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Spatial biases in processing mirror letters by literate subjects

Katarzyna Patro[1] · **Antonia Gross**[1] · **Claudia Friedrich**[1]

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Abstract
Preschool children often confuse letters with their mirror images when they try to read and write. Mirror confusion seems to occur more often in line with the direction of script (e.g., left-to-right for the Latin alphabetic script), suggesting that the processing of letter orientation and text directionality may be interrelated in preliterate age. When children go to school, mirror mistakes in writing/reading letters disappear. Here we ask whether the processing of letter shapes and text direction are still related in readers at different proficiency levels. Literate subjects – school children from the 1st and 4th grades and adults – decided under time pressure whether a displayed letter was oriented correctly or incorrectly (mirrored). We observed that reaction times were faster when a letter was oriented rightward, i.e. in line with the cultural text direction (left-to-right), but we did not find any differences between the groups. We conclude that, even if mirror mistakes disappear during primary school years, letter shapes are still processed in a close relation to the left-to-right reading direction in the Latin script.

Keywords Mirror letters · Script direction · Spatial bias · Letter orientation · Literacy

Introduction

Written language is subject to various spatial principles, such as linear organization, directionality of a text flow or characters' orientation. Some of these principles are highly consistent. For instance, the common rule of the Latin script states that reading and writing always proceeds from left to right. There is no exception to this rule - the opposite direction would upset the whole meaning of a text. Other spatial principles

✉ Katarzyna Patro
katarzyna.patro@gmail.com

1 Department of Psychology, University of Tuebingen, Tuebingen, Germany

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are less consistent. For example, individual letters are oriented in different directions. Even though some letters are symmetrical in plane about a vertical axis (o, i), others have a vertical or semi-vertical stem and a distinctive feature at one side, thus either facing to the left (j, a) or to the right (k, r). Having a text directed in one direction, that is however being composed of diversely oriented letters, creates some sort of inconsistency, which may be challenging for mastering each of the spatial principles.

Mirror confusion, directionality confusion, and the relation between them

As regards learning letters in Latin script, preschool children often make orientation mistakes, i.e. they reverse letters into their mirror images and show a high acceptance rate for letters that are presented to them in reverse orientation (Brennan, 2012; Fischer & Koch, 2016a; McIntosh et al., 2018). This phenomenon has been observed in beginning readers of different languages including English (Brennan, 2012), French (Fischer & Koch, 2016a), Italian (Cubelli & Della Sala, 2009) or Portuguese (Fernandes et al., 2016). Although preliterate children are able to perceive the difference between mirror-contrasted images from very early on at a perceptual level (e.g., McGurk, 1970; Sireteanu & Rieth, 1992), they may lack the ability to mentally consolidate a particular letter orientation in memory (Fischer & Koch, 2016a; Fischer & Luxembourger, 2021; Fischer & Tazouti, 2012; Gregory et al., 2011; Over & Over, 1967). This probably leads to mirror generalization (invariance). From an evolutionary perspective, generalization over mirror images, which takes place in the Visual Word Form Area (VWFA), might help us to quickly recognize common objects in the surroundings regardless of their orientation, thus ensuring our survival (Pegado et al., 2014). Yet, such generalization could make it difficult to learn cultural asymmetrical symbols like letters or numbers.

There is less research on when and how children gain sensitivity to the directionality of text flow. Some studies suggest that this process occurs gradually, starting from application of a canonical orientation to their own name or single words around the age of 3–4 years (Cubelli & Della Sala, 2009; Puranik & Lonigan, 2011; Treiman et al., 2007). However, children might have problems generalizing this rule to more complicated text components like sentences or text lines until they reach school age (Justice & Ezell, 2001; Patro & Haman, 2017; Puranik & Lonigan, 2011). So, even though text direction does not vary within a culture, the visual processing system of the preliterate brain might confuse direction nevertheless.

Previous research showed that the preliterate cognitive system might strive for a spatial correspondence between letters and text, even if each component is partly determined by separate spatial principles. Respective studies tested French- and English-speaking preschoolers, who acquire Latin script (Fischer, 2011, 2013, 2017, 2018; Fischer & Koch, 2016a, b; Treiman & Kessler, 2011; Treiman et al., 2014; see also McIntosh et al., 2018; for review see Fischer & Luxembourger, 2018). Participants more often reversed left-facing characters (like the letter *d* or the number *2*) than right-facing characters (like the letter *c* or the number *6*). That is, they mirror-reversed letters oriented incongruently with script direction more often than they mirror-reversed letters oriented congruently with script direction. A unifying role that the writing direction may play was also attested when French-speaking children were enforced to start writing from the right margin of a page. Participants did not only reverse writing direction (because there was not enough space to write in a canonical rightward direction), but they also oriented asymmetric letters within the word in the same direction as they wrote (Fischer, 2017 (Study 2); Portex et al., 2018). Based on these observations, one may conclude that the preliterate cognitive system seeks for spatial congruity between letters and text, even though each component might in part follow separate spatial principles. Relying on that congruity may partially be a good strategy, given that in the Latin alphabet only a minority of asymmetrical letters are incongruent with the script direction, i.e. left-facing (e.g., only 8% of capital letters are left-facing, but 46% are right-facing; Treiman et al., 2014). Nevertheless, the congruency-based strategy is still a bit "risky", as it does not always lead to correct writing.

On a macroscopic behavioral level, children's confusion of different letter orientations and different text directionalities lasts approximately until school age. Different studies report slightly different time points when mirror mistakes disappear, and these may vary between languages (countries) and experimental tasks. For instance, using a letter writing task, Fischer and Koch (2016a) reported the drop of mirror mistakes to about 10% in French-speaking children aged 6-7-years, whereas in Scottish-speaking children a similarly low level of mistakes was found from the age of 7 (Brennan, 2012) or 8 years (McIntosh et al., 2018). On the other hand, in the speeded same-different task (judging whether two separately presented letters are identical), Portuguese-speaking 1st graders (around 7 years old) still had relative problems discriminating mirror images of the same letter, but they considerably improved as compared to preschoolers (Fernandes et al., 2016). Despite these slight differences, one may conclude that – at least for Latin script – mirror confusion disappears gradually during the first years at school, in the course of proper training with reading and writing. At the time when mirror confusion disappears, children also start consistently applying the mandatory direction for reading and writing of the target script. Accordingly, Cornell (1985) reported that from the age of 8 years on, Canadian children consistently wrote their names in left-to-right order even if they had to begin on the left side of a vertical line (spatial constraint which induce right-to-left writing in younger children, cf. Fischer & Koch, 2016a; Portex et al., 2018). Thus, explicit behavioral measures reveal that children learning Latin languages process spatial principles applying to script in general and to letters in particular seemingly separately when they receive formal reading and writing instructions in primary school.

Here we ask whether the relation between processing letter orientation and text direction indeed totally vanishes with literacy acquisition, or whether both are still interfering with each other at a more subtle implicit level of processing in literate individuals. Below, we present arguments for both alternatives and, based on that, we propose a study which shall clarify whether and how literacy acquisition may affect the relation between spatial processing of letters and text.

Literates process letter shapes independently of script directionality

There are good reasons to assume that experience with various canonical letter shapes - via reading and writing them - sufficiently consolidates their visual representation in the memory. Given an imperfect match between script and letter directionalities, reliance on a general script directionality to decide about letter orientation appears to be a less efficient strategy. A more successful strategy regarding decisions about letter orientation might rely on visual-motor processes involved directly in graphic reproduction of characters. Indeed, there is evidence showing that learning letter characters by writing them by hand decreases the number of mirror confusions as compared to learning by typing (Araújo et al., 2022; Longcamp et al., 2005, 2006; Mayer et al., 2020). Furthermore, mere visual exposure to letters seems to lead to decreasing numbers of mirror errors (cf. evidence in trained pigeons: Scarf et al., 2017). So, there are reasons to suspect that in the course of formal literacy acquisition, robust visual-motor representation of spatial features of individual characters are established in the cognitive system. Rather than directionality in general, particular individual features might guide processing and recognition of respective letters. According to this line of argumentation, literates should process letter and script directionality separately.

Reading direction influences processing of letter shape in literates

Beyond the level of individual letters, we know from plenty of studies that a particular script directionality may act like a visual-motor training for other attentional and cognitive processes in literates (for reviews see Chokron et al., 2009; Faghihi & Vaid, 2023). Cross-cultural studies show that there is a clear difference between users of left-to-right languages (like English, French or Hindi) and right-to-left languages (like Hebrew or Arabic) in the way they draw (Vaid, 1995), count (Shaki et al., 2012), kiss (Shaki, 2013), represent time (Fuhrman & Broditsky, 2010) and numbers (Dehaene et al., 1993), etc. Such spatial biases caused by directional reading training appear to increase with age and literacy experience (e.g., Wood et al., 2008, for number processing). Crucially, script directionality also determines judgements about individual objects. Objects oriented in line with the mandatory reading direction (left-to-right or right-to-left) are judged as more aesthetical and preferable than those oriented in a different way (e.g., Chahboun et al., 2017; Chokron & De Agostini, 2000). This could imply that there is an overall preference or higher acceptance for culturally compatible facing direction among literate subjects, which may potentially affect processing of letters shapes.

Expecting that influences exerted by script directionality extend to letter processing in literate subjects is consistent with the recent line of research on mirror letters within a masked priming paradigm. These studies demonstrated that a mirror-reversed prime may substantially affect processing of a letter target in literate subjects, making the letter target either harder (for reversible letters like *b* or *d*) or easier (for non-reversible letters like *r* or *k*) to process (e.g., Brossette et al., 2022; Fernandes et al., 2022; Perea et al., 2011; Pittrich & Schroeder, 2023). The exact mechanism of these priming effects have been widely discussed elsewhere (Ahr et al., 2016; Borst et al., 2015; Duñabeitia et al., 2011; Fernandes et al., 2022; Fernandes et al., 2024; Kinoshita & Liong, 2023; Perea et al., 2011). Here we point to a more general message emerging from these findings: they show that, even in expert readers, visual representation of a letter shape/orientation might be susceptible to certain modulations.

Two recent studies with participants using left-to-right Latin script showed that experience with text directionality could exert some impact on letter priming effects. For readers of European Portuguese, Soares and colleagues (2019, 2021) showed that the priming effect was restricted to canonically left-facing letters, that is to letters that are oriented against script direction. Crucially, the effect was observed only in adults and 5th graders, but was absent in younger readers (Soares et al., 2019). Kinoshita and Liong (2023) found a similar effect in their priming study with English-speaking adults, but this time it was very unstable and small in magnitude. Given the unconscious processing of letter shapes in masked primes, one may suppose that such influences are only subtle, and operate mainly at the early level of orthographic processing, e.g., as an effect of noisy perception (cf. Kinoshita & Liong, 2023). Thus, the question arises whether processing of letter orientation is indeed biased towards the left-to-right direction of a Latin script in literate subjects, in a similar way as spatial processing of numbers, time or pictures are biased. If so, how does this relation potentially change once reading and writing is acquired and further trained in the course of life?

The current study

Here we investigated the processing of letter orientation in relation to literacy acquisition, in an experimental situation when subjects made a conscious decision about the orientation of an individual letter. We examined the pattern of mirror confusion in three different age groups of readers of German (left-to-right Latin script). In contrast to other languages of the Latin family like French or English, mirror writing in German has not been much examined. However, it is important to know that in Germany children are formally introduced to letters and numbers only in 1st grade of an elementary school. Our youngest group consisted of schoolchildren attending 1st grade during the end of a summer term. Children at this level of education were thus supposed to develop sufficient competence to read and write letters. The second group consisted of children attending 4th grade, also during the end of a summer term. This group represented beginning readers with higher level of literacy experience. We also tested adult skilled readers, whose reading and writing skills are supposed to be highly automatized and at ceiling level. To test the role of literacy skills more directly, we administered a reading test to the children.

We measured participants' reaction times in a task where they had to decide under time pressure if the letter was written correctly or not. On the one hand, such a task enforces activation of explicit knowledge about canonical letter orientation. In this sense, it is based on a conscious decision rather than unconscious processes like those involved in masked priming. On the other hand, speeded-judgment settings with reaction time (RT) recording could allow capturing potential implicit spatial biases (e.g., preferences for rightward orientation) in letter representation, even if the subjects theoretically know how the letter should be oriented. Based on this experimental design, we formulated the following predictions:

(i) If the experience with reading direction (which goes from left-to-right in the tested culture) exerts any influence on spatial letter representation, we would expect faster reaction times to right-facing letters (because they are oriented in line with reading direction) than to left-facing letters (because they are oriented against reading direction).

(ii) If the experience with reading direction exerts a stronger influence on spatial letter representation than experience with individual letter shapes does, we would expect that the above effect (i.e., faster reaction times to right-facing vs. left-facing letters) increases with age and reading skills (because more literacy experience means more exposure to left-to-right spatial training).

(iii) If the experience with individual letter shapes was more crucial, then we would expect that the above effect decreases with age and reading skills (because more literacy experience also means better consolidated representation of individual letter shapes).

Method

Participants

The group of participants consisted of 24 adults (15 females, 9 males; mean age: 32.65 years; age range: 20–61 years; right-handed: 23) and 51 children. The group of children consisted of 21 4th graders (11 females, 10 males; mean age: 10.29 years; age range in years; months: 9; 10–11; 1; right-handed: 21) and 30 1st graders (19 females, 11 males; mean age: 7.30 years; age range in years; months: 6; 10–8; 0; right-handed: 28) from German elementary schools. Initially, eight additional children and one adult were tested but were excluded either because of their experience with languages that have other than left-to-right reading or writing directions, or because of technical problems either with the keyboard or caused by distraction in the lab. All subjects were familiar with the Latin alphabet. Written informed consent was obtained from the participating adults and from all parents or caregivers of the children. Information about the children's demographics, language proficiency in German and other languages were collected based on a questionnaire that their parents or caregivers filled in at home. Adults were asked about these data right before the experiment.

Materials and stimuli

Reaction time task

The task was run on a laptop with a 17.3-inch display (1920×1080 pixels) using the software PsychoPy, version 1.90.3 (Peirce, 2007).

Two left-facing (a, j), two right-facing (h, k), and two symmetrical (i, x), lowercase letters from the Latin alphabet were used as stimuli. Our main research question concerned the difference in response speed to left- vs. right facing letters. Nevertheless, we added symmetrical letters in order to control for an overall processing cost resulting from the mere presence of asymmetrical features in the letters. Therefore, in addition to our three predictions, which directly refer to the research question, we expected that symmetrical letters would be responded to faster than asymmetrical ones.

All letters were presented in "Calibri (body text) font - bold" on a white background and were dark green in color. The letters were 4.4–7.8 cm high and 1.1–4.0 cm wide. To select particular letter stimuli, we only considered those letters which were non-reversible letters (hence b, d or p were not considered), and which were clearly classified as left- or right-oriented according to other studies (e.g., Treiman et al., 2014). In order to avoid influences due to varying degrees of familiarity with the letters, they were selected so that the mean frequency in which they appeared in the German language was similar for all three orientations. To determine this, the lexical database dlexDB (Heister et al., 2011) was used. This database is based on the reference corpus underlying the Digital Dictionary of the German Language (DWDS) (Geyken, 2007; Klein & Geyken, 2010). The asymmetrical letters were presented in their canonical orientation and mirrored along their vertical axis. Two symmetrical letters as well as the correct and mirrored depiction of four asymmetrical letters were repeated three times in a random order. In total, the testing procedure consisted of 30 trials. Five additional trials, with the lowercase letters "a" and "k" in correct and mirrored depiction, and the symmetrical letter "x", all presented in a random order, constituted a training phase.

For a child-friendly appearance of the instruction and task, the image of a front-facing blue alien (20.5 cm high × 14.5 cm wide) was used. The "Y“ key on the left side of the QWERTZ-keyboard, and the "1“ key on the right side of the digit field were labeled as response keys. In addition, two adhesive stickers, one with a happy and one with a sad face were placed directly above the keyboard, located in the extension of the response keys. For one response key condition, the happy face was placed on the left side and the sad one on the right (38 participants). For the other condition, the faces were arranged the other way round (39 participants). Participants were randomly assigned to one response key condition, resulting in near balancing for this variable.

Letter knowledge task

To ensure children's familiarity with all letters presented in the *Reaction time task*, a short *Letter knowledgetask* was applied. All six letters used in the previous task were displayed one by one on separate PowerPoint slides, right at the center. Their color, font and background were the same as before. Each letter was presented only once.

Reading test (SLRT-2)

As a measurement of children's reading experience, their reading fluency was assessed with a standardized one-minute reading fluency test developed for the German language (*SLRT-2*; Moll & Landerl, 2010). The test consists of two subtests presented in a paper form. One subtest consists of 156 words, and another one of 156 pseudowords, each organized in 8 columns on a separate paper sheet. Each subtest contains in addition two columns of pseudowords/words printed on the other side of the sheet, which are used for training. The test gives separate raw values about the number of correctly read words and correctly read pseudowords within a minute time limit.

Procedure

Each participant was tested individually. Children were tested in a separate quiet room located in their elementary school building. Adults were tested in a separate quiet room at the University building or at home. All instructions were explained orally to avoid any potential influence of a recent reading activity.

Children's testing was conducted as a part of a larger project, which focused on the development of the mental timeline. Thus, the testing procedure relevant for this research report was preceded by two additional tasks: ordering animals and temporal classification of events. Then, it was followed by a short oral survey concerning the mental timeline. These tasks, as not relevant for our research questions, will not be described here. Adults' testing was conducted as a separate project.

At the beginning of the *Reaction time task*, the picture of a blue alien was displayed in the middle of the screen. For children, the task was embedded in a short story about the alien. Participants were told to decide during the task whether a letter presented on the screen was displayed correctly or not and to respond as fast as possible. For correctly written letters, participants were instructed to press the response key on the side of the happy face, for any false oriented letters, on the side of the sad face. Both speed and accuracy of the responses were recorded. Participants placed their left index finger on the left response key and their right index finger on the right one. The experimenter pressed the "U" key in order to let a fixation cross appear in the center of the screen. As participants looked at it and signaled to be ready for the task, the experimenter again pressed the key to start the task. Another fixation cross was presented in the center of the screen for a second, followed by five training trials. Each training trial started with a fixation cross presented in the center of the screen for two seconds. A lowercase letter followed in the center of the screen and was presented until the participant pressed a response key or in case of no response for a maximum of five seconds. In either case a new trial started. At the end of the training phase the image of the alien reappeared. Then, the testing phase started, which was conducted identically to the procedure of the training phase. Only the results of the testing phase were included into analysis. Since adults were expected to have higher social pressure of expectations in this task, the experimenter left the room for the duration of the testing phase when testing adults. At the end of this phase, the image of the alien reappeared. The entire *Reaction time task* took approximately five minutes to complete.

For the children sample, the *Reaction time task* was followed by the *Letter knowledge task*, in which the experimenter presented the above-described PowerPoint slides and asked the children to name the letter shown. All the letters were presented only once. There was no time limit for the response. Both sound and name of the respective letter were rated as correct. This task took approximately three minutes.

Right after the *Letter knowledge task*, the children were administered with the *SLRT-2* test. The experimenter placed the sheet of the *Word subtest* in front of the child. She instructed the child to read the words as fast and as correctly as possible. Children started with two columns of the training list. Then, they had one minute to read as many words as they could from the testing list. The same procedure was applied for the *Pseudowords* subtest.

The whole testing procedure (including tasks on the mental timeline) lasted approximately 40 min. Afterwards, the child received a small gift for participation.

Results

Since the chance level in our task (with two alternative responses) was 50%, we planned to include only those subjects whose accuracy rate was at least 75%, to ensure enough correct responses without guessing. From the adult group, we had to exclude only one subject. However, there were much more children, especially among 1st graders (i.e. 16 out of 30 children), who did not meet this criterion. This might reflect their poorer literacy knowledge and/or cognitive control compared to the older participants. Therefore, we decided to apply a more liberal criterion to the children's sample, which was the accuracy level of at least 60%. As a result, we had to eliminate only three children from the 1st grade, and one child from the 4th grade.

For the reaction time analysis, we included only correct responses. Incorrect responses constituted 17% of all the trials in children and 5% of all the trials in adults. Before the analyses, we cleaned these data from outliers. That is, responses which deviated more than +- 3 SD from the mean calculated individually for each participant were excluded. We repeated this cleaning procedure until no outliers were detected anymore. In order to obtain average RTs for each orientation condition, we only included subjects for whom there were at least three data points left per each condition. Thus, we further removed six children from the 1st grade and one child from the 4th grade.

Our final sample consisted of 21 children from the 1st grade, 19 children from the 4th grade and 23 adults.

The RT data violated the assumptions of homoscedasticity and the assumption of normal distribution of residuals within each cell of the design. Therefore, we run a permutation test for a mixed ANOVA (using the *aovperm* function of the Permuco package in R), which has been proposed as an alternative to a parametric ANOVA when assumptions are violated (Kherad-Pajouh & Renaud, 2015). Our analysis included canonical letter shape as a within-subject factor with three levels (canonically left-facing, canonically right-facing, symmetrical) