The fact that some participants had prior experience in writing two-story *a* may play some role in accounting for these differences. As we have seen, however, participants with and without prior two-story *a* writing experience did not differ significantly on the two-story *a* tasks in Experiment 1. In the General Discussion we consider in greater detail the potential reasons for differences in performance between looptail *g* and two-story *a.*

Experiment 2

In this experiment we asked whether repeatedly attending to looptail *g* would enable participants to recall having seen the looptail allograph, and to write it correctly. Participants were asked to search for *G*s in a printed paragraph that included multiple instances of the looptail allograph. This task required not only attending to looptail *g* stimuli, but also identifying these stimuli as exemplars of the letter *G*. Immediately after completing the G-search task, participants were asked to write the form of *G* they had seen.

A participant who retains, even briefly, at least some episodic memory for the form of *G* in the paragraph should produce a written response that clearly resembles looptail *g*—in other words, a response that clearly represents an attempt at writing looptail *g*. If the episodic memory is sufficiently detailed and accurate—or if the participant has a stored looptail *g* allograph representation that is detailed, accurate, and accessible, perhaps as a result of performing the task—then the attempt at writing looptail *g* should be successful.

Method

Sixteen undergraduate students at Johns Hopkins University (6 male, 10 female; mean age 19.8, range 18–21) participated in exchange for extra credit in courses. None had participated in Experiment 1.

Participants were asked to read a 91-word paragraph printed on paper in Times New Roman Font, which uses the looptail *g* allograph. The paragraph contained 14 looptail *g*s and one uppercase *G*. Participants read the paragraph silently, except when they encountered a word containing the letter *G*, in which case they read the word aloud. All participants performed well in detecting *G* words, with few or no omissions.

Immediately after participants finished reading, the experimenter removed the paragraph, and asked participants to write lowercase *g* in the form they had seen in the paragraph. Participants were asked to replicate the form they had just observed as closely as possible.

Results and Discussion

Immediately after searching for *G*s in a paragraph with multiple looptail *g*s and no opentail *g*s, fully half of the participants (8/16) wrote opentail *g* when asked to produce the form appearing in the paragraph. Seven of the remaining 8 participants produced an incorrect shape bearing some resemblance to looptail *g*, and only 1 of the 16 participants succeeded in writing looptail *g* correctly.

The participants who wrote opentail *g* apparently had no recollection of having seen the looptail allograph, and simply took for granted that they had seen the form that most readily came to mind when they thought about lowercase print *g* (i.e., the opentail form). One participant seemed to think that writing opentail *g* was the only conceivable response to the task: When asked to write the *G* she had seen, she said, "This is stupid."

The remaining 8 participants exhibited some memory for the *g* allograph in the paragraph. However, 7 of these 8 participants failed to write the looptail *g* accurately. These participants apparently failed to retain a sufficiently detailed and accurate episodic memory for the looptail *g*s in the paragraph. Furthermore, performing the task evidently did not enhance the completeness, accuracy, or accessibility of their stored looptail *g* allograph representations to an extent sufficient to support accurate writing of the character.

Participants' relatively poor performance in reporting the form of the *G*s is perhaps not entirely surprising, given the many results suggesting that people tend to remember gist rather than surface details of stimuli even after short retention intervals (e.g., Bransford, Barclay, & Franks, 1972; Sachs, 1967). However, our participants did not merely read a text but actively searched for *G*s, and consequently one might reasonably have expected somewhat better memory for the form of the *G*s. We also note that many studies have demonstrated explicit memory for attributes such as the case, color, and orientation of stimulus words, even when participants were not instructed to remember these attributes, and even after delays considerably longer than that in the present experiment (e.g., Hintzman, Block, & Inskeep, 1972; Kolers, 1973; Kolers & Ostry, 1974; Light & Berger, 1976; Meiser & Bröder, 2002). In any event, the results of Experiment 2, in conjunction with those of Experiment 1, raise questions about the types and amounts of experience required to yield detailed, accurate, and accessible knowledge of letter shapes. We will have more to say about these questions in the General Discussion.

