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Review

On the Legibility of Mirror-Reflected and Rotated Text

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Abstract: We happened to observe that text that was reflected about either the horizontal or vertical axis was more difficult to read than text that was reflected about first one and then the other, which amounts to a 180-degree rotation. In this article, we review a number of studies that examine the nature of recognizing reflected and inverted letters, and the frequency of mirror reversal errors (e.g., confusing 'b' for 'd') in children and adults. We explore recent ideas linking the acquisition of literacy with the loss of mirror-invariance, not just for text, but for objects in general. We try to connect these various literatures to examine why certain transformations of text are more difficult to read than others for adults.

Keywords: mirror-reversal; left-right reversal; reading; reversal errors; mirrored text

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Recently, one of us held up a page of printed text (Figure 1A) to their webcam to take a picture. The camera software by default created a mirror-image snapshot (i.e., the text was reflected or mirrored about the vertical axis, Figure 1B) thereby rendering the text virtually illegible. Correcting or undoing this sort of reflection can be trivially accomplished using any number of image processing software packages that include built-in functions such as 'reflect vertical', 'reflect horizontal', 'rotate left', and 'rotate right'. It was with some surprise that when the wrong function was accidentally applied and instead of reflecting along the vertical axis, the image was reflected along the horizontal axis, the text, although now reflected twice, was now more easily legible (Figure 1D). It is of note that this 'double reflection' is equivalent to a 180° rotation of the text. With only a few mouse clicks, it was clear that when normally-oriented text is mirror reflected about the horizontal axis it again becomes virtually illegible (Figure 1C). This brief series of webcam-picture inspired observations demonstrated a basic property of text perception and reading: the legibility of text is reflection variant and rotation invariant.

Inspired by these observations, we conducted a review of the corresponding work on the intersection of symmetry, reflections, and the legibility of text. We found a large body of literature on mirror-reading and writing; mirror-reversal errors of single letters in reading, copying, and writing; many studies on perception of normal and mirrored single characters; but only a small number of studies on combinations of geometric transformations including both inversion (up-down mirroring) and reflection (left-right mirroring). In this paper, we review the literature on mirror-reversals and inversions of text and synthesize some recent work and ideas on how representational mirror-invariance not only for letters but also for objects may be lost when someone learns how to read.

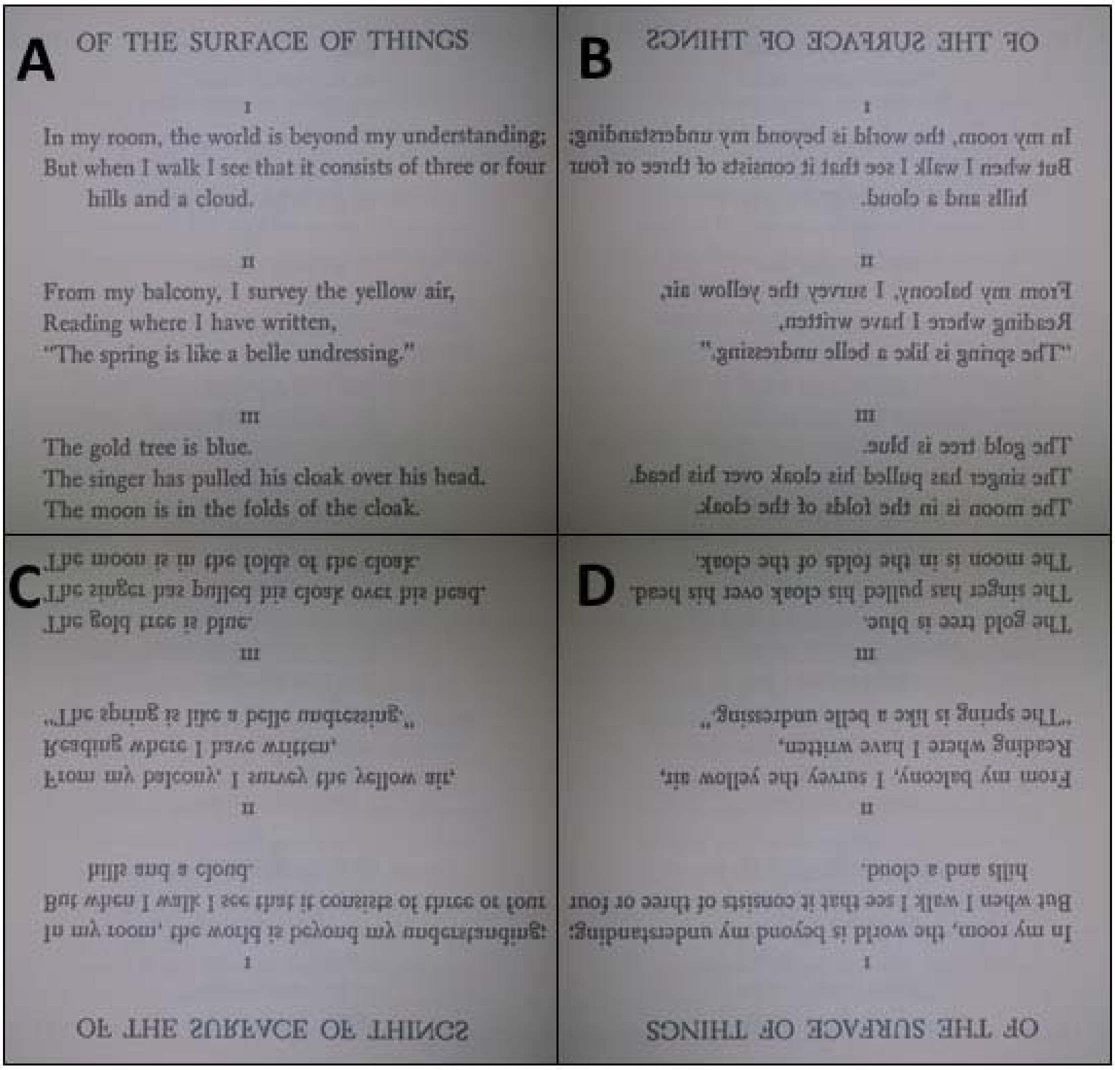

Figure 1. Four examples of the same poem "On the Surface of Things" by Wallace Stevens. (**A**) Normal (upright); (**B**) Reflected about the vertical axis; (**C**) Reflected about the horizontal axis; (**D**) Reflected about the vertical and horizontal axes, which is equivalent to a 180° rotation.

Before proceeding with a survey of the literature, we wish to make several observations about mirrored text as it occurs outside of a laboratory setting. Apart from webcams and mirrors, mirrored text can be seen on the front of ambulances, where the word "AMBULANCE" is mirror-reflected so that it appears correctly in one's rearview mirror (Figure 2A). Mirrored text is also a feature of certain scripts: Boustrophedon, literally meaning "ox-turning", is text that is written left-to-right and right-to-left on alternating lines as one would plow a field, forwards and then backwards. The letters of alternating lines are mirror-reversed (Figure 2B). Some inscriptions in ancient Greek and Latin as well as Luwian (Hittite) hieroglyphics were written in this manner. Tablets found on Easter Island appear to be written in rongorongo (Figure 2C), a script or protoscript that may be in reverse boustrophedon, meaning that alternating lines are flipped about the horizontal axis instead of reflected about the vertical axis. A tablet would be read bottom-to-top, rotating the tablet 180° after every line.

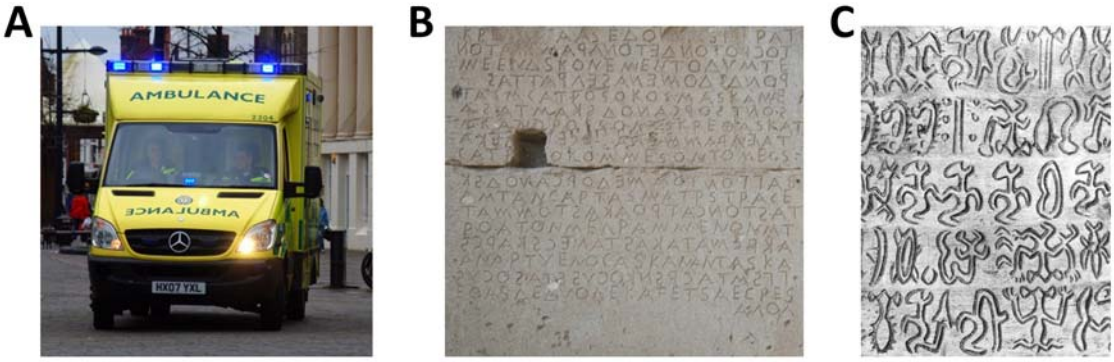

Figure 2. (**A**) An ambulance with mirrored text on the hood so that it appears in the correct orientation in one's rearview mirror. By neiljohnuk from East a bit., ENGLAND! (DSC_0068) CC BY 2.0 via Wikimedia Commons; (**B**) Fragmentary inscription of a code of law from Gortyn (Crete). Written in boustrophedon so that alternating lines are read left-to-right and right-to-left. Each other line is left-right mirror-reversed. By PRA (Own work) CC BY-SA 3.0 via Wikimedia Commons; (**C**) Fragment of rongorongo script.

The fact that the mirror-reversed word "AMBULANCE" can still be read in Figure 2A suggests that the visual system may incorporate some amount of mirror invariance, at least with respect to simple single-letter or single-word representations of text. This notion is bolstered by the fact that young children often make spontaneous mirror-reversals of single letters when learning to read and write [1–4]. Typical errors include reading or writing 'b' for 'd' or transposing the position of letters in a word as in 'was' for 'saw', but also include mirror-reversals of other letters that do not form a new letter upon reversal (e.g., 'a'). Left-right mirror reversal errors are more common than up-down errors [1,5,6]. Confusions between mirror images of letters and letter-like symbols occur when recalling symbols from memory as in writing [7], but also for matching tasks, where a child is asked to pick out a symbol that looks exactly like a target that is continuously visible, even if given explicit instructions and training to not select the mirror image [4]. These results suggest some degree of left-right mirror-invariance in children (see also [8]), which may account for why the left-right mirrored text in Figure 1B may seem easier to read than up-down mirrored text in Figure 1C [9,10].

Initially, however, mirror-reversal errors in children were not thought to be the result of normal developmental or general perceptual process; rather, reading and writing errors were seen as diagnostic of disorders that could persist into adolescence and adulthood. Consistent mirror-reversal errors in identification and reading were called strephosymbolia, meaning "letter turning" [11–15]. Throughout the 20th century, researchers were interested in mirror-reversals in reading and writing as diagnostic features of some disability that predicted good and poor adult readers. Jastak [16] reviewed 170 papers already published by the early 1930s on reading difficulties and their purported causes. We examine several proffered explanations for why mirror-reversals occur any why they may occur more often in poor readers to get a flavor of direction of research at the time and subsequent trends. One theory posited that mirror-reversal errors are perceptual in nature, perhaps having to do with early visual processing of orientation or spatial perception that is underdeveloped or deficient [17–22]. Others suggested possible physiological underpinnings [12,23], differences in memory capacity or ability [24,25], differences in eye movements or oculomotor control [26–28], and differences in mental imagery ability [29]. Attempts had also been made to connect mirror-reversal errors and reading ability more generally to handedness [27,30,31], dyslexia (e.g., that individuals with dyslexia were more fluent at reading and writing inverted and mirrored text than normals, [32–34]), and intelligence [35]. Part of the impetus for considering mirror-reversal errors as symptomatic of disorders were reports of acquired mirror-writing and reading after stroke or injury [36–40] and Gerstmann's syndrome [41,42], of which left-right confusion is a symptom [43,44]. These lines of research emphasized mirror-reversal errors, and therefore mirror-invariance, or an inability to discriminate between left-right mirrored images as an acquired perceptual deficiency.

However, it is ultimately very difficult to conclude anything diagnostic in terms of reading disorders based on reading reversal errors made at a young age [6,45–47]. Nearly all children make reversal errors when learning to read in English [5,48,49]. In addition, mirror reversals of letters are not the most common sort of error in children learning to read [27] (although see [50]), and the amount of reversal errors that children make gradually decreases with age until they almost disappear by age 10 [48,51–53] (although see [54]). Relatively few mirror writing errors occur in children who learn a language in which facing direction does not distinguish between characters, like Japanese [55]. Furthermore, adults also make similar mirror-reversal errors when familiar characters are replaced with reversible, unfamiliar, letter-like symbols [17]. As we will discuss in greater detail later, illiterate adults make the same sorts of mistakes as children [56]. Taken together, these results suggest that there is nothing unusual about mirror-reversal errors in reading and writing, either for children or for adults. One exception may be in the case of dyslexia, where reversal errors may persist for longer [32,57–61].

Towards the latter half of the 20th century, theories for explaining mirror-reversals shifted to attentional and learning-based approaches [48,62]. Some of these ideas had been suggested early on [63,64], but were not popular. According to these perceptual learning accounts, mirror-reversal errors are due to a failure in recognizing facing direction as a relevant stimulus dimension. Gibson, et al. [48] argued that the knowledge of the relevance of this dimension is acquired when learning how to read. That is, learning to read is a perceptual learning problem that requires learning which features are relevant for letter identification, including the facing direction of 2-D symbols [65,66]. This is a matter of feature selection, not feature detection. Mirror images are readily discriminable and look different when presented simultaneously, even for children [67–70] (although see [71]). With age, children learn to discriminate between and remember different types of mirror-symmetric objects [71,72]. Mirror confusions arise because children have not learned that when a letter is reflected or rotated, it is called something else [73]: a ‘b’ is called “dee” when it is reflected about the vertical axis. This is not true for virtually any other objects, for which infants and adults exhibit some amount of mirror- and rotational-invariance.

In the natural world, there are few objects whose left-right directionality matters for identification—whether you see a tree or car from one side or the other, it is still the same object. Observers have difficulty in distinguishing between previously seen scenes and mirror-reflected images of those scenes in memory tasks [74]. One exception may be the crescent moon, which is illuminated from different sides depending on whether it is new or old, but observers seem not to internalize this difference or remember it in memory tasks [75]. It is with some irony that some of the simple heuristics for determining whether the moon is waxing or waning involve mirror-reflected letters (i.e., in the northern hemisphere, if the moon is shaped like a ‘p’ it is progressing—waxing, and like a ‘q’ it is quiescing—waning). Certain man-made artifacts do have distinctive facing directions such as the faces on coins, but these are also notoriously misremembered [76,77]. In fact, Latin letters seem to be one of the few examples where facing direction is a distinguishing feature that we must remember for identification. One exception may be navigation, relative position, and the representation of space (egocentric and allocentric)—it is important to know whether your home is on the left or the right side of the street, whether the train is facing in the correct direction of travel, or which way to turn if you are in a maze [78]. Based on similar observations, Corballis and Beale [79] proposed that mirror discriminability emerges from first acquiring left-right discriminability in the course of learning to distinguish left and right on our own bodies before applying it to the world, objects, and ultimately letters. However, environments are rarely perfectly symmetrical and illiterate adults have no difficulty distinguishing between the sides of their body or navigating in the world, but still make more mirror-reversal errors than literate adults [56,80].

Learning to read calls to attention the fact that facing direction is an important distinguishing feature for a certain class of objects. When one learns to read, one therefore loses mirror-invariance, at least with respect to letters in a reading context. Several studies have indeed found that most mirror-reversal errors occur for children between three and four years of age and the number of errors gradually decreases until about age 10 when performance reaches adult levels [48,62,81]. For age-matched children, weak readers make more errors overall and more of those errors are reversal errors than strong readers [82,83]. Likewise, children for whom learning to read has been deferred by a year make more reversal errors than children of the same age who have started to learn to read [52]. The act of learning to read reduces these errors not solely because they have become more proficient in reading, but because they have improved in discriminating between mirror-symmetric objects.

One of the more compelling tests of this hypothesis has been the investigation of mirror-reversal errors in illiterate and ex-illiterate individuals. Danziger and Pederson [84] tested 10 different language communities for mirror-discriminability of abstract line figures. Literates in almost all tested languages were more sensitive to these differences than illiterates. The one exception were readers of Tamil, a language that has no enantiomorphs (mirror-reversed letters), who were as poor at the task as illiterate individuals. In a follow-up study, it was found that individuals who spoke only Tamil were worse at this task than those who were familiar with both Tamil and a second language that used the Latin alphabet [85]. It was therefore not specific exposure to language in general that led to a loss of mirror-generalization (and therefore a reduction in mirror-reversal errors), but, rather, exposure to a specific stimulus class for which facing direction was a non-accidental, identifying feature. In a more comprehensive study comparing illiterate, ex-illiterate, and literate adults, participants had to sort cards with pictures of circles with a diagonal drawn through them based on either the size of the circle or the orientation of the diagonal [56]. Sometimes, the second feature was uninformative (e.g., small and large circles with vertical lines); sometimes, the second feature was redundant (e.g., all small circles also had left-tilted lines); and sometimes the features were orthogonal to each other such that if the task was to sort based on the orientation of the lines, both small and large circles had left-tilted lines. Illiterates made the most errors in the orthogonal condition, indicating that they were unable to ignore the irrelevant feature of stimulus size, even when told to sort based on the orientation of the diagonal. They had no trouble doing this task if the two dimensions were colors and shapes. This suggests that the effect of literacy is attentional and not perceptual: ex-illiterates and literates were able to perform the task well. It also illustrates that just a small amount of training (ex-illiterates had taken a few courses as adults) could learn that facing direction was a relevant feature rather quickly. Importantly, this effect was observed as a function of reading experience, not instructional manipulation within the experiment. When given more explicit instructions and training trials to point out mirror symmetry and how it can be used to perform the task, illiterates still made errors. In a different study, illiterates, ex-illiterates, and literates performed a same-different matching task with pseudo-words made from letter strings, false fonts (letter-like symbols), and pictures [86]. Illiterates showed no response time difference between normal and mirrored images when the response was "same" for any of the stimulus types. Ex-illiterates and literates, however, were slower at responding "same" to mirror images, with the largest difference being for literates responding to pseudo-words (e.g., "iblo oldi"). This finding is taken to show that, with literacy, the visual system loses some mirror symmetry invariance, especially for letter strings (see also [87]).

Illiteracy and poor reading proficiency not only lead to mirror-reversal errors in identifying and copying letters, but also result in errors for non-letter objects. For example, poor readers tend to make left-right reversals in reassembling matchstick figures from memory [88] and in remembering the facing direction of shapes and asymmetrical figures [89]. The detection of mirror symmetry of figures can also be negatively primed by briefly presented mirror-symmetric letters [90]. This negative priming effect increases with age [91], suggesting that it is the result of inhibition of a mirror generalization process acquired during reading. Recently, Dehaene and colleagues have summarized these results as the "neuronal recycling hypothesis" [92–96]. According to this hypothesis, cultural acquisitions (such as reading) must find a "neuronal niche" in pre-existing, perhaps evolutionarily determined, cortical organization structures. New functions are mapped onto structures that subserved evolutionary older functions, sometimes resulting in small functional losses as those older functions are "overwritten". This may include a repurposing of face-selective neurons for word recognition, resulting in neural competition and left-lateralized word processing (visual word form area, VWFA) and consequently right-lateralized face processing [93,94,97–100]. For a review of the implications and predictions of this idea, see [92,101]. To test this hypothesis, Kolinsky and Fernandes [102] showed illiterates, ex-literates, and literates two sequential pictures of objects and asked them to say whether they were the same or different, ignoring inversions (planar rotations) and mirror reflections (rotations about the vertical axis). Accuracy improved as a function of literacy. Importantly, reaction time for saying "same" for illiterates was no different for identical, rotated, or mirror-reflected objects. However, for ex-literates and literates, reaction times were fastest for second presentations of identical objects, slower for mirror-reflected objects, and slowest for rotated objects. Similar to [86], literacy in adult readers disrupts mirror generalization for objects and abstract geometric shapes, interfering with non-linguistic object recognition. Literacy also has a greater effect on the ability to make mirror-image discriminations than on rotation or orientation-based discriminations [87]. This difference may reflect the special kinds of features that are learned in literacy (i.e., discriminating 'b' from 'd'), although it should be pointed out that 'b' and 'p' are planar rotations that also must be distinguished.

At the same time, adults who are proficient readers often still make reversal errors with novel objects and symbols [17] (although more errors are typically made about an object's axis rather than left-right reflection [103]), suggesting that the unlearning of mirror generalization is somewhat stimulus- or at least domain-specific [33,104,105]. Even for letter stimuli, mirror generalization may be inhibited or unlearned only for certain letters (those that reverse to other letters) and not others [106]. Likewise, training to read mirror-reversed text made up of a specific subset of letters does not transfer to new words composed of unstudied letters [107,108]. It is therefore interesting to examine the extent to which mirror generalization still persists after learning to read.

Acquiring literacy may have a general effect on holistic processing of stimuli. For example, illiterates tend to rely on more holistic processing of faces and show greater influence of irrelevant, aligned facial features on task-specific features [109]. Mirror-reversal errors may arise due to different encoding strategies, in particular, a greater reliance on holistic visual coding of the letters or words than on analytic coding of individual features to allow for greater letter discriminability. For example, poor readers also make more errors in memory for relative spatial positions and orientations of objects [89,110]. Learning to read may therefore engage a more analytic form of processing by which individual letters are identified and special attention is paid to the distinguishing features of, for example, mirror-reversible letters [104,111]. As a result, reading upside-down text (i.e., rotated 180°) may become more difficult with reading experience [112]. Another example of such holistic processing occurs in three- and four-year-old children who were taught to discriminate between differently oriented U-shaped figures [113]. They were readily able to learn the difference between upward and downward facing shapes, but had difficulty with left-right discriminations. Training on this task becomes easier until age 10, when performance stabilizes and resembles that of adults. The largest increase in performance occurs around ages five or six when children learn to read. Similar results obtain for oblique discrimination (/ vs. \), although the results depend on how the stimuli are presented, simultaneously or one at a time, side-by-side, or one above the other [1,67,114–121]. Adults do not show as many errors, but show similar patterns in reaction time, such that same-different judgments on left-right mirror symmetric U-shaped objects are slower than for up-down mirror symmetric objects [122] (see [120] for a review). Children can learn to make left-right mirror discriminations at a young age if given detailed feedback [7,123–125]. However, these results are task dependent, with some tasks in which mirror discriminations must be learned being harder than others [69,115,123]. Overall, children, even before they learn to read, can use orientation and facing direction as a form cue, but it is not the most salient feature, especially when contour and color information can be used instead [126–130]. In all of the above examples, learning to identify and differentiate letters and letter-like forms occurs by focusing attention on specific stimulus features, that is, a transition to a more analytic processing style. These effects, however, appear to be domain- and stimulus-specific as opposed to a broad change in how all objects are represented by the visual system. Furthermore, a general loss of mirror-invariance (or, equivalently, a gain of mirror-discriminability) does not explain why different kinds of transformations of text (left-right mirroring, up-down mirroring, and 180° rotation) result in varying reading difficulty.

We began this article by making the observation that when an entire word or sentence is mirrored first left-right then up-down (or rotated 180°), it is easier to read than when it is mirrored only once. Most of the studies considered thus far have focused on mirror-reversals of single letters, either viewed individually or in the context of a word. There is reason to believe that different processes may be involved in the identification of individual rotated characters or symbols in contrast to reading of rotated or inverted text [131]. For example, in reading passages of text, reading difficulty increases as a function of orientation away from vertical, either upright or upside-down [132–135]. In the following description of results, we will follow Kolers in using "rotation" to refer to rotations in the plane, that is, about the depth axis, "reflection" or "mirroring" to refer to rotations about the vertical axis, and "inversion" to refer to rotations about the horizontal axis.

To our knowledge, Kolers' work in the 1960s is the first systematic investigation of the effect of a large number of geometric transformations on reading speed as a function of practice [136]. In addition to normal text and the three types of transformations mentioned above, reading speed was also examined for text in which each letter was individually reflected about the vertical axis prior to application of the other kinds of transformations. On the first day, it took approximately one minute to read aloud as quickly and accurately as possible 25 lines of the normal (untransformed) text, three minutes to read rotated text and normal text with individual letters left-right reflected, and 4.5–5.5 min to read all other types of transformed text. Participants practiced reading for eight days and on the eighth day showed improvement with all types of transformations. Reading time of normal text with individual letters reversed improved from 3 to 2 minutes, reading time of rotated text improved from 3 to 2.5 min, and all other transformations improved from 4.5–5.5 to 3–3.5 min. Dividing the subjects by familiarity with a language in which text is read right-to-left such as Hebrew or Arabic, it was found that some of those subjects took less time to read left-right mirrored text than inverted (up-down mirrored) text. In a separate study, individuals with familiarity with one of those languages read mirrored text faster than those who only knew English, suggesting that reading direction practice may interact with reading speed in a different language [137]. However, the results were not clear-cut as native speakers of Hebrew who were familiar with English showed a different pattern, with left-right mirrored English text being read the slowest (7 min on the first day and 3.5 min on the eighth), while rotated and inverted text were read faster, but at comparable speeds (5 min on the first day and about 3 min on the last) [136]. Both rotated and mirrored text were read right-to-left so differences in reading time could not solely be explained by reading direction familiarity.

Subsequent work examining training and transfer in English speakers between different types of transformations found that learning to read mirrored text was easiest to do, irrespective of the type of text practiced during training [138]. That is, training on any type of transformed text had almost the same effect on subsequent transfer to mirrored text during testing as initially practicing with mirrored text. Interestingly, when an outlier in transfer from training with normal text with letters left-right reversed to rotated text is excluded, transfer to rotated text is just as good as to mirrored text. The measure used was percentage of transfer from training to test, not reading speed during test. Absolute reading speed was considered a biased measure of trainability because it failed to account for differences in initial difficulty in reading the different transformation types. Therefore, although normal text with letters left-right reversed was fastest to read during test (after normal, un-transformed text) at 3.24 min on average, there was greater transfer (as measured by a difference in reading time before and after training normalized by the difference in reading time between when training and testing with the same transformation type) to mirrored, reversed, and reversed text with individual letters reflected when averaging across training type. That is, learning to read those text transformations was more trainable. When compared to a pre-training baseline, the reading speed of inverted text improved at almost twice the rate of rotated text, but this was likely due to the relatively faster rate at which participants read rotated text before training. There was no correlation, however, between training proficiency and difficulty of the training material. The largest number of geometrical reading errors (e.g., confusing 'b' for 'p') during training occurred not in the inverted, but in the mirrored text condition, while the least number of errors (about half as many) occurred when training with rotated text.

Across these several studies, it is difficult to extract any meaningful patterns. Kolers and Perkins were not able to find a simple set of transformation types whose elements could be combined either additively or multiplicatively in order to predict reading errors, reading time, or trainability [9,136,138]. Combinations of different kinds of rotations did not increase reading difficulty in a linear way, suggesting that readers of geometrically transformed text are not performing sequences of mental rotations or transformations on letters or words in order to read them. Further evidence that readers are not performing rotations of individual letters comes from the fact that when single letters embedded in words are mirror-reversed, reading time is longer than if the entire word is mirror-reversed [9,10,136,139]. Observers are in fact able to identify a rotated letter even before determining whether it is mirror-reflected or not, suggesting that they do not need to perform mental rotation for identification or naming of simple patterns [140–145] and even for novel letter-like shapes [66] (although they can mentally rotate the images if the task demands it [146]). Unlike for objects [147,148], identification time for letters does not depend on letter orientation. It should be noted that while these early studies found no effect of orientation on letter identification reaction time, the data were noisy, sometimes effects were found [141], and single letter identification is not rotation-invariant when accuracy is the dependent measure and presentation times are very brief (<30 ms) [149] or when observers are asked to make same-different judgments of rotated letters [150]. Inverted, reflected, and rotated letter recognition may therefore involve some sort of corrective process such as mental rotation either before or concurrent with identification [135,151–153], but not necessarily performed on a letter-by-letter basis [138]. This may explain why inverted and mirrored texts are more difficult to read than upright and why, when the orientation of a letter is unknown (whether 'p' is upright, rotated, mirrored, or inverted), there is a bias for preferring upright or rotated interpretations [9,10]. Note, however, that only the 180° rotated text can match normal text with a rotation in the plane; left-right and up-down mirrored text must be rotated through the plane in order to return to their normal orientation. There may therefore be something special about the nature of 180° rotated text (Figure 1D) that contributes to its relative readability. Indeed, Kolers suggested that each type of transformation may involve its own decoding mechanism: if correct letter orientation were simply a matter of applying some common mental operation (e.g., mental rotation), then the frequency of errors of mistaking 'u' and 'n' and 'f' and 't', for example, would be the same for all kinds of text transformations, but that is not the case [10].

Another reason why certain transformations are harder to read than others can be explained by familiarity with reading direction. Individuals familiar with Arabic or Hebrew are able to read mirrored text faster than those only familiar with English [136]. There may also be an interaction with writing direction familiarity: letter-facing direction may partially be encoded by pairing motor actions (writing) with orientation direction. When adults learn new characters, they remember their proper facing directions better if they have to write the characters by hand rather than typing them [154]. The production of mirror-reversals during writing, however, is beyond the scope of this review. Mirror-writing involves qualitatively different processes from mirror-reading since, in reading, the letters are continuously visible, but in writing the correct facing direction of letters must be retrieved from memory. For some recent work on mirror-writing see [3,155–161].

Finally, we consider several other factors that may contribute to differential reading times for types of text transformations. One possibility is that difficulty in reading mirrored and inverted text may arise due to temporary lapses of frame of reference—i.e., forgetting which way the entire sentence is oriented [162]. This is particularly problematic if letters face one way and scanning direction is reversed [9]. A letter's facing direction therefore depends on reading direction: the symbol 'b' can be either the letter 'b', 'p', 'q', or 'd' depending on which transformation was applied. When one encounters that symbol, there may be a temporary lapse in the frame of reference rendering the rest of the sentence difficult to read and the reader has to reorient to remember not only which way letters are facing, but also in which direction they should be reading [4,149]. When presented with an inverted word in which several letters are upright, it is difficult to notice that some of the letters are actually upright [163–165]. This has been described as a Thatcher effect for letters [166]. The explanation is that inverted letters become egocentrically upright when we begin to read the word and, in losing the frame of reference, nothing appears out of the ordinary when we encounter an upright letter. When most of the word is upright however, and in the standard egocentric frame, the inverted letters stick out just like inverted parts of a face in the Thatcher illusion.

The idea of a frame of reference can also apply to objects: although it is true that we can recognize a picture of a hammer and a mirror-image of the same hammer equally well, the hammer still has some directionality associated with it [167,168] and a canonical orientation [147,148,169–172]. This notion is supported by the fact that mirror-reversals of letters of children in matching and copying tasks are asymmetric—upright letters are rarely mismatched with their mirror images, but mirror-reversed letters are often copied and matched to normal letters [4]. Young children who have not yet learned to read, make more orientation errors in copying, drawing from memory, and matching shapes with no inherent directionality (e.g., a stretched-out diamond) than with objects, e.g., a spoon, [173].

Under this view, in acquiring literacy, a reader develops templates or schema for letters in canonical orientations [174]. A letter's orientation can be used to determine the frame of reference for an entire word or sentence. For example, an inverted 'A' may provide a cue that the entire text is inverted. Reading of inverted, mirrored, or rotated text involves a detection or an alignment of an appropriate frame of reference [143,167,175–177]. As a result, response time to individual letters at different orientations is predicted by the orientation of the previously seen letter [178]. In the context of an entire word or sentence, therefore, moving from one letter to another could facilitate the maintenance of a consistent frame of reference (as determined by the previous letter) until a reversible letter is encountered, which leads to confusion. When combined with changes in reading direction, this creates additional opportunities for confusion. Although note that the text that 180° rotated text (Figure 1D), which is read right-to-left is easier to read than the up-down mirror reflected text (Figure 1C) which is read left-to-right. Reading direction on its own therefore does not account for the differences in reading difficulty. It is interesting to note that in Kolers' original experiments in which subjects practiced reading aloud geometrically transformed text, the text was transformed one line at a time [136]. For example, 180° rotated text was not read from the bottom of the page to the top, but was still read top-to-bottom because each line was rotated independently. This may have complicated the results by putting into conflict the frame of the text on the whole page with that of a single line. To our knowledge, an experiment that dissociates these confounders has yet to be performed.

The notion of a frame of reference can apply more generally to how individuals understand reflections in mirrors [179,180]. Although we have been describing some text transformations as "left-right mirror reversals", a mirror does not reverse left-right, but through an axis perpendicular to the mirror, i.e., front-to-back [181–187]. When examining their own reflections in mirrors, observers tend describe them as identical instead of reversed or opposite, suggesting an important role for an exocentric (as opposed to egocentric) frame of reference [179]. Familiarity with certain frames of reference over others may account for why the recognition of one's own face is better when it is shown mirrored, while the faces of others are better recognized when shown in the manner in which we are used to seeing them (i.e., not mirrored) [188–192]. In general, however, naïve understanding of how reflections work and appear is quite poor [193–197]. It is possible that given an appropriate frame of reference with many cues to text direction, such as seeing a mirrored image of a person holding a sheet of text, may facilitate the maintenance of a consistent frame of reference during reading. In contrast, in all experiments reviewed here, a reader is presented with mirrored text on a sheet of paper, which, out of context and at odds with the rest of the un-mirrored environment (e.g., their hands holding the paper, the table at which they sit, etc.), may present an especially difficult situation in which the appropriate frame of reference must be maintained for reading. To our knowledge, no experiments have examined the effect of scene and environment context on the reading of transformed text.

We began this article with the observation that certain geometric transformations of text are easier to read than others. We have gone over several lines of research that speak to why mirrored text is more difficult to read: confusions in facing-direction of mirror-symmetric letters like 'b' and 'd', loss of frame of reference, incomplete loss of mirror-invariance (or, conversely, development of mirror-discriminability), etc. Unfortunately, there is not as of yet a conclusive explanation for why text that is reflected twice is easier to read than text that is only reflected once [9]. Part of the effect may be due to reading and writing direction familiarity or the fact that twice-reflected text is equivalent to a 180-degree rotation in the plane and there may be something special about that transformation as opposed to others. What is clear however is that our technological age has taken image transformations out of the reflecting pool and looking glass, and placed them at our fingertips with our webcams, smart-phones, and image processing software packages. This digital proximity reminds us that our curiosity and empirical exploration of symmetries in our environment and in the legibility of text has a long and robust history.

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