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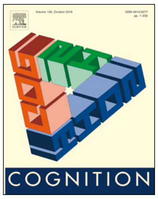

Brief article

Braille readers break mirror invariance for both visual Braille and Latin letters

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ABSTRACT

For this study, we started from the observation that the poor adequacy of a script to the requirements of the human visual system strongly impacts some aspects of reading expertise (e.g., fluent reading). Here we investigated another of these aspects, namely the ability to break mirror invariance, which makes it hard for readers to ignore the mirrored contrasts of letters even if this hinders performance. In particular, we hypothesized that this ability would be preserved for the visually presented letters of the Braille alphabet despite their poor fit to the constraints of the human visual system, as it did for congenital Braille readers when they explored the same letters through the tactile modality (de Heering, Collignon, & Kolinsky, 2018). To test so, we measured visual Braille readers' mirror costs, indexing for their difficulty to consider mirrored items as identical compared to strictly identical items, for three materials: Braille letters, geometrical shapes and Latin letters, which invariant properties are typically considered as having been selected through cultural evolution because they match the requirements of the visual system. Contrary to people having never experienced Braille, Braille readers' mirror cost was of the same magnitude for Latin letters and Braille letters and steadily increased the more they had experience with the latter material. Both these costs were also stronger than what was observed for geometrical shapes. Overall these results suggest that the poor adequacy of the Braille alphabet to the visual system does not impede Braille readers to break mirror invariance for the Braille material.

1. Introduction

Mirror invariance refers to the predisposition to associate two mirrored images to the same object despite their different retinal projections (for a review, see e.g., Corballis & Beale, 1976). These so-called reversals (Orton, 1937) are, in fact, typically associated to a change of viewpoint in the natural world that do not induce a change of identity. They therefore convey little information about the object that is viewed ("a tiger is equally threatening when seen in right or left profile", Rollenhagen & Olson, 2000). Yet literacy (reading-writing) is known to profoundly reorganize *mirror invariance*, most probably because of the cultural recycling of pre-existing cortical maps (Dehaene & Cohen, 2007; for other more general explanation such as the suppression of holistic strategies, see Fernandes, Vale, Martins, Morais, & Kolinsky, 2014; Lachmann, 2018; Lachmann & van Leeuwen, 2014). When literacy is acquired, people consider mirrored letters such as "b" and "d" as *different* despite they are mirror reflections of each other, which improves their discrimination of this type of letters. This phenomenon is typically referred to as the ability to *break mirror invariance* and has been associated to four main observations.

The first observation is that this capability requires the learnt script to include mirrored characters to be discriminated from each other. Tamil does not include such letters and Tamil readers treat mirror-image reflections of simple figures as identical despite the instruction to treat them differently (Danziger & Pederson, 1998). The second observation is that the ability to break mirror invariance partially transfers outside the alphabetic domain, and therefore not only applies to reversible letters such as "b" and "d" (e.g., Duñabeitia, Dimitropoulou, Estévez, & Carreiras, 2013; Fernandes, Leite, & Kolinsky, 2016; Pegado, Comerlato et al., 2014) but also to non-reversible letters (e.g., "h"), false fonts, and non-linguistic materials such as geometrical shapes and pictures of objects, even though to a smaller extent (e.g., Fernandes & Kolinsky, 2013; Kolinsky et al., 2011; Pegado, Comerlato et al., 2014). Third, it has been observed that the ability to break mirror invariance develops as a function of literacy, even if it is acquired at an adult age (Fernandes & Kolinsky, 2013; Kolinsky et al., 2011; Pegado, Comerlato et al., 2014). Fourth, both beginning child readers and adult fluent readers, but not preliterate children (Fernandes et al., 2016) or illiterate adults (Kolinsky & Fernandes, 2014; Nakamura, Makuuchi et al., 2014), break mirror invariance *compulsorily* and are therefore unable to ignore

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mirror-image differences even when this hinders performance (Dehaene et al., 2010; de Heering, Collignon, & Kolinsky, 2018; Fernandes et al., 2016; Kolinsky & Fernandes, 2014; Pegado, Nakamura et al., 2014). In fact, only literates show a *mirror cost* when performing a speeded same–different orientation-independent comparison task, responding more slowly "same" to mirrored stimuli compared to strictly identical ones. In particular, they show a mirror cost for letters or letter strings that generalizes to false fonts, geometric shapes and pictures of objects (de Heering et al., 2018; Pegado, Nakamura et al., 2014). In children, this interference from irrelevant mirror variations emerges first for letters before generalizing to geometrical shapes (Fernandes et al., 2016).

At the same time, recent findings have suggested that fluent reading can only be acquired for scripts which visual characteristics have been culturally selected because they match the statistics of the human visual environment (Changizi & Shimojo, 2005; Changizi, Zhang, Ye, & Shimojo, 2006) and hence the pre-existing constraints of the visual system (Dehaene & Cohen, 2007; Dehaene, 2005; Szwed, Cohen, Qiao, & Dehaene, 2009). Among these visual properties are symmetry (as for "H"; for a review, see Wagemans, 1997), collinearity (i.e., property of a set of points that lies on a single line, as for "I"), vertices (i.e., viewpoint-invariant line junctions, as in "L"), mid-segments (i.e., line fragments) and curvilinearity (as for "S"). Under this view, efficient reading is only possible for scripts that show adequacy to the natural capabilities of the visual cortex, as the Latin alphabet, and should therefore be compromised for *visual Braille*. Braille has indeed been originally created to best fit the tactile modality of blind and visually impaired people, and its adequacy to the constraints of the visual modality is only moderate. In particular, visual Braille lacks vertices, mid-segments, and curvilinear global shapes. In line with this assumption is the observation that Braille learners who have had significant prior experience with visual Braille read it with much more difficulty than Cyrillic learners do read Russian after only three months of an introductory course (Bola et al., 2016). The same Braille readers also show a stronger word length effect in Braille, namely increased reading times (as estimated through a lexical decision task) the longer the words are, compared to Cyrillic learners with Russian words (Bola et al., 2016).

In the present study, we tested the prediction that other aspects of reading expertise than those evaluated through a lexical decision task might develop in readers having learnt Braille through the visual modality. More precisely, we hypothesized that this particular population could compulsorily break mirror invariance for visually presented Braille, as they do for the Latin alphabet, because this behavior typically emerges quite early during the acquisition of a novel script, i.e., around first grade (Fernandes et al., 2016). As many other developmental functions (e.g., letter-speech sound integration, Froyen, Bonte, van Atteveldt, & Blomert, 2009), we also hypothesized that the size of the effect could increase as Braille expertise increases. To test so, we took advantage of a group of sighted Braille readers and compared their results to those of people having never experienced Braille. We screened their Braille expertise by means of visual Braille words, pseudo-words and text reading. All participants were exposed to a speeded same–different comparison task of simultaneously presented pairs of items being either Braille letters, geometrical shapes or Latin letters. All three materials were organized so that sometimes their associations would lead to their elements being mirrors of each other and critically, they also varied in how their visual features fit the constraints of the human visual system. Latin letters indeed present the visual features of symmetry, collinearity, vertices, mid-segments and curvilinearity. Braille presents less of these properties, being a script, which letters are always collinear (i.e., matrices of 2 × 3 aligned dots) and sometimes symmetric (i.e., some of them are perfect flips of themselves across the vertical or horizontal axis). The geometrical shapes we used in this study present all the visual features of the Latin alphabet except for curvilinearity. We expected Braille readers, and not matched controls, to show a comparable mirror cost for Braille and Latin letters. In line with previous observations (de Heering et al., 2018), we also expected the two groups to show a weaker mirror cost for geometrical shapes than for the script(s) they have experience with, i.e., the Braille and Latin scripts for Braille readers, but only the Latin script for controls.

2. Method

2.1. *Participants*

The Research Ethics Boards of the department of Psychology of the Université Libre de Bruxelles (Belgium) approved the experiment. Twenty-five Braille readers were tested (2 males; 1 left-handed; mean age: 40 years, SD = 9), from which most were Braille teachers or educators. All reported to have learnt Braille visually for professional reasons and to not be capable of using it in its tactile form. The only exception was for a woman who, in addition to visual Braille, had learnt tactile Braille on her own. She was a violin player and learnt to play the instrument when she was a child, which is most probably the reason why she maintained such high finger sensitivity. The Braille readers reported having been using Braille for a minimum of 1 year to a maximum of 35 years (average number of years = 8; SD = 9). This highly variable visual expertise was also illustrated by the number of Braille words and pseudo-words they could read per minute from a list (minimum = 1; maximum = 43; averaged number = 14; SD = 10). Interestingly, the first index of Braille expertise (i.e., years of Braille expertise) also correlated significantly with the second (i.e., Braille reading fluency) (1-tailed Pearson correlation: $r = 0.387$, $p = .046$). The control participants were 25 participants who reported to have never experienced Braille (2 males; 1 left-handed; mean age: 39 years, SE = 2). They partially overlap with the control group referred to in de Heering et al. (2018). Both groups were matched on native language (French), age, gender and education. All participants gave written informed consent and reported normal or corrected-to-normal vision.