Experiment 3

In Experiment 1 we found that nearly all of the participants who attempted to write looptail *g* produced inaccurate renditions. We argued that because most individuals have not learned a graphic motor plan for looptail *g*, attempts to write the looptail allograph require generating a motor plan from the stored allograph representation that underlies letter recognition in reading. To interpret the inaccurate written productions of looptail *g* we suggested that the allograph representation for looptail *g* is often underspecified or even inaccurate. However, as we acknowledged in Experiment 1, participants' attempts to write looptail *g* may conceivably have been based not on the looptail allograph representations implicated in reading, but rather on some other type(s) of letter-shape knowledge. This alternative interpretation can also be applied to the inaccurate written renderings of looptail *g* in Experiment 2, where participants may have relied for their writing attempts on (insufficiently detailed) episodic memories for the appearance of the *G*s in the paragraph they had just read.

In the present experiment we tested participants in a visual letter recognition task that more straightforwardly probes the allograph representations implicated in reading. For looptail *g*, and also two-story *a*, participants were presented with a 4-alternative forced-choice recognition task in which they were asked to select the correct letter shape from among distractors differing in location or orientation of important features.

Method

Participants. Participants were 44 native English-speaking adults (22 male, 22 female; mean age 25.3 years, range 18–53) who had not participated in either of the preceding experiments. Twenty-five participants were tested on looptail *g*, 24 were tested on two-story *a*, and 5 were tested on both letters.

Stimuli and procedure. The four versions of looptail *g* are shown in Figure 4. Version 1 is correct. In Version 2 the tail (the lower loop plus the line connecting the loops) is left-right reversed, with the result that the connecting line is on the wrong side and has reversed curvature; in Version 3 the 'ear' is misplaced; and in Version 4 the entire letter is left-right reversed. The figure also shows the four versions of two-story *a*. Version 1 is correct. In Version 2 the top hook is reversed; in Version 3 the lower straight vertical line segment is reversed; and in Version 4 the entire letter is reversed.

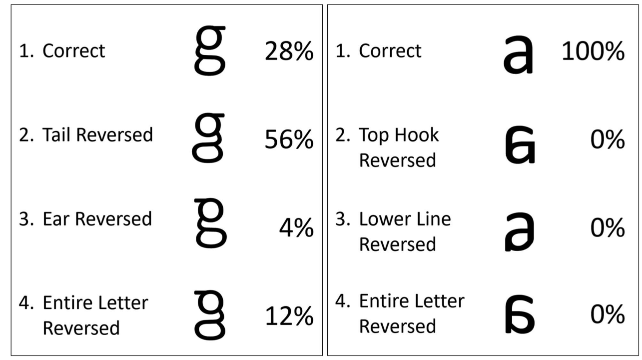

Figure 4. The four versions of looptail *g* and two-story *a* presented in Experiment 3. For both letters, Version 1 is correct, and the other alternatives are incorrect. For each version we indicate the percentage of participants who chose it in Experiment 3.

For each letter, the four versions were arranged in a 2 × 2 array, with the positions of the various versions counterbalanced across participants. Each participant was shown a printed page with the four versions, and asked to select the correct form of the letter. No time limit was imposed. Each character was approximately 8 cm in height on the printed page, to ensure that all features were highly visible.

Results and Discussion

For two-story *a,* all 24 participants chose the correct version without hesitation, indicating that their two-story *a* allograph representations were sufficiently detailed and accurate to distinguish the correct shape from similar incorrect forms.

For looptail *g*, however, performance was remarkably poor (see Figure 4): Only 7 of the 25 participants (28%) chose the correct version, a level of accuracy that obviously does not differ from the 25% expected by chance. A majority of participants (14/25) chose the incorrect version with the tail reversed. Three participants (12%) selected the completely reversed version, and one participant (4%) selected the version with the reflected ear. These results suggest that despite massive exposure to looptail *g*, and despite having the ability to read text printed with this form of *G*, many if not most skilled readers lack detailed, accurate knowledge of the allograph's shape. As we suggested in Experiment 1, the stored allograph representation may typically specify little more than two loops, one above the other, with a connecting line somewhere in between. This underspecified representation may be adequate for distinguishing *G*s from other letters in the course of reading, but is insufficient for choosing the correct looptail *g* from similar pseudoletter distractors, and cannot support accurate writing of the allograph.

In Experiment 1 most participants who attempted to write looptail *g* erroneously placed the line connecting the loops on the far right side of the character (see Figure 2). Similarly, in the present experiment two thirds of the participants (17/25) chose a looptail *g* version with the line on the right side (see Figure 4). This bias toward a right-side connecting line may reflect the fact that the descending vertical stroke in the opentail form of *g* is on the right side of the character. Given an underspecified allograph representation that failed to designate the location of the connecting line, participants may have opted for the location that maximized the resemblance to opentail *g*. Another possibility is that confusion between the opentail and looptail *g* shapes in children learning to read sometimes leads to acquisition of a looptail allograph representation that erroneously specifies a far right location for the connecting line.

