Knowledge about writing influences reading: Dynamic visual information about letter production facilitates letter identification

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Abstract

How are reading and writing related? In this study, we address the relationship between letter identification and letter production, uncovering a link in which production information can be used to identify letters presented dynamically. By testing an individual with a deficit in letter identification, we identified a benefit which would be masked by ceiling effects in unimpaired readers. In Experiment 1 we found that letter stimuli defined by the direction of dot motion (tiny dots within letter move leftward, background dots move rightward) provided no advantage over static letters. In Experiment 2, we tested dynamic stimuli in which the letter shapes emerged over time: drawn as they would be written, drawn in reverse, or with the letter shape filled in randomly. Improved identification was observed only for letters drawn as they are typically written. These results demonstrate that information about letter production can be integrated into letter identification, and point to bi-directional connections between stored letter production information (used for writing) and abstract letter identity representations (used in both reading and writing). The links from stored production information to abstract letter identities allow the former to activate the latter. We also consider the implications of our results for remediation of acquired letter identification deficits, including letter-drawing treatments and the underlying cause of their efficacy. (214 words)

Keywords: reading; writing; letter identification; acquired dyslexia; cognitive neuropsychology; graphic motor plans

Visual letter identification processes are vital for reading, providing input to the processes that recognize written words (e.g., Dehaene, Cohen, Sigman, & Vinckier, 2005; Grainger & Van Heuven, 2003; Norris & Kinoshita, 2008; Paap, Newsome, & Noel, 1984). Various deficits to letter identification processes have been described in cases of acquired dyslexia (reading impairments resulting from brain damage in previously-literate adults). The study of these deficits provides a richer understanding of the cognitive processes that perform letter identification in the unimpaired reading system (e.g., Caramazza & Hillis, 1990; Hillis, Rapp, Benzing, & Caramazza, 1998; Schubert & McCloskey, 2013).

Acquired dyslexias affecting letter identification can be understood within a cognitive theory first proposed by Caramazza and Hillis (1990), and recently refined by Schubert and McCloskey (2013). According to the theory, which is depicted in Figure 1, letter identification involves multiple types of letter representation, from visual to abstract. When a visual letter stimulus (e.g. 'B') is presented, visual shape perception processes generate a representation of the letter's shape. The computed letter shape representation maps onto a stored allograph letter representation. Allographs represent the various familiar forms of letters, including upper and lower case (for the stimulus 'B', the uppercase print B allograph would be activated). Finally, an abstract letter identity is activated, an amodal representation of the identity independent of the physical characteristics of the letter stimulus.

Deficits of letter identification have been described which affect different stages of the letter identification process, and these cases provide valuable support for the cognitive theory. For example, individuals RW (Hillis & Caramazza, 1991) and VB (Ellis, Flude, & Young, 1987) had difficulty representing letter shapes. Individuals JE (Rapp & Caramazza, 1989) and LHD (Schubert & McCloskey, 2013), among others, have deficits in accessing abstract letter identities, despite intact activation of allographs. New cases, with deficits that cannot be accommodated by the existing theory, would suggest the need to modify or elaborate the theory.

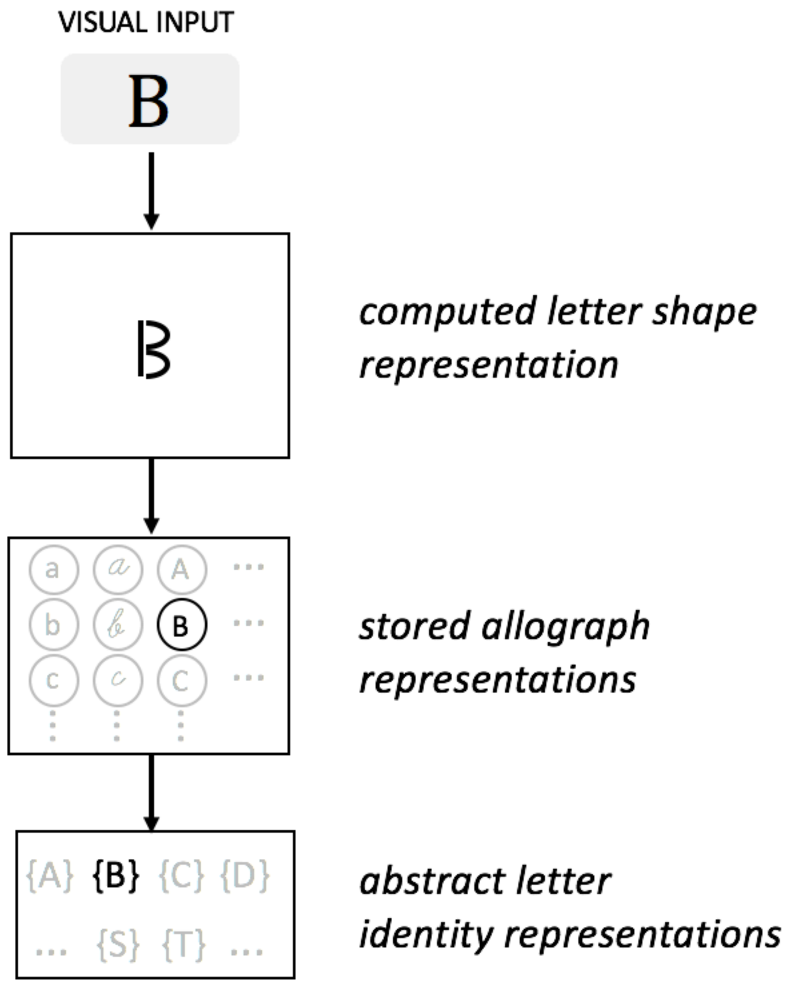

Figure 1. Schematic of the visual letter identification process. Letter visual features are computed from the stimulus at the letter shape level, then mapped onto a stored letter form representation (allograph) and then mapped onto an abstract letter identity.

We studied an individual, NGN, who was impaired at visual letter identification as the result of a stroke. For example, his accuracy in naming single uppercase letters was only 72%. However, an informal observation suggested that NGN's letter identification might be considerably improved by dynamic as opposed to static letter stimuli: When an experimenter drew the uppercase letters on paper one at a time while NGN watched, he correctly named 25 of the 26 letters (96%). This result motivated us to further investigate NGN's identification performance for dynamic letter stimuli.

We are unaware of other cases in which letter identification improvement has been demonstrated when observing letters drawn dynamically. For unimpaired readers, this is likely because identification performance is at ceiling for static letters, leaving no room for improvement with dynamic stimuli. The cognitive neuropsychological literature includes anecdotal reports of letter naming improvement when the patient is allowed to draw the shape of a stimulus letter in the air (Bub, Arguin, & Lecours, 1993; Maher, Clayton, Barrett, Schober-Peterson, & Gonzalez Rothi, 1998; Stachowiak & Poeck, 1976), or when identifying a letter drawn on the skin (Kreindler & Ionasescu, 1961). Furthermore, there are reports of reading improvement resulting from a strategy of tracing a letter prior to naming it (Maher et al., 1998; Nitzberg Lott et al., 2010; Nitzberg Lott, Friedman, & Linebaugh, 1994; Nitzberg Lott & Friedman, 1999; Seki, Yajima, & Sugishita, 1995). However, the improvement in these studies is typically attributed to use of tactile and/or kinesthetic information.

The theory of visual letter identification described above does not include mechanisms that could account for improved identification performance for dynamic as opposed to static letter stimuli. However, multiple theories address the perception-action link in more general terms. For example, Jeannerod (2001) suggests that perception of actions and their outcomes involves neural simulations of the actions involved. Freyd (1987) suggested that some domains, including spoken language and motion perception, may use 'dynamic representations', which involve a temporal element. She suggests that rather than static representations of letter features, recognition of handwritten letters may be supported by dynamic representations of letter production (Babcock & Freyd, 1988). Work by Viviani and Stucchi (1992) espouses a general principle that visual perception of line drawings (including written letters) is constrained by motor production capabilities. This principle is also supported by the case of an individual with an acquired motor disorder who could not use typical writing movements (which she could not produce) in the same way as controls (Chary et al., 2004). Kandel and colleagues have shown that handwriting contains cues to upcoming letters, and that viewing the first letter of a digram provides sufficient information to narrow down the identity of the following letter (Kandel, Orliaguet, & Boe, 1994; Kandel, Orliaguet, & Boë, 2000; Orliaguet, Kandel, Boë, & Boe, 1997). Other theorists have offered proposals that suggest ways in which dynamic stimuli could enhance letter identification (Flores d'Arcais, 1994; Parkinson & Khurana, 2007; Rauschecker et al., 2011). Following on from these general proposals, we articulate specific hypotheses about the effects of dynamic letter stimuli on letter identification. We evaluate these hypotheses by testing NGN with several forms of dynamic visual stimuli, assessing whether his letter identification does improve with dynamic stimuli and, if so, what form(s) of dynamic stimuli are effective. On the basis of our results, we extend the cognitive letter identification theory to address identification from dynamic letter input, offering a specific proposal about the impact of knowledge about writing on reading processes.

Potential Effects of Dynamic Letter Stimuli

The dynamically-drawn letters for which NGN performed well in informal testing have two properties that are potential sources of the apparent improvement in his letter identification performance. First, drawing involves visual motion: The lines forming the letter shape appear dynamically over time as the pen moves across the writing surface. Second, a standard sequence of writing strokes is used to produce the letters (e.g., for P, first drawing the vertical stroke from top to bottom, then drawing the loop from top to bottom). Either, or a combination, of these factors may be responsible for the apparent improvement in NGN's performance. The standard letter identification theory does not include mechanisms by which either of these sources of information would affect identification performance. Hence, regardless of the source of improvement, the theory would require modification to explain processing of dynamic letter inputs.

The use of visual motion input in reading has been considered by Rauschecker and colleagues (2011) in a study of normal readers. Rauschecker et al. presented visual word stimuli in which the letters were defined by the motion direction of small dots: the dots making up the letters moved in one direction, whereas background dots moved in the opposite direction. (In a still frame of a motion-dot stimulus, the word is not visible.) Although the stimuli contained no explicit contours, the words were readily identifiable from motion cues alone, supporting accurate lexical decision performance. Functional magnetic resonance imaging (fMRI) revealed that despite their differences from typical word stimuli, the motion-dot stimuli activated brain areas involved in word reading (e.g., the visual word form area, VWFA). In addition, the stimuli activated the human motion complex (hMT+), a bilateral dorsal brain region involved in visual motion perception but not in reading of static stimuli. Rauschecker et al. (2011) argued that the motion-dot stimuli activated the VWFA via hMT+, a route different from that implicated in reading of static words. Transcranial magnetic stimulation (TMS) applied to hMT+ reduced lexical decision performance for motion-dot words but not for standard (static) words. These TMS results suggest that the hMT+ pathway is required for perception of words defined by motion alone (Rauschecker et al., 2011). Rauschecker and colleagues speculated that in individuals with damage to standard reading mechanisms, the use of visual motion might bypass the damaged mechanisms by activating the alternate pathway through hMT+, thereby improving reading. In Experiment 1 we present letter stimuli constructed following the procedure of Rauschecker et al. (2011), allowing us to assess the impact of visual motion on NGN's performance. Importantly, unlike letters drawn dynamically by hand, these stimuli do not involve a standard letter stroke production sequence, avoiding any potential influence of this information.

In addition to involving visual motion, the experimenter-drawn letter stimuli also provide information about the process whereby each letter is written (e.g., the direction and sequence of writing strokes). It is possible that this information can be recovered from the stimulus and contribute to letter identification. Prior work is consistent with extraction and use of character production information from (static or dynamic) visual input in recognition tasks (e.g., Babcock & Freyd, 1988; Flores d'Arcais, 1994; Kandel, Orliaguet, & Viviani, 2000; Kandel et al., 1994; Parkinson & Khurana, 2007), though the stimuli and methods differ considerably from those used here. To test the impact of standard production information on identification, in Experiment 2 we contrast NGN's performance for letters drawn according to the standard production sequence with those drawn in a non-standard (reverse) sequence.

Before proceeding to test these two hypotheses, we precisely delineate NGN's letter identification deficit by reference to the standard letter identification theory. Then we present two experiments, testing the predictions of the visual motion hypothesis and the standard writing sequence hypothesis, respectively. Based on the results we propose an extension of the letter identification theory. Finally, we discuss broader conclusions regarding the relationship between the cognitive processes of reading and writing, and implications for rehabilitation strategies for individuals with letter identification deficits.

Case History

NGN was a 79-year-old right-handed man when testing began in 2014. He had a high-school education and was the co-owner of a local restaurant. He had suffered a large left ventromedial occipito-temporal lesion due to a stroke in September 2013. Magnetic resonance imaging (MRI) demonstrated damage to the lingual, fusiform, and parahippocampal gyri, as well as the posterior part of the left hippocampus (see Figure 2). Portions of the retrosplenial cortex, splenium, and posterior cingulate were also affected. Dorsal visual regions, including hMT+, appeared spared. Ophthalmological exam revealed a right homonymous hemianopia. NGN provided informed consent prior to participating and all study procedures were approved by the university institutional review board.

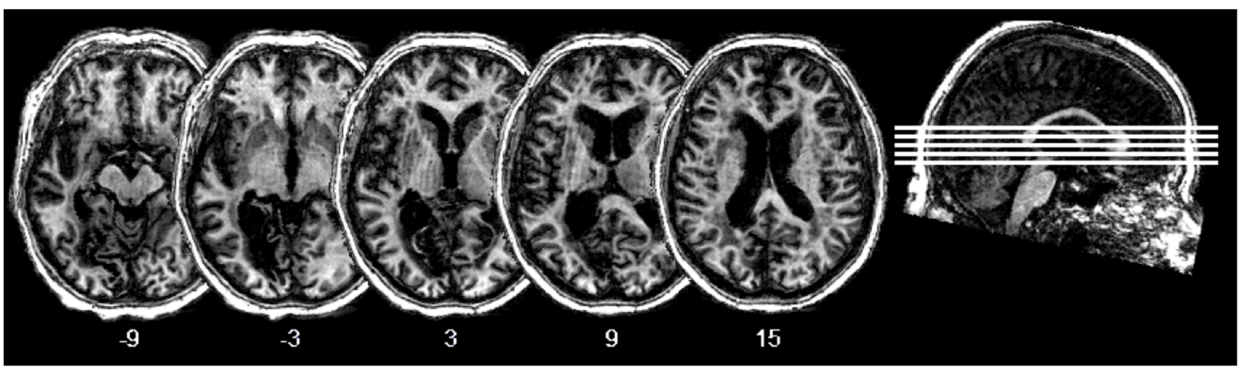

Figure 2. MRI (axial view) of NGN's brain showing left-hemisphere lesion. Numbers indicate distance from the AC-PC plane in millimeters (negative = inferior). Motion artifact (striations) is visible in slices 3 and 9.

NGN showed no evidence of visuospatial neglect, performing normally in picture copying, line bisection and line cancellation tasks. He was 100% correct (24/24) in copying simple shapes (e.g., square, triangle) and in copying 10 stimulus figures from the Benton Visual Retention Test (BVRT; Sivan, 1992); most of the BVRT stimuli are composed of multiple shapes. NGN also performed at ceiling (26/26) on a screening test for apraxia (e.g., miming flipping a coin). He had a mild to moderate expressive aphasia, including spoken and written language impairments. Word-finding difficulties were evident both in spontaneous speech and confrontation naming. For example, NGN correctly named only 17 of the first 30 pictures on the Boston Naming Test (Kaplan, Goodglass, & Weintraub, 1983) before testing was discontinued. Spelling assessment revealed intact oral spelling but impaired written spelling: He was 94% correct in oral spelling of words on the Johns Hopkins Dysgraphia Battery (Goodman & Caramazza, 1985; control range: 93-100% correct), but only 57% correct for written spelling of the same words. Results from a variety of tasks (McCloskey, Reilhac, & Schubert, in preparation) established that NGN's written spelling deficit involves occasional failures in activating, or maintaining activation of, graphic motor plans (the learned representations of writing-stroke sequences that mediate written production of letters). The graphic motor plans themselves are intact, and NGN is capable of producing all letters correctly. In writing words, his accuracy at the level of individual letters is 93%.

NGN's Letter Identification Deficit

NGN's principal complaint was a severe reading difficulty: He was almost entirely unable to read even single words, due to a deficit in visual letter identification. A precise description of NGN's letter identification deficit within the identification process allows us to narrow down possible mechanisms involved in identification improvement with dynamic letter input. We tested each of the letter identification stages (see Figure 1) to determine the locus of NGN's deficit. More details on the rationale for each task can be found in Schubert and McCloskey (2013).

Letter shape representations: Letter and pseudoletter copying task

NGN copied individual letter and pseudoletter stimuli that remained in view. He performed nearly perfectly, correctly copying 186 of 187 characters across several sessions. This result indicates that his ability to compute the shapes of visual letter and letter-like stimuli is intact.

Allograph representations: Letter/pseudoletter classification task

NGN was presented with a string of three characters and asked to indicate whether the string contained only (lowercase) letters, or also a pseudoletter. The strings contained either three letters, or two letters and one pseudoletter, appearing equally often in each of the string positions. The pseudoletters were created from the same letters of the font by rotating and re-arranging the visual features (Schubert & McCloskey, 2013). To determine whether a given character is a letter or false character, stored allograph representations must be consulted. NGN was 100% correct (156/156), indicating intact access to allograph representations.

Abstract letter identities: Within- and cross-case same/different task

NGN judged whether two letters presented on the screen corresponded to the same or different identity. On within-case trials the two letters were both in upper case or both in lower case (e.g., 'D D', 'e f'), whereas in cross-case trials one letter was in upper case while the other was in lower case (e.g., 'D d', 'e F'). On within-case trials the correct response can be determined based on physical appearance alone; however, cross-case trials require accessing an abstract letter identity representation to determine whether the two letter shapes correspond to the same letter identity. NGN was 100% correct (40/40) on within-case trials, but only 75% correct (30/40) on cross-case trials (Fisher's exact test $p < .01$). His perfect performance on within-case trials provides further evidence that he accurately processes the shapes of letters, whereas his impaired performance on cross-case trials indicates that he is impaired in accessing the abstract letter identities required for these trials.

Abstract letter identities: Single-letter naming task

Across multiple sessions NGN was asked to name letters presented individually in upper or lower case. Even though exposure duration was unlimited and NGN was under no time pressure to respond, he was only 72% correct (782/1092) for upper-case letters and 68% correct for lower-case letters (626/917). Given that NGN's oral spelling is intact, his letter-naming errors cannot be attributed to a deficit in spoken production of letter names. Hence, the letter-naming errors support the conclusion of impaired access to abstract letter identities.

In summary, NGN's visual perception and access to stored letter forms (allographs) was intact but his ability to subsequently access abstract letter identity representations was disrupted. This deficit in mapping from allograph to abstract letter identities results in poor performance on cross-case tasks, letter naming, and reading.

Experiment 1

This experiment tests the motion hypothesis proposed by Rauschecker and colleagues (2011) as a source of identification improvement. Single letters were presented in two conditions which differed in whether they included visual motion. Neither condition provided information about standard letter stroke production. In the *Static-Dot* condition, the letter was defined by the luminance of small static dots (Figure 3A). This condition does not involve visual motion and should not activate motion-processing mechanisms. In the *Motion-Dot* condition, the letter was defined solely by the motion of small dots (Figures 3B and 3C). This condition is expected to engage visual motion-perception mechanisms. It mimics the motion-dot condition from Rauschecker et al. (2011), except that we presented single letters rather than whole words.

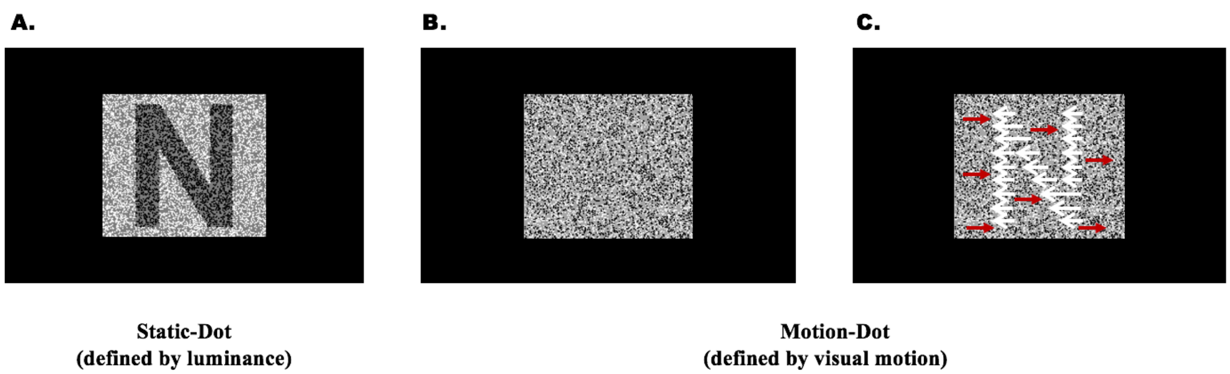

Figure 3. Schematic illustration of the stimuli in Experiment 1. In the Static-Dot condition, upper-case letters were defined by dot luminance, with black or white dots on a gray background (A). In the Motion-Dot condition, letters were defined by direction of dot motion. In any single frame of this condition (B), the letter is not visible. In each successive frame, both white and black dots within the letter moved left (C, white arrows); dots outside the letter moved right (C, red arrows). (Arrows were not present in the stimuli.) See Supplemental Video 1 for a dynamic stimulus example.

Rauschecker and colleagues (2011) found that their motion-dot stimuli were processed by area hMT+ and disrupted by TMS to this area. They suggested, therefore, that motion-dot stimuli could bypass impaired reading processes and improve reading performance for some individuals. However, Rauschecker et al. did not offer explicit assumptions about what aspects of the reading process might be carried out within the hMT+ route to the VWFA and hence could support improved performance. In the context of letter identification, we consider two possibilities for the cognitive processes accomplished by the hMT+ pathway, both consistent with the results of Rauschecker et al. (2011).

One possibility is that the motion pathway computes a letter shape representation from motion-dot letter input, as illustrated in Figure 4 (see Version 1 arrow). On this account, the hMT+ pathway bypasses only the processes that compute letter shape representations for static letter stimuli; subsequent letter identification processes are the same for motion-dot and static stimuli. Depending upon the locus of a letter identification deficit within the cognitive system, dynamic input might or might not improve identification performance: A deficit in computing letter shape representations from static stimuli should be ameliorated by motion-dot stimuli; however deficits in subsequent letter-identification processes (activation of allograph representations from letter shape representations, activation of letter identities from allographs) should be equally evident with static and motion-dot stimuli.

A second potential version of the Rauschecker et al. (2011) hypothesis holds that the motion pathway bypasses the entire static-letter identification process, activating abstract letter representations through a completely separate route (see Version 2 arrow in Figure 4). Given this version of the hypothesis, we might expect letter stimuli that include visual motion to be identified accurately by an individual with a deficit to any stage of the static-letter identification process (if abstract letter identity representations are intact).

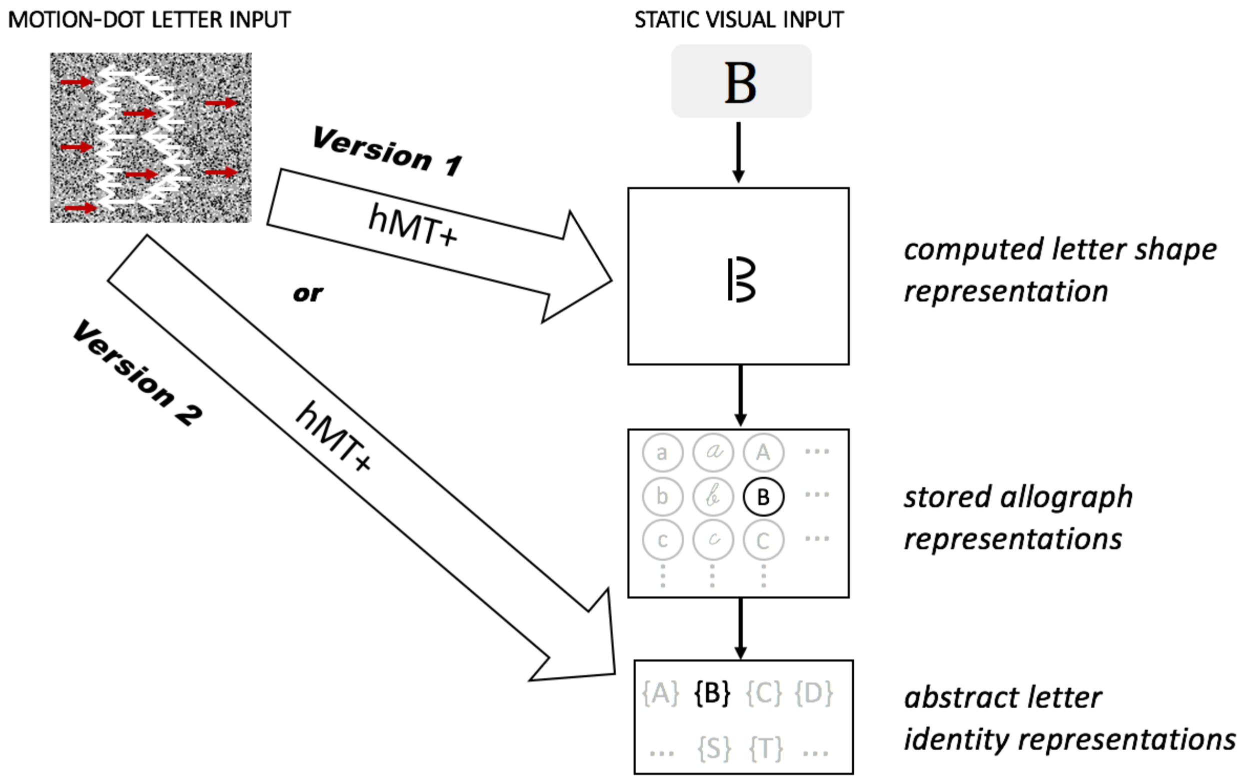

Figure 4. Two possible interpretations of the cognitive processes in the hMT+ motion pathway proposed by Rauschecker et al., (2011). In the first, letter shape representations are computed from motion letters and processed normally in the identification system (Version 1 arrow). In the second, abstract letter identities are computed from motion letters, in processes independent of the standard letter identification system (Version 2 arrow).

Turning to specific predictions for NGN's performance in this experiment, we expect him to identify the Static-Dot stimuli with similar accuracy to standard static letters. The predictions for his performance on the Motion-Dot condition differ for the two versions of the motion hypothesis. According to the first alternative, the hMT+ pathway serves only to compute letter shape representations for motion-dot stimuli, with processing otherwise being the same as for static stimuli. Given that NGN's deficit is localized subsequent to letter shape computation (specifically, in activating letter identity representations from allograph representations), motion-dot as well as static-dot stimuli should be affected by the deficit, and he should show comparably impaired performance for both stimulus types. On the other hand, if the hMT+ pathway engaged by motion-dot stimuli bypasses the entire static-letter identification process, activating abstract letter identities via a completely separate route, we would expect NGN's performance to improve with motion-dot stimuli.[1]

Materials and methods

Letter stimuli were defined by populations of small dots that contrasted in luminance (black vs. white) or motion direction (left vs. right), as illustrated in Figure 3. Each letter stimulus was created within a rectangular grid, 160 units wide x 140 units high. The letter shape was centered within the grid, with a height that covered 90% of the grid (126 units) and a width that varied from letter to letter (e.g., M wider than N). The background color of the grid was a uniform gray. In the Static-Dot condition, 30% of the grid cells were filled with a black or white dot. Dots falling within the strokes of the letter were black, and those falling outside the letter shape were white (Figure 3A). The difference in dot luminance was the only means by which the letter shape was defined; no continuous contours distinguished the letter from the surrounding space.

In the Motion-Dot condition, the letter shape was defined by motion rather than luminance. The stimuli were displayed as a sequence of frames within a rectangular grid of the same size used for the Static-Dot stimuli. The initial frame for each letter was created by filling 30% of the grid cells with dots, half black and half white. The black/white value for each dot was determined randomly, without regard to whether the dot was within the letter shape.

[1] Note that although NGN is impaired in activating abstract letter identities from allograph representations, the abstract letter representations themselves are intact, as demonstrated by results from a variety of tasks (e.g., intact oral spelling, which requires abstract letter identities). Therefore, according to version 2 of the motion hypothesis, he should show improved performance with motion-dot stimuli.

Consequently, black and white dots were scattered randomly across the entire grid, as illustrated in Figure 3B. To create each successive frame of the stimulus, the dots within the letter shape were shifted one grid cell to the left, whereas dots outside the letter shape were shifted one cell to the right (see Figure 3C). Hence, when the frames were presented in sequence, dots within the letter shape moved leftward, whereas those outside the shape moved rightward. Dots that reached a boundary (the edge of a letter stroke, or the edge of the grid) disappeared and new dots entered at the opposite edge. Dot motion was the only means by which the letter shape was defined. The Motion-Dot displays yield a perception of smooth motion, with sharp (illusory) boundaries between the letter and the background. (See Supplementary Video 1 for an example of a motion-dot stimulus.)

Stimuli were presented on a 15-in MacBookPro laptop monitor with a 60-Hz refresh rate (16.67 ms/cycle). The experiment was controlled by custom Matlab (version R2013a, MathWorks, Inc.) scripts using Psychtoolbox-3 (Kleiner, Brainard, & Pelli, 2007; Pelli, 1997). At the viewing distance of 50 cm, the letters subtended 10° of visual angle vertically and the dots measured approximately .08° on each side. Display duration in both conditions was 10.67s. In the Motion-Dot condition, each frame was presented for two refresh cycles (33.33 ms), for a total of 320 frames. Foreground dots in this condition moved at a rate of 2.5°/s.

NGN was not required to maintain fixation, and no time limit was imposed on his responses. Prior to testing with letters, we familiarized him with the motion-dot displays by presenting simple shapes (e.g., square, triangle, arrow) in motion-dot form, and he readily identified all of the shapes. In each of two sessions all 26 upper-case letters were presented in random order in each condition, for a total of 52 trials per condition. In this and the following experiment, we collapsed data across sessions to produce an accuracy for each letter of the alphabet (N = 26) and then conducted paired t-tests to compare conditions. Effect sizes and confidence intervals were calculated using the methods described by Lakens (2013).

Results and Discussion

NGN correctly named 73.1% (38/52) of the letters in the Static-Dot condition, consistent with his 72% accuracy in naming standard printed upper-case letters. In the Motion-Dot condition he was 63.5% correct (33/52), demonstrating that the visual motion in the dynamic condition failed to improve his performance and in fact was numerically lower than the static condition. Accuracy did not differ significantly between conditions, $t(25) = 1.15$, $p = .26$, $M_{\text{diff}} = 9.62$, 95% CI [-7.54, 26.77], Cohen's $d_z = 0.23$. Accuracy for each letter in each condition is presented in Table A.1 in the Appendix.

These results have implications for the two versions of the Rauschecker et al. (2011) motion hypothesis illustrated in Figure 4. The results are not readily explained by the second version, which holds that the hMT+ motion pathway implements a full letter identification process that is applied to letters defined by motion, and is separate from the process mediating identification of static letters (see Version 2 arrow in Figure 4). According to this version, the motion pathway should have bypassed the static letter identification process that is impaired in NGN, leading to improved identification performance for motion-dot stimuli. However, NGN's performance was no better for motion-dot letters than for static letters.[2]

[2] We might consider the possibility that NGN's impaired performance with motion-dot letters stems from a deficit affecting the motion pathway (separate from, and in addition to, the deficit responsible for his impairment in identifying static letters). However, several considerations argue against this possibility. First, NGN's anatomical MRI scans indicate that hMT+ is structurally intact (though nearby white matter may be affected). Second, NGN reported no difficulties with motion perception after his stroke. Third, he readily identified motion-defined shapes (e.g., triangle, arrow) presented to familiarize him with the motion-dot displays (see Materials and methods section). Finally, in the next experiment we report that NGN's letter identification improved with a type of stimulus that involved perception of motion.

In contrast, our results are consistent with the first version of the motion hypothesis, which states that the motion pathway serves only to compute letter shape representations for letter stimuli defined by motion. According to this version, subsequent stages of the letter identification process are the same for static and motion-defined letters (see Version 1arrow in Figure 4). Because NGN's letter identification deficit is localized to one of the shared processes, in which allograph representations activate their corresponding abstract letter identity representations, both static and motion-dot stimuli should be affected by the deficit.

More generally, NGN's impairment in identifying the Motion-Dot letters suggests that the presence of visual motion is not the underlying factor that led to the apparent improvement in letter identification when NGN watched an experimenter draw the letters. Accordingly, in Experiment 2 we test the hypothesis that the active ingredient for identification improvement is not visual motion, but the availability of information consistent with typical letter production.

Experiment 2

In this experiment, we presented NGN with letter stimuli which differed in whether they provided information about standard letter production. As illustrated in Figure 5, single uppercase letters were presented in four display conditions, one static and three dynamic. In the *Static* condition, the entire letter was displayed for the whole duration of the trial. In the *Dynamic-Forward* condition, a large black dot 'drew' the letter, following a typical writing sequence. This condition mimics, in a controlled manner, the experimenter drawing the letter with pen on paper. For example, for P, the dot drew the vertical stroke from top to bottom, and then drew the loop, starting again at the top. The *Dynamic-Reverse* condition was identical to the Dynamic-Forward condition except that the dot drew the letter in reverse, from the endpoint to the start point (e.g., for P the loop was first drawn from bottom to top, followed by the vertical stroke, also from bottom to top). In the *Dynamic-Random* condition, the dots making up the letter strokes appeared in random order until the entire letter was displayed. (See Supplementary Videos 2-4 for examples of Dynamic-Forward, Dynamic-Reverse, and Dynamic-Random stimuli, respectively.)

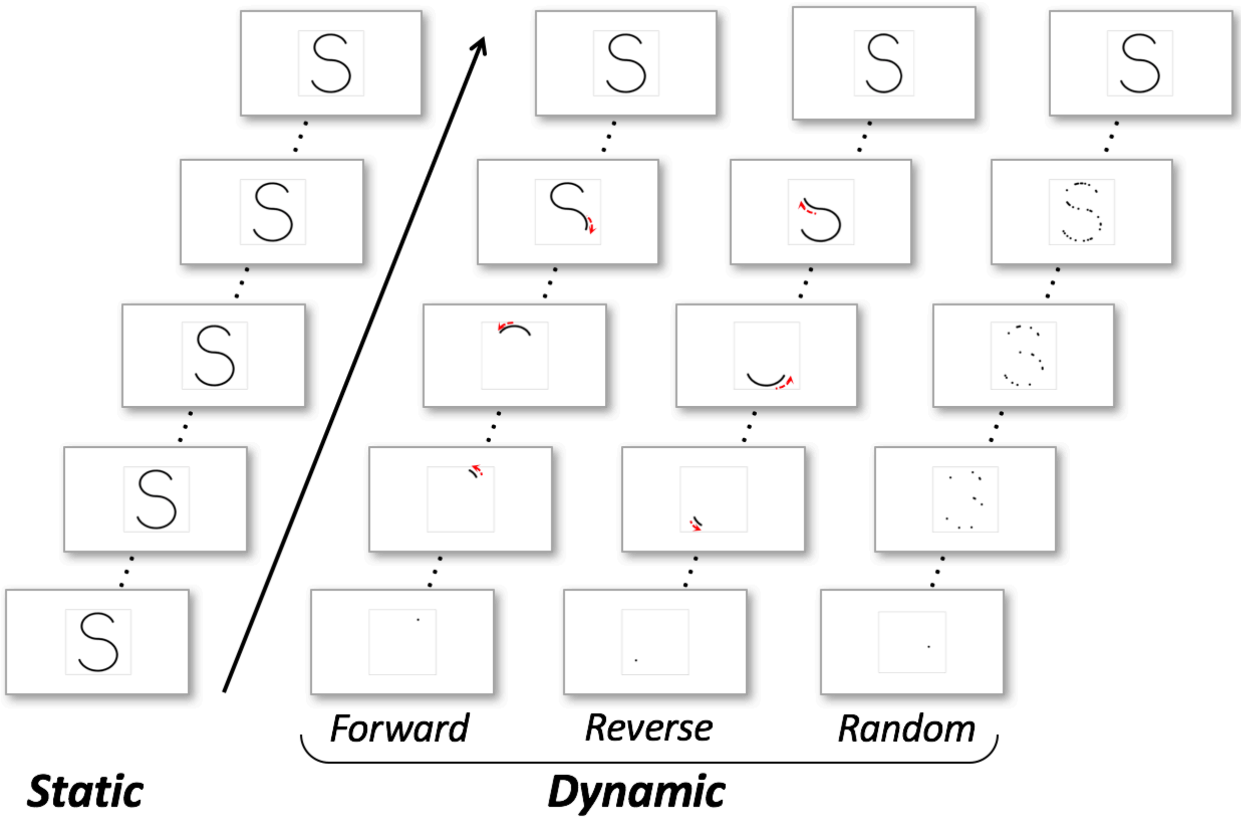

Figure 5. Sample stimuli from Experiment 2. In the Static condition, whole upper-case letters were presented. In the Dynamic-Forward condition, letters were drawn by a moving dot in the natural writing direction. In the Dynamic-Reverse condition, letters were drawn with a reversed stroke order and direction. In the Dynamic-Random condition, dots appeared in random order. Red arrow indicates direction of motion, and was not present in the stimuli.

The Static condition provides a baseline measure of NGN's letter identification performance in this task. The Dynamic-Forward condition tested whether his performance would be facilitated by visual information about the standard sequence of writing movements for producing a letter. The Dynamic-Reverse condition allowed us to assess whether facilitation would occur only for the standard writing movements shown in the Dynamic-Forward condition, or also for non-standard writing movements. Finally, the Dynamic-Random condition tested whether any facilitation in the other dynamic condition(s) was due merely to the emergence of the letter shape over time (perhaps drawing additional attention to the stimulus).

Materials and methods

As in Experiment 1, stimuli were presented on a 15-in MacBookPro laptop controlled by Matlab/Psychtoolbox scripts. In the dynamic conditions, dots were added to the display at a rate of one dot every 33.33 ms (i.e., every two refresh cycles). In the Dynamic-Forward and Dynamic-Reverse condition, dots appeared in a continuous sequence along each letter stroke, giving the appearance of a dot 'drawing' the letter. The direction and ordering of strokes in the Dynamic-Forward condition followed the standard stroke pattern for writing each letter (as taught in elementary schools in the United States). In both the Dynamic-Forward and the Dynamic-Random condition the distance between consecutive dots was constant, and hence the velocity of the simulated writing movement was constant from the beginning to the end of a stroke. In this respect the displays did not mimic natural writing movements; in natural writing, pen velocity varies systematically within strokes (e.g., for straight strokes, increasing from the beginning to approximately the middle of the stroke, and then decreasing from middle to end).

In the Dynamic-Random condition, the dots comprising the letter strokes appeared in random order rather than sequentially along the letter strokes. In all conditions the dot diameter, which defined the width of the letter strokes, was 7 mm on the screen (.8° visual angle). Completed letters had a height of 17 cm and subtended 18.8° of visual angle at the viewing distance of 50 cm. Dots were black, and the background was white.

In the Dynamic-Forward and Dynamic-Reverse conditions, there was a 500-ms pause at the endpoint of a stroke if the next stroke began at a different location (e.g., for P, a pause was taken after ending the vertical stroke at the bottom of the letter, prior to starting the loop). In the Dynamic-Random condition pauses occurred at random times, with the number of pauses for each letter matched to the Dynamic-Forward/Reverse conditions.

Total presentation time varied across letters, depending upon the number of dots making up the shape. Presentation times ranged from 4.6 seconds (for the letter J) to 10.9 seconds (for W), with a mean of 7.6 seconds. For each letter, the total presentation time was the same in all four conditions: In the Static condition the entire letter was presented for the same duration required for the dynamic conditions. In the dynamic conditions, after all dots had been added to the display, the complete letter remained on the screen for 1500 ms before the display was terminated. The complete letter was displayed for a much longer time in the Static condition than in the dynamic conditions (i.e., throughout the trial vs. for 1500 ms at the end of the trial). Given that a longer display of the whole character might improve identification performance, the Static condition is a conservative control condition for assessing the effects of the dynamic displays.

On each trial, a 21° x 21° black outline square was first presented in the center of the screen, to define the region within which the letter would be displayed. Presentation of the letter stimulus began 1000 ms later. NGN was instructed to wait until the letter was complete before attempting to name it. He was tested in fifteen sessions from July 2014 through April 2015. In each session, all 26 uppercase letters were presented in random order in two or more of the experimental conditions. The letters were presented a total of 13 times in the Static condition, 12 times in the Dynamic-Forward condition, 8 times in the Dynamic-Reverse condition, and 3 times in the Dynamic-Random condition. Because NGN's performance remained stable across sessions (χ^2(df = 14) = 28.08, p = .20) we report data combined over the entire study.

Results and Discussion

In the Static condition, NGN's letter identification accuracy was 73.7% (249/338), consistent with his accuracy in the Static-Dot condition of Experiment 1 (73.1%) and in standard letter naming (72%). Accuracy in the Dynamic-Forward condition was significantly higher, with 89.4% correct responses (279/312), $t(25) = 4.63$, $p < .001$, $M_{\text{diff}} = 15.78$, 95% CI [8.75, 22.80], Cohen's $d_z = 0.91$. This result demonstrates that some aspect(s) of the Dynamic-Forward stimuli facilitated NGN's letter identification.

In the Dynamic-Reverse condition, NGN's accuracy was 80.3% (167/208), which is significantly lower than the 89.4% accuracy for the Dynamic-Forward condition, $t(25) = 2.31$, $p < .05$, $M_{\text{diff}} = 9.14$, 95% CI [0.98, 17.31], Cohen's d_z =0.45. Thus, viewing the letter drawn with standard writing movements was more beneficial than viewing non-standard movements. Although accuracy was numerically higher in the Dynamic-Reverse condition than in the Static condition (80.3% vs. 73.7%), this difference did not reach significance, $t(25) = 1.96$, $p = .061$, $M_{\text{diff}} = 6.63$, 95% CI [-0.34, 13.60], Cohen's d_z =0.38. Hence, it is not clear that the Dynamic-Reverse displays conferred any benefit relative to the Static stimuli. Finally, accuracy in the Dynamic-Random condition was 74.4% (58/78), which is significantly lower than accuracy in the Dynamic-Forward condition ($t(25) = 2.80$, $p < .01$, M_{diff} =15.07, 95% CI [4.00, 26.13], Cohen's d_z =0.55), and not significantly different from accuracy in the Static condition ($t(25)$ = .13, $p = .9$, $M_{\text{diff}} = 0.71$, 95% CI [-10.30, 11.72], Cohen's $d_z = 0.03$) or the Dynamic-Reverse condition ($t(25) = 0.94$, $p = .36$, $M_{\text{diff}} = 5.92$, 95% CI [-7.09, 18.94], Cohen's $d_z = 0.18$). Accuracy for each letter in each condition is presented in Table A.2 in the Appendix. In summary, NGN's identification accuracy was significantly higher in the Dynamic-Forward condition than in the Static condition, and no other dynamic condition produced significant facilitation.

The improved performance found in the Dynamic-Forward condition is consistent with the observation that experimenter-drawn letters produced higher letter identification accuracy than static letters. The lack of improvement in the other dynamic conditions suggests that it was not the fact that the letters appear over time, or the presence of visual motion in the stimulus, which led to higher accuracy in the standardly-drawn condition. Instead, these results suggest that information about a standard letter-production sequence can be used by the identification process.

General Discussion

We found a facilitative effect of dynamic letter production information in letter identification. NGN's letter naming performance was impaired for letters defined by direction of dot motion (Experiment 1: Motion-Dot), letters defined by the contrast between scattered white and black dots (Experiment 1: Static-Dot), standard static letters (Experiment 2: Static), letters drawn in an atypical direction (Experiment 2: Dynamic-Reverse), and letters generated by adding dots in a random order (Experiment 2: Dynamic-Random). Only when letters were drawn in a typical writing direction (Experiment 2: Dynamic-Forward) did NGN's identification accuracy improve. These results provide a basis for conclusions about the potential role of visual motion information in reading, and about the contribution of letter production information to letter identification.

Visual motion pathway for reading

Rauschecker and colleagues found that moving word stimuli (like the Motion-Dot stimuli in Experiment 1) activate motion areas of the brain (hMT+) and subsequently the visual word form area (VWFA). They found that TMS to hMT+ disrupted word recognition for motion-dot but not static stimuli, suggesting that this neural pathway is required for processing dynamic but not static word stimuli (Rauschecker et al., 2011). Although Rauschecker and colleagues hypothesized that a motion pathway including hMT+ carries out processes critical for reading stimuli defined by motion, these researchers did not offer proposals about the specific reading processes performed by the motion pathway. We formulated two specific versions of the hypothesis, both consistent with the Rauschecker et al. (2011) findings. NGN's performance in Experiment 1, in conjunction with evidence localizing his deficit to a specific stage of the letter identification process, were consistent with only one of the two versions. According to this version, the motion pathway computes a letter shape representation for letter stimuli defined by motion, and subsequent letter identification processes are shared between static and motion-defined letters (see Version 1 arrow in Figure 4).

Our results not only shed light on the potential roles of the motion pathway in reading, but also allow us to clarify the suggestion of Rauschecker and colleagues that motion-dot stimuli might ameliorate reading deficits in some individuals. On the basis of our results, we can make more specific predictions: Individuals with deficits selectively affecting the computation of letter shape representations from static stimuli should show improvement with motion-dot stimuli. However, individuals with deficits affecting later stages of the letter identification process (like NGN) will not derive any benefit from stimuli defined by motion.

Letter production information in identification

NGN's identification performance was improved in Experiment 2 when letters were drawn dynamically in accordance with the standard letter production sequence. Only the order in which the letter was produced differed between the Forward and Reverse stimuli, with all other visual properties (including stroke thickness and kinematics) remaining the same, strongly suggesting that the standard order of stroke production was the key ingredient of the improvement. This result suggests that information about letter production can be recovered from a dynamic visual stimulus, and further that this information can contribute to letter identification. How, though, does this effect of production on identification take place?

Many theorists assume that abstract letter identity representations play a central role not only in reading, but also in writing (Brunsdon, Coltheart, & Nickels, 2006; Ellis, 1982, 1988; James & Atwood, 2009; Margolin, 1984; Rothlein & Rapp, 2017; Tainturier & Rapp, 2001, 2003; van Galen, 1991). In the case of writing, abstract letter identities—in conjunction with a specification of case and style (e.g., lowercase print)—are assumed to activate graphic motor plans, as illustrated in Figure 6. The graphic motor plans are often assumed (e.g., Goodnow & Levine, 1973; van Sommers, 1984) to reflect a 'grammar of action', a set of general principles for producing efficient, well-controlled movements (e.g., minimize lifts of the pen, draw vertical strokes from top to bottom).[3]

[3]Writing theories vary to some extent in their assumptions about levels of representation, and in the terminology used to describe these levels. Some theorists (e.g., Miozzo & De Bastiani, 2002; Rapp & Caramazza, 1997) assume that abstract letter representations are mapped directly to graphic motor plans (as in Figure 6), whereas others posit an intervening level of letter shape representations (e.g., Ellis, 1982, 1988; Margolin, 1984). This issue is not relevant to our concerns, and so we have illustrated the simpler hypothesis. With respect to terminology, the term *allograph* is used inconsistently in the writing literature, sometimes referring to letter shape representations with no motoric content (e.g., Ellis, 1982), and sometimes to stored motor programs for production of a letter (e.g., van Galen, 1991). We use allograph in the former sense and refer to the motor programs as graphic motor plans.

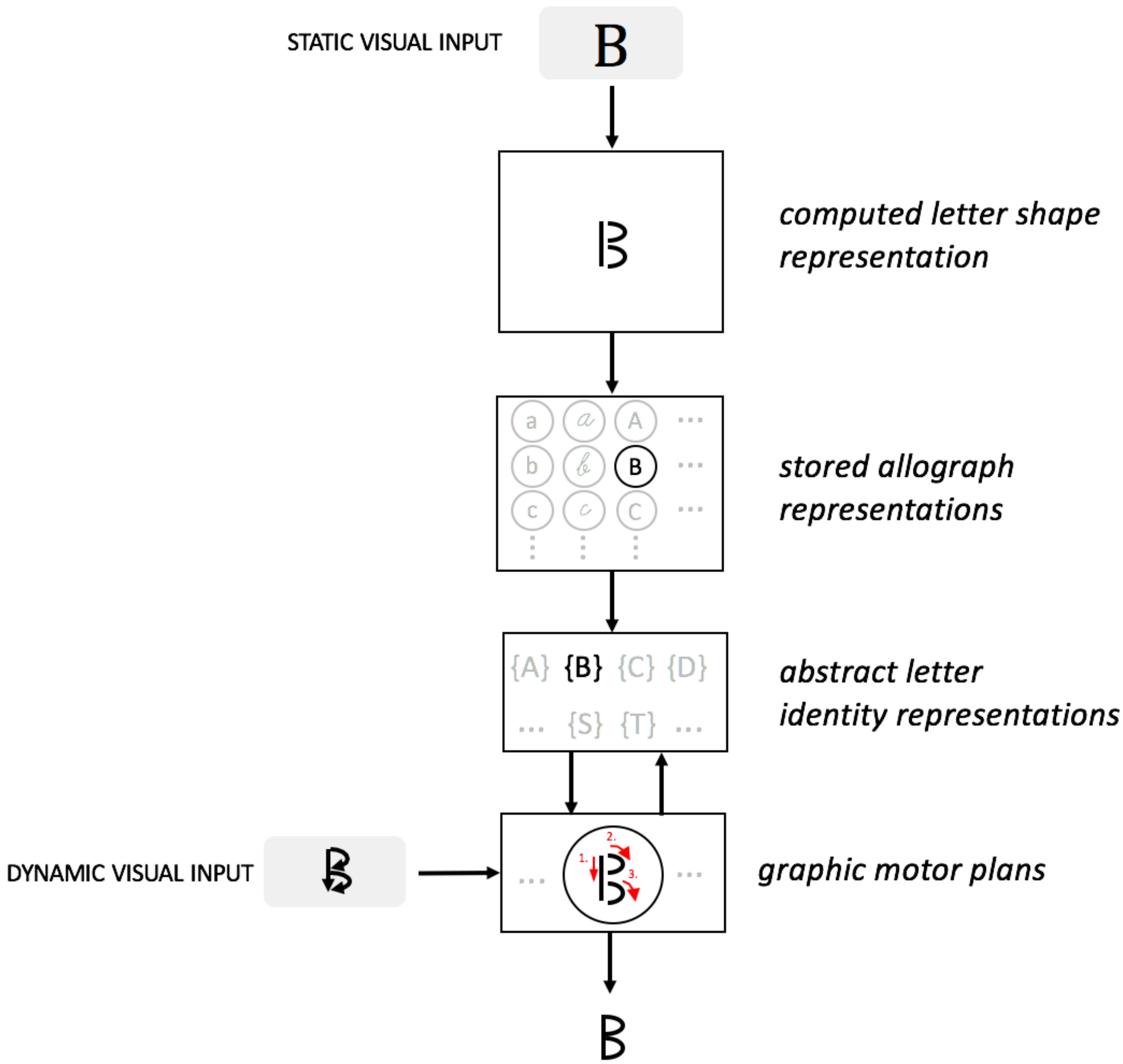

Figure 6. Schematic indicating the proposed mapping from dynamic letter input to letter graphic motor plans to abstract letter identities. Recall that NGN's deficit affects the mapping between allograph representations and abstract letter identities.

We propose that the links between abstract letter identities and graphic motor plans are bi-directional, such that activation flows not only from abstract letter identities to graphic motor plans, but also from graphic motor plans to abstract letter identities. In addition, we propose that observing the standard production of a letter activates the corresponding graphic motor plan. Taken together, these assumptions provide a straightforward explanation for the effects of letter production information on NGN's letter identification performance. When NGN observes the standard production sequence for a letter, as in the Dynamic-Forward condition of Experiment 2 or when watching an experimenter write letters, the corresponding graphic motor plan is activated, leading in turn to activation of the abstract letter identity. This process bypasses NGN's deficit in mapping allographs to abstract letter identities, allowing him to perform well despite the deficit.

Conceivably, NGN might have shown even more improvement in letter identification if our Dynamic-Forward displays had more closely mimicked natural writing. As we have noted, the displays did not reproduce the within-stroke variation in writing velocity characteristic of natural writing. Our simulated writing was also quite slow, with a mean of 7.6 seconds for completing a letter (as opposed to less than one second for typical natural writing). These variables might fruitfully be explored in subsequent research. Nevertheless, our results demonstrate a clear beneficial effect of the Dynamic-Forward displays, despite the slow, constant-velocity motion.[4]

Observing a non-standard letter production sequence, as in the Dynamic-Reverse condition of Experiment 2, does not strongly activate the letter's graphic motor plan, because the observed production sequence does not match the sequence represented in the motor plan. As a

[4] NGN's mild deficit in activating graphic motor plans (see Case History) may also conceivably have limited the improvement observed with the Dynamic-Forward displays. If the graphic motor plan for the stimulus letter was occasionally not activated by the dynamic display, then of course any facilitatory effect of the motor plan on letter identification would not occur. However, the clear identification improvement observed with the Dynamic-Forward displays suggests that the corresponding graphic motor plans were usually activated.

consequence, the abstract letter identity accrues little if any activation via the links from motor plans to letter identities.[5]

Conclusions about the relationship between letter identification and letter writing in NGN also apply to intact reading and spelling systems. Our study adds to a growing literature demonstrating an impact of letter production information on recognition in unimpaired readers (e.g., Babcock & Freyd, 1988; Freyd, 1983; Parkinson & Khurana, 2007; Wiley, Wilson, & Rapp, 2016). For example, Freyd and colleagues (Babcock & Freyd, 1988; Freyd, 1983) have argued that cues to the letter production process (e.g., direction of strokes) are often present in static handwritten characters, and that these cues can contribute to character identification. In addition, adults' and children's letter recognition performance has been shown to benefit from writing training, and by production information provided during letter identification (Babcock & Freyd, 1988; Flores d'Arcais, 1994; Li & James, 2016; Longcamp, Boucard, Gilhodes, & Velay, 2006; Longcamp, Lagarrigue, & Velay, 2010; Longcamp, Zerbato-Poudou, & Velay, 2005). Wong, Wadee, Ellenblum, and McCloskey (in press) recently presented another form of relevant evidence, demonstrating surprising gaps in skilled readers' knowledge of a very common form of the letter *G* (the lowercase looptail *g* consisting of two closed loops, a connecting line, and an 'ear'). Wong et al. argued that the knowledge deficiencies reflected lack of experience in writing the looptail allograph. There is also neural evidence for activation of premotor brain regions (used in writing) during passive letter viewing, suggesting automatic activation when letters are perceived (e.g., James & Gauthier, 2006; Longcamp, Anton, Roth, & Velay, 2003, 2005;

[5]NGN's accuracy in the Dynamic-Reverse condition (80%), although significantly lower than that in the Dynamic-Forward condition (89%), was numerically higher than his accuracy in the Static condition (73%), and the difference between Dynamic-Reverse and Static conditions approached significance (p = .061). Hence, it is conceivable that the Dynamic-Reverse displays resulted in some activation of the standard graphic motor plans.

Longcamp, Tanskanen, & Hari, 2006; for a recent review, see: Longcamp, Richards, Velay, & Berninger, 2016). These data are consistent with our suggestion of bi-directional connections between specific representations used in reading and in writing of single letters, and suggest that letter production information may play some role not only in identification not only when letters are presented dynamically, but also in typical reading circumstances involving static letter stimuli.

Implications for acquired letter identification deficits

NGN’s letter identification deficit for static letters was attenuated when identifying characters drawn according to the standard writing sequence. This pattern suggests that cognitive deficits can selectively impair the (static) letter identification system, without eliminating the influence from the letter production pathway. That is, provided that the pathway from graphic motor plans to abstract letter identities is intact, dynamic letter stimuli drawn in a typical fashion should facilitate successful identification even if the static letter identification process is impaired.

A treatment that has been tested in some patients with acquired letter identification deficits may take advantage of the bi-directional connection between production and identification. In this treatment, patients are encouraged to trace letters they cannot identify (either tracing over the letter, or drawing it with a finger in the air or on a surface). Alternatively, the letter is drawn on the patient’s skin (by the patients themselves or by an experimenter). These methods have been shown to improve letter naming performance and word reading accuracy in some individuals (Maher et al., 1998; Nitzberg Lott et al., 2010, 1994; Nitzberg Lott & Friedman, 1999; Seki et al., 1995). Maher and colleagues (1998) suggested that “motor activity of copying the letters yielded an alternate modality of activation of the lexicon” (p. 645) for the individual they tested. Though underspecified, and proposed only for the particular individual tested, this account resembles the pathway we propose from graphic motor plans to abstract letter identities. Otherwise, positive training outcomes have typically been interpreted as an impact of tactile/kinesthetic information on letter identification. We suggest, however, that the beneficial effects may be due (at least in part) to the visual information about writing movements made available when letters are traced. Our results from NGN demonstrate that dynamic visual information about letter production can be sufficient to improve performance even without tactile/kinesthetic input. Additional research will be required to sort out the relative contributions of visual, tactile, and kinesthetic information (which may differ across individuals with different forms of impairment), and also to articulate and test theoretical claims about the cognitive mechanisms underlying tactile/kinesthetic contributions.

Conclusions

We have presented results adding to a growing body of evidence that knowledge about writing can contribute to reading. Perhaps more importantly, we have offered theoretical proposals more specific than those in previous research concerning how letter production knowledge affects reading at the level of cognitive representations and processes. We proposed that letter stimuli carrying information about the standard production of the letters activate stored motor plans for letter production, which in turn activate abstract letter representations. In addition, we proposed that this pathway from stimulus to abstract letter identities is independent of the pathway that identifies letters on the basis of their static shapes. We hope that these proposals will stimulate additional research, and contribute to the broader discussion about the relationship between reading and writing processes.

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List of Supplementary Videos:

Video S1: Motion-Dot Stimulus Example from experiment 1

Video S2: Dynamic-Forward Stimulus Example from experiment 2

Video S3: Dynamic-Reverse Stimulus Example from experiment 2

Video S4: Dynamic-Random Stimulus Example from experiment 2

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Appendix A

Table A.1 Percentage correct by letter for Experiment 1.

	Condition	
	Static-Dot	Motion-Dot
A	100	100
B	50	100
C	100	100
D	50	0
E	100	100
F	100	100
G	0	50
H	100	50
I	100	100
J	100	100
K	50	100
L	100	0
M	100	100
N	100	0
O	100	100
P	100	0
Q	0	0
R	50	50
S	50	50
T	0	0
U	50	100
V	100	100

W	100	100
X	50	50
Y	50	0
Z	100	100

Table A.2 Percentage correct by letter for Experiment 2.

	Condition			
	Static	Dynamic-Forward	Dynamic-Reverse	Dynamic-Random
A	92.3	75	100	100
B	76.9	100	100	66.7
C	84.6	91.7	75	100
D	61.5	83.3	100	66.7
E	100	83.3	87.5	100
F	92.3	91.7	100	66.7
G	23.1	66.7	12.5	0
H	92.3	100	100	100
I	92.3	100	87.5	100
J	76.9	83.3	100	100
K	53.8	100	75	33.3
L	76.9	91.7	50	33.3
M	84.6	100	100	100
N	53.8	100	100	100
O	92.3	100	100	100
P	84.6	91.7	75	100
Q	53.8	83.3	37.5	66.7
R	30.8	41.7	12.5	33.3
S	61.5	100	62.5	100
T	76.9	91.7	87.5	66.7
U	92.3	100	100	33.3
V	92.3	91.7	100	66.7
W	30.8	75	50	100

X	84.6	100	100	66.7
Y	84.6	91.7	87.5	66.7
Z	69.2	91.7	87.5	66.7