2.2. *Stimuli*

Three categories of visual stimuli were used: Braille letters (B), geometric shapes (S) and lower-case Latin letters (L). Seven items were selected from each category, exactly as in a previous study conducted with congenital blind and sighted readers (de Heering et al., 2018; see also Fernandes et al., 2016 for shapes and Latin letters) (Fig. 1A). Critically for the purpose of the present study, only 2 out of the 7 letters of the Latin alphabet were mirrors of each other and therefore reversible (e.g., "b" into "d") whereas all Braille letters were reversible. It is the intrinsic nature of visual Braille that makes it so that every matrix of 2 × 3 black dots presented against a white background can be mapped onto a meaningful representation after mirroring. As in the previous study, participants viewed them at full contrast and at 57 cm from a laptop computer, which renders their size being approximately of 3 × 2 and 2 × 1.5 degrees of visual angle for Braille and Latin letters, respectively, whereas geometrical shapes approximately reached the size of 6 × 4 of visual angle to participants.

2.3. *Procedure*

Stimuli presentation and data recording were monitored thank to *E-prime 2.0* (http://www.pstnet.com/eprime). Participants were tested on each visual category separately presented in a counterbalanced order. For each category, they had to decide, as fast and as accurately as possible, whether the simultaneously presented items of each pair were the same or different, independently of their orientation. As a consequence, stimuli mirrored along either the horizontal or the vertical axis had to be considered as being the same. As presented in Fig. 1B, a trial started with an initial screen inviting participants to place their thumbs on two separate button boxes placed in front of them (the right/

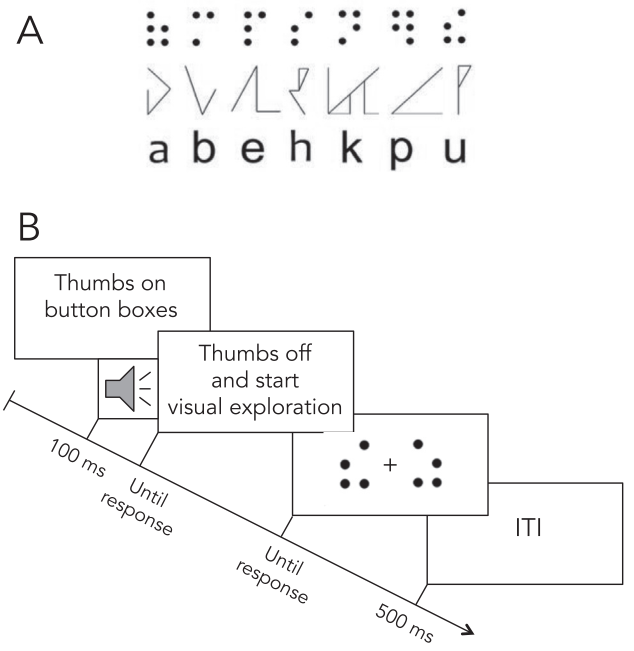

Fig. 1. A. Participants were visually presented with Braille letters, geometric shapes and Latin letters. B. Time course of an experimental trial. None of the items shown in this figure is scaled as it was for the actual experiment.

left position of these boxes was counterbalanced). They were then asked to lift their thumbs as soon as they heard a beep launched for 100 ms after this initial screen, which they knew initiated the moment they could start exploring visually the two stimuli presented side by side around a central fixation cross. This auditory peculiarity was used to mimic the design previously used with blind individuals (de Heering et al., 2018). Pairs of items remained on the screen until the participant pressed a button. Each of the three tasks started with 8 practice trials that had to be performed with a minimum of 75% of correct responses to be engaged in the rest of the experiment consisting, in each case, of 42 different, 14 same and 28 mirror trials for which a "same" response was expected. The inter trial interval was of 500 ms [490–510 ms].

3. Results

The task was very easy to participants. They performed with an averaged accuracy rate of 96% (SE = 0.02) on Braille letters, 96% (SE = 0.01) on geometrical shapes and 94% (SE = 0.01) on Latin letters. Given that instructions emphasized both accuracy and speed and that most of accuracy rates were skewed rightwards (i.e., towards 100% of correct responses), we decided to focus on participants' reaction times (*RT*s, in ms) for correct trials, from which outliers (3 SD) were removed at an individual level. Their analyses indicated that the Braille group was generally slower than the non-Braille group. This pattern was particularly obvious for mirrored Braille letters (137 ms vs. 64 ms: $t(48) = 2.180$, $p = .034$, Cohen's d = 0.617) and mirrored geometrical shapes (122 ms vs. 61 ms: $t(48) = 2.413$, $p = .020$, Cohen's d = 0.683). To control for this overall difference, we transformed participants' correct RTs into normalized interference indexes, namely *mirror costs*, calculated for each participant as the ratio between correct RTs on mirror (M) and identical (I) trials, as in former studies (i.e., (M − I)/(M + I); de Heering et al., 2018; Fernandes et al., 2016; Kolinsky & Fernandes, 2014; Pegado, Nakamura et al., 2014; for the same indexes extracted from accuracy rates, see[1], suggesting also that there was no speed-accuracy trade-off in the data). These indexes were filtered at the group level to remove outliers (3 SD) when necessary, and tested for significance (one-sample *t*-tests) as well as across conditions (paired *t*-tests), groups (independent *t*-tests) and individuals (Pearson correlations). One-tailed statistical tests were favored when we had strong a priori theoretical assumptions about the direction of the results.

As illustrated in Fig. 2, the two groups differed for Braille letters, with Braille readers showing stronger interference from irrelevant mirror variations than controls (1-tailed *t*-test: $t(48) = 1.962$, $p = .028$, Cohen's d = 0.555). This was not the case for either geometrical shapes or Latin letters, for which we did not have specific predictions regarding the direction of the effect (2-tailed *t*-test: shapes: $t(47) = 1.424$, $p = .161$, Cohen's d = 0.407; Latin letters: $t(47) = 0.482$, $p = .632$, Cohen's d = 0.138). Critically, the magnitude of the mirror cost was similar for Braille and Latin letters in Braille readers (1-tailed *t*-test: $t(23) = -1.433$, $p = .083$, Cohen's d = −0.293) and stronger for both these materials than for geometrical shapes (1-tailed *t*-test: $t(23) = -2.210$, $p = .019$, Cohen's d = −0.451 and = −2.949, $p = .004$, Cohen's d = −0.602, respectively). The profile of the control group was quite different, with a significantly stronger mirror cost for Latin letters than for both Braille letters and geometrical shapes (1-tailed *t*-test: $t(24) = -2.069$, $p = .025$, Cohen's d = −0.414 and = −2.805, $p = .005$, Cohen's d = −0.561, respectively), but no significant difference between Braille letters and geometrical shapes (1-tailed *t*-test: $t(24) = -1.406$, $p = .086$, Cohen's d = −0.281). Yet, it is worth noting that all mirror costs significantly differed from zero (all *ps* < 0.001, Cohen's d between 1.051 and 2.045), which confirms that automatic breaking of mirror invariance generalized to materials other than experienced scripts.

Critically, we also observed that in Braille visual readers the magnitude of the mirror cost for Braille increased with Braille reading expertise. A similar trend had already been observed in congenital blind readers (de Heering et al., 2018). As illustrated in the left part of Fig. 3, the greater was the number of years they reported to have learnt Braille, the stronger was their mirror cost ($r(23) = -0.384$, $p = .029$). This correlation increased even more when the most expert participant of the Braille group was excluded from the sample ($r(22) = -0.679$, $p < .001$). Similarly, Braille readers' mirror cost for Braille increased with increasing Braille fluency, indexed through the number of Braille words and pseudo-words read per minute (4 participants excluded from the sample for technical reasons; $r(18) = -0.473$, $p = .017$; Fig. 3, right). Finally, the mirror costs for Braille and Latin letters did not correlate with each other in Braille readers ($r(23) = 0.132$, $p = .539$), whereas they did in controls ($r(23) = 0.457$, $p = .011$), signing for competition between the two materials when one is of expertise and the other one is not (Fig. 4).

4. Discussion

In the present study, we investigated whether people having developed visual expertise for Braille do break mirror invariance automatically for Braille letters as they do for Latin letters. Although visual Braille lacks many characteristics that have been reported as essential for fluent reading (i.e., vertices, mid-segments and curvilinearity; Bola et al., 2017; Changizi et al., 2006; Dehaene, 2005; Dehaene & Cohen, 2007; Szwed et al., 2009), it includes many mirrored letters and shares with other written scripts the characteristics of symmetry and collinearity. To explore this question, we relied on a special population of visual Braille readers, contrasted their performance with the performance of participants who never had any experience with Braille, and examined their mirror costs indexing for the cognitive interference

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[1] The Braille group mirror costs calculated on the basis of their less sensitive accuracy rates revealed no difference between materials (B = S = L). The same

(*footnote continued*)
measures for the control group revealed, as for correct RTs, a difference between materials (L > B; L > S; B = S).

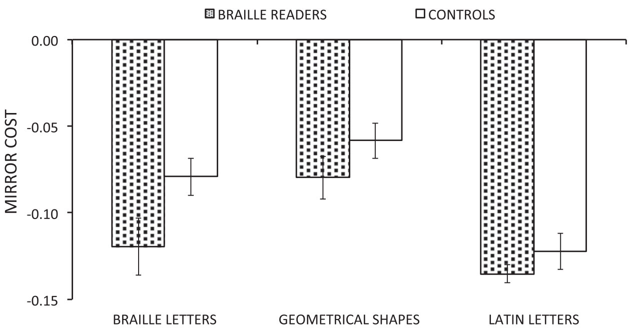

Fig. 2. Braille readers' and controls' averaged mirror cost for each material (Braille letters, geometrical shapes and Latin letters). The more negative is the cost the greatest is the group's difficulty to consider mirror contrasts as "same" as compared to strictly identical items.

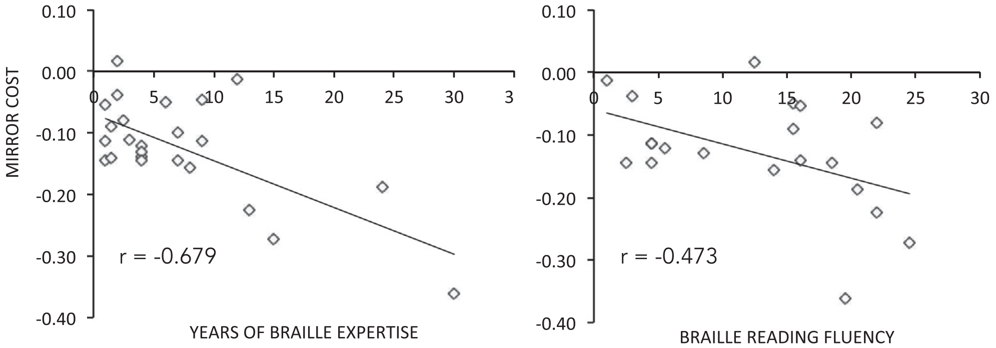

Fig. 3. Braille readers' mirror costs for Braille increased with the number of years of Braille expertise they reported (left; N = 24) and with their fluency at Braille reading (average number of words and pseudo-words visually read per minute; right; N = 20).

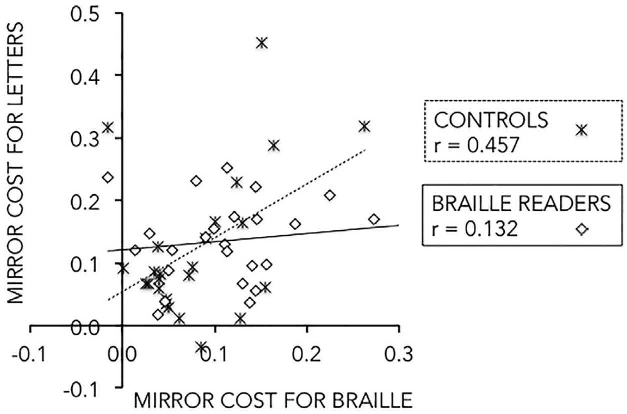

Fig. 4. The mirror cost for Braille and Latin letters did not correlate in Braille readers, but did so in controls.

generated when people have to consider mirrored images as identical compared to strictly identical images. Three materials were used – Braille letters, geometrical shapes and Latin letters – because they vary in how they fit the requirements of the human visual system.

In a nutshell, we observed that Braille readers displayed a stronger mirror cost for visually presented Braille letters than control participants and that this cost increased (i.e., greater interference) along with their expertise with this material. In Braille readers, this cost did not statistically differ from the one displayed for Latin letters and both were significantly more pronounced than the one obtained for geometrical shapes, which attests from their lack of experience with the latter material. Conversely, participants who had no expertise at reading Braille showed a reduced mirror cost for Braille compared to Latin letters. In fact, their mirror cost for Braille was comparable to the one of geometrical shapes, most probably because none of these materials were familiar to them (for a similar trend with the same materials, see de Heering et al., 2018).

Given these results, we would suggest that all visual properties typically characterizing most written scripts (i.e., symmetry, collinearity, vertices, mid-segments and curvilinearity), but not visual Braille, do not constitute a prerequisite to automatically break mirror invariance. The Braille data collected here as well as the data collected on congenital blind readers who use the tactile modality to read Braille (de Heering et al., 2018) indeed suggest that only a restricted number of these properties are necessary to push the reader to start compulsorily breaking mirror invariance. Nonetheless it also seems that an additional factor, perhaps not visually driven, triggers the phenomenon since the Braille readers tested in the current study showed a mirror cost of a smaller amplitude for geometrical shapes than for visual Braille despite the fact that those shapes presented many more of the above mentioned features. We hypothesize that this factor could involve the symbolic level of letter representations. Mirrored Braille and Latin letters are indeed graphemically contrastive (Danziger & Pederson, 1998; Pederson, 2003), which is not the case for any of the mirrors of geometrical shapes created artificially or for the meaningless dot patterns used in Lachmann and van Leeuwen (2007). Train participants on artificial scripts to have them progressively associating a meaning to each of its symbols, including mirrors, could help overcoming the difficulty of processing their mirrors. In the future, it would also be interesting to vary parametrically the proportion of mirrored characters included in that script to match the proportion of either Braille or Latin mirrored letters naturally composing each of these alphabets. This would indeed allow testing, with the exact same material, whether the number of mirrored characters plays a role in driving the effect.

In line with previous evidence of longstanding brain plasticity (e.g., Polk & Farah, 1995), the present results also remarkably emphasize that the representations underlying the capacity to break mirror invariance can be reshaped qualitatively, even after years of exposure to another written material (i.e., Latin letters). Exactly as teachers have refined, at an adult age, how they process children faces (de Heering & Rossion, 2008), the Braille readers we tested here learnt to break mirror invariance compulsory for Braille letters years after they started to break mirror invariance for Latin letters. Even more strikingly, the current results also favor the idea that the cortical representations underlying this perceptual bias can be reshaped to the point of not leading to any brain competition between the old and the novel material of expertise, presumably to facilitate efficient processing of the novel script (see Dehaene et al., 2010; Pegado, Nakamura, Cohen, & Dehaene, 2011; but see Nakamura, Makuuchi et al., 2014; for a review, see Pegado, Nakamura et al., 2014).

Finally, it is worth noting that except perhaps for one participant, the Braille readers examined here were far from being as fluent at visually reading Braille as at reading the Latin alphabet, which can be taken as a limitation of the study. Their fluency scores with visual Braille were indeed highly variable and much lower compared to the 400 Latin-letter words good readers typically read per minute. As a group, they nevertheless broke mirror invariance compulsory for Braille letters and their Braille expertise was sufficient for the effect to be as marked as for Latin letters. In the future, it would be interesting to explore whether Braille readers with even greater Braille expertise would show, in addition to the ability to break mirror invariance for Braille letters, some refinement in the mechanisms they use to read Braille. The absence of a word length effect indexing for serial letter-by-letter decoding could, for example, be illustrative of such pattern since it is modulated later during reading acquisition than the compulsorily breaking of mirror invariance, and therefore requires significant expertise (Bola et al., 2016; Fernandes et al., 2016; Zoccolotti et al., 2005). Finally, it would also be tempting to test what facilitates visual Braille fluency. One possibility would be to superimpose, at the visual level, connecting lines on the dot patterns of Braille, which would bring mid-segments and vertices in the learning process and hence enhance its fit to the constraints of the human visual system. Another possibility would be to enhance the symbolic value of Braille patterns through their association to meaningful words (e.g., approach, bridge, closed, detour, empty, fuel…) which would be further introduced into meaningful sentences (e.g., one day you decide you want to cross a river, so you approach a bridge, but it is closed, so you take the detour, but you realize your run on empty, so you fill up with fuel…).

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Competing interests

The authors declare that no competing interests exist.

Author contributions

AH and RK designed the research, AH performed the research, AH analyzed data, AH wrote the paper and RK reviewed it.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2019.03.012.

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