Participants' bias toward a right-side connecting line is reminiscent of a finding reported by Jones and colleagues (Jones, 1990; Jones & Martin, 1992) in studies concerning memory for the appearance of British coins. Although the queen's profile always faces right on British coins, participants showed a strong tendency to report that the profile faces left. Jones and colleagues suggested that the leftward bias might stem from a similar bias in Western European portraiture, or from the fact that the queen's portrait on stamps always faces left. This proposal is similar to our suggestion that preference for the reversed tail of looptail *g* reflects knowledge about the tail of opentail *g*.

General Discussion

We have described striking limitations in skilled readers' knowledge about a very common letter shape, the looptail form of lowercase *G*. Looptail *g* is far more common in printed materials than the alternative opentail form. Nevertheless, we found in Experiment 1 that skilled readers often failed to recall the existence of looptail *g*, despite multiple opportunities to do so, and despite very specific questions (e.g., *Does the letter G have two forms in lowercase print?*). Even among participants who reported knowing that *G* has two lowercase print forms, almost none were able to write the looptail form accurately.

In Experiment 2 we found that immediately after searching for *G*s in a paragraph with multiple instances of looptail *g* (and no opentail *g*s), half of the participants produced an opentail *g* when asked to write the form of *G* they had just seen. Among participants who demonstrated some memory for the form of the *G*s in the paragraph, only one was able to write the looptail shape accurately. Finally, in Experiment 3 participants performed at chance when asked to select the correct looptail *g* shape from among distractors with important features mislocated or misoriented.

We interpreted these results by reference to a theoretical framework that posits several forms of knowledge about letters, including representations of the various shapes a letter may have (allograph representations), a representation of the letter's name and, for letters they have learned to write, a graphic motor plan that specifies a sequence of writing strokes (see Figure 3). All of these representations are linked to an abstract, amodal representation of the letter's identity.

Skilled readers clearly have stored allograph representations for looptail *g*, as evidenced by their ability to recognize looptail *g*s in ordinary reading. When a looptail *g* is encountered, the looptail allograph representation is activated, leading in turn to activation of the letter identity representation. Nevertheless, many participants in Experiment 1 failed to recall the existence of the looptail allograph. This result suggests that the learned association from the {G} letter identity representation to the looptail *g* allograph representation is often so weak that activation of the letter identity representation (e.g., by dictation of the letter name) fails to activate the looptail allograph representation. Nor, apparently, can skilled readers readily access other types of knowledge that would allow them to report the existence of looptail *g* (e.g., episodic memories for occasions on which they noticed odd-looking *g*s). Failures to acquire, retain, or access episodic knowledge about looptail *g* were evident as well in Experiment 2, where many participants failed to recall that they had seen looptail *g*s in a paragraph they had just searched for instances of the letter *G*.

Our results also point to limitations in readers' knowledge about the looptail *g*'s shape. In Experiments 1 and 2, participants who were able to recall the existence of looptail *g* were nevertheless almost uniformly unable to write the allograph accurately; and in Experiment 3 participants performed at chance in selecting the correct looptail *g* shape from among distractors with major features incorrectly located or oriented. We concluded that many if not most readers have underspecified or perhaps even inaccurate allograph representations for looptail *g*. These representations are apparently adequate for recognizing looptail *g*s in ordinary reading, but are not sufficient to distinguish the correct shape from similar distractors, or to support accurate writing of the looptail allograph.

Although our principal focus was on looptail *g*, we also examined readers' knowledge about the most common form of lowercase print *a*, the two-story *a*. In Experiment 1 some participants failed to recall the existence of two-story *a*, but these failures were less frequent than for looptail *g*. In addition, we found that participants who recalled the existence of the two-story allograph were almost always able to write it accurately. Furthermore, in Experiment 3 participants were 100% accurate in selecting the correct two-story *a* shape from among similar distractors.

Our results and interpretations raise several sets of interrelated questions, which we discuss in the following sections.

Letter-Shape Awareness

The first set of questions concerns the experiences that do, and do not, give rise to what we might call *letter-shape awareness*: The ability to recall the existence of a letter shape (i.e., an allograph) that is not visually present. Our results strongly suggest that letter-shape awareness does not always accompany the ability to recognize a letter shape via automatized reading processes, and hence that forms of experience sufficient for acquisition of letter recognition do not always suffice for acquisition of letter-shape awareness. Note also that letter-shape awareness does not imply detailed and accurate knowledge of the letter shape. We have argued that even among participants demonstrating letter-shape awareness for looptail *g*, knowledge of the letter shape was usually incomplete or perhaps even inaccurate.

[3] In referring to failures of letter-shape awareness for looptail *g* and two-story *a* we are not making any claims about readers' conscious experience *when they view these allographs*. Although it is not entirely clear what level of awareness skilled readers experience for letter shapes while reading, individuals who are asked to look at a looptail *g* or two-story *a* would undoubtedly be aware of what they are seeing and, as Experiment 1 demonstrated, would be aware that they had seen the allographs before. Our contention is only that when the allographs are not visually present, individuals frequently fail to recall the existence of looptail *g* and two-story *a* even when asked pointed questions, and so under these conditions show lack of awareness for the allographs.

We take it as obvious that skilled readers have strong letter-shape awareness for nearly all letter allographs. Why, then, did we observe failures of letter-shape awareness for looptail *g,* and to a lesser extent, for two-story *a*?[3] Frequency of exposure clearly cannot account for the failures, given that looptail *g* and two-story *a* are far more common than many other letter allographs, including their alternative lowercase print forms (opentail *g* and one-story *a*, respectively).

The mere fact that most letters have only a single form for each case-by-style combination (e.g., lowercase print, uppercase cursive) may be relevant. If, for example, most letters had two lowercase print forms we might well have observed greater letter-shape awareness for looptail *g* and two-story *a*. However, the rarity of multiple lowercase print allographs cannot by itself explain why letter-shape awareness was weaker for looptail *g* than for opentail *g*, or for two-story *a* than for one-story *a*.

The most salient factor distinguishing looptail *g* and two-story *a* from allographs showing stronger letter-shape awareness—opentail *g*, one-story *a*, and allographs of other letters—is writing experience. Although some of our participants reported having written two-story *a*, most individuals almost certainly have less writing experience for looptail *g* and two-story *a* than for other letter allographs. Acquiring and exercising the ability to write could very plausibly contribute to letter-shape awareness. Prior to acquisition of a complete, readily activated graphic motor plan for an allograph, a child attempting to write that allograph must activate other stored knowledge about the shape (i.e., the allograph representation). The process of learning to write may therefore strengthen links from letter identity representations to allograph representations. These links, we have suggested, support letter-shape awareness by activating allograph representations when letter-identity representations are activated. Weak letter-shape awareness for looptail *g* and two-story *a* may therefore reflect the absence of the link-strengthening writing experience.

We do not intend to suggest that writing experience is necessary for letter-shape awareness. Some of our participants recalled the existence of looptail *g* and two-story *a* despite never having written the allographs. More generally, we presume that most literate individuals can recall at least something about the shapes of symbols they may never have attempted to write (e.g., the ampersand, or the uppercase Greek letter omega). Our contention is simply that writing experience contributes to the development of letter-shape awareness, and hence that weak letter-shape awareness for looptail *g* and two-story *a* stems at least in part from lack of writing experience for these characters.

Why was letter-shape awareness somewhat stronger for two-story *a* than for looptail *g*? Greater writing experience for two-story *a* may be one relevant factor: In Experiment 1, participants who reported previously writing two-story *a* performed better on the letter-shape awareness tasks for this allograph than participants reporting no prior writing experience, although the differences did not reach significance. Another potentially relevant factor concerns the frequency of two-story *a* and looptail *g* relative to their alternative lowercase print forms. In particular, the predominance of two-story *a* relative to the alternative one-story form may be greater than the predominance of looptail *g* relative to opentail *g*. In our sampling of library books, the proportion of two-story *a*s was somewhat higher than the proportion of looptail *g*s, and the advantage of two-story *a* may be even greater in electronic media: Some of the most popular online fonts (e.g., Arial, Helvetica, Verdana) use the two-story form of *a* but the opentail form of *g*. If there is any sort of competition between alternative allograph representations (e.g., between looptail and opentail *g* as alternative forms of lowercase print *g*), the greater predominance of two-story *a* relative to its alternative form might contribute to the development of better letter awareness for two-story *a* than looptail *g*.

Letter-Shape Knowledge

A second set of questions raised by our results concerns the types and amounts of experience necessary for acquisition of detailed, accurate knowledge about the shape of a character. These questions arise from our finding that many skilled readers have incomplete or perhaps even inaccurate knowledge about the shape of looptail *g*. Here again the lack of writing experience for looptail *g* is almost certainly relevant. Recent studies suggest that experience in writing letters may improve learning of letter shapes (e.g., James, 2010, 2017; Li & James, 2016; Longcamp, Boucard, Gilhodes, & Velay, 2006; Longcamp, Lagarrigue, & Velay, 2010; Longcamp, Zerbato-Poudou, & Velay, 2005), although the evidence is not extremely strong. In addition, functional neuroimaging studies have revealed that passive letter viewing activates premotor areas implicated in writing, raising the possibility that letter production knowledge contributes to letter recognition even in skilled readers (e.g., James & Gauthier, 2006; Longcamp, Anton, Roth, & Velay, 2003, 2005; Longcamp, Tanskanen, & Hari, 2006; for a recent review, see: Longcamp, Richards, Velay, & Berninger, 2016). Furthermore, behavioral evidence (e.g., Babcock & Freyd, 1988; Freyd, 1983) indicates that recognition of handwritten characters can be facilitated by information about how the characters were produced (e.g., information about the direction of writing strokes).

The notion that writing characters can be helpful in learning their shapes seems plausible. Why, though, shouldn't massive visual experience suffice on its own? We suggest that in the absence of experience in writing a letter, readers learn only those visual features that are important for distinguishing letters from one another. Fiset and colleagues (2008) have argued that, for most letters, successful recognition does not require information about the entire shape; rather, recognition can be accomplished on the basis of a (sometimes rather small) portion of the character. The Fiset et al. (2008) results do not allow strong conclusions about the amount of shape information required for identification of looptail *g*, because the stimuli in their study did not include looptail *g*s. More generally, Fiset et al. (2008) may have underestimated the amount of visual information required for letter recognition, in part because their conclusions were based on results from a task requiring participants to distinguish only among characters within a single font. Nevertheless, it seems reasonable to assume that partial shape knowledge can suffice for identifying looptail *g*s in ordinary reading. Consequently, readers may acquire allograph representations that are adequate for recognizing looptail *g*s yet fail to specify major aspects of the shape (e.g., the placement of the line connecting the upper and lower loops).

An obvious question arising at this point is why readers have more detailed and accurate letter-shape knowledge for two-story *a* than for looptail *g* (as demonstrated by our writing and forced-choice discrimination results). Several possibilities may be considered. First, ordinary reading may require more complete shape knowledge for two-story *a* than for looptail *g*. That is, distinguishing two-story *a* from other letters may require fuller shape knowledge than distinguishing looptail *g* from other letters. We offer this possibility only as a speculation, as we are not aware of any evidence sufficient to warrant firm conclusions.

Another potentially relevant factor is visual complexity. According to at least one shape complexity metric—perimetric complexity (Attneave & Arnoult, 1956; Pelli, Burns, Farell, & Moore-Page, 2006)—looptail *g* is considerably more complex than two-story a, and this complexity difference might well contribute to the difference in learning difficulty.

Finally, the letter *A* is far more frequent in English than the letter *G* (e.g., Jones & Mewhort, 2004). We consider it unlikely, however, that this frequency difference accounts for the differences in letter-shape knowledge between two-story *a* and looptail *g*. Even though looptail *g* is encountered less frequently than two-story *a*, skilled readers' experience with looptail *g* is nevertheless massive. Pelli et al. (2006) estimated that an individual who reads for one hour per day for 40 years will encounter more than one billion letters. Taking into account the age of our participants, the frequency of *Gs* relative to the other letters of the alphabet, and the frequency of looptail *g*s relative to other *G* allographs, we estimate that our participants had previously encountered at least 2.5 million looptail *g*s. For two-story *a* the number of prior exposures was probably around 10 million. To interpret the results showing better letter-shape knowledge for two-story *a* than for looptail *g* in terms of this frequency difference, we would have to assume that after 2.5 million exposures have failed to result in detailed, accurate knowledge of a letter shape, an additional 7.5 million would remedy the deficiencies. We are inclined to think, however, that if a few million exposures have not sufficed for learning of a letter shape, even several million more are unlikely to make much difference.

Broader Implications

Our results have a number of significant theoretical and perhaps also practical implications. First, the finding that skilled readers have incomplete or inaccurate knowledge about the shape of looptail *g* is consistent with the claim that for purposes of letter recognition, readers need only a subset of the shape information available in a stimulus letter (e.g., Fiset et al., 2008). Moreover, our finding supports a stronger claim, that readers learn only the letter shape features necessary for discriminating among letters. A potential educational implication is that beginning readers should be exposed to text in multiple fonts (e.g., both serif and sans serif fonts). Students exposed primarily to a single font may fail to learn letter shape features that are not essential for distinguishing letters within the training font, but may be useful or even necessary for accurate letter identification in alternative fonts. This suggestion is consonant with Li and James' (2016) argument that learning to write letters may facilitate acquisition of letter recognition skill because children are exposed to variable exemplars of each letter when they look at the letters they have written. Extending this line of argument, it might be interesting to compare adults who predominantly type and those who predominantly hand-write, to see whether writing experience subsequent to initial acquisition of reading and writing may contribute to letter-shape knowledge or awareness.

Readers' incomplete knowledge about the shape of looptail *g* calls to mind a number of previous findings showing that people often fail at tests of knowledge or memory despite extensive exposure to the relevant information (e.g., Jones, 1990; Lawson, 2006; Nickerson & Adams, 1979; Rinck, 1999; Snyder et al., 2014). One series of studies (e.g., Jones, 1990; Nickerson & Adams, 1979) demonstrated poor memory for the direction in which profiles face on coins, and other studies have shown that skilled typists have surprisingly poor explicit memory for the locations of keys on a keyboard (e.g., Snyder et al., 2014; see also Rinck, 1999, for similar evidence concerning knowledge of numeric keypads). People also perform poorly when asked to draw a bicycle (Lawson, 2006) or the Apple company logo (Blake, Nazarian, & Castel, 2015).

Although consistent with these previous findings, our study is distinctive in several respects. First, exposure to looptail *g* is almost certainly greater than exposure to the stimuli examined in previous studies (e.g., coins, bicycles, or even keyboards). Second, letters are obviously relevant stimuli in reading, and so looptail *g*s must be processed frequently and repeatedly in the course of reading. In contrast, the stimuli in most earlier studies did not require this sort of continuous active visual processing. For example, recognition of a coin does not require, and is probably not usually accomplished via, processing of the profile stamped on one side. Third, we demonstrated not merely that most people lack detailed knowledge of looptail *g*, but also that most people fail to recall the existence of the allograph even under direct questioning. We are not aware of any comparable result in previous studies. Finally, we interpret our findings within an explicit theoretical framework that describes the representations and processes underlying letter recognition and production. This framework provides a basis for characterizing the deficiencies we observed in letter-shape awareness and letter-shape knowledge, as well as the reasons for these deficiencies.

Taken together, our results and the previous findings highlight the limits of current understanding about the circumstances, and cognitive processes, that do and do not lead to acquisition of detailed, accurate knowledge about frequently encountered stimuli. The results also raise questions about the completeness and accuracy of knowledge about other sorts of stimuli (e.g., familiar objects, faces, spatial environments). These questions, we suggest, deserve broader and more thorough investigation.

The present study also raises questions about the hypothesis that learning to write a letter plays an important role in acquisition of the ability to recognize the letter. As we have noted, a number of researchers (e.g., James, 2010, 2017; Longcamp, Zerbato-Poudou, et al., 2005) have argued in favor of this hypothesis, but the available evidence is not definitive. We have suggested that learning to write probably contributes to acquisition of letter-shape awareness, and also to acquisition of detailed, accurate letter-shape knowledge. However, these conclusions do not necessarily imply that learning to write contributes to acquisition of letter recognition ability, given that letter recognition may not require either letter-shape awareness or detailed and fully accurate letter-shape knowledge.

Accordingly, additional evidence bearing on the hypothesis that writing facilitates reading acquisition would be valuable. Looptail *g* and two-story *a* represent, we suggest, a natural experiment waiting to be performed. If writing experience contributes significantly to acquisition of letter recognition ability, then children learning to read and write should show a recognition disadvantage for looptail *g* and two-story *a* relative to opentail *g* and one-story *a*, respectively. More specifically, the disadvantage should become apparent once the children have learned to write opentail *g* and one-story *a*. If the predicted disadvantage is observed, the hypothesis that learning to write is important for learning to read would be strengthened, whereas failure to find the disadvantage would cast doubt on the hypothesis. Evidence supporting the hypothesis would also have potential educational implications: Educators should consider teaching children to write looptail *g* and two-story *a* as a means of improving recognition for these characters.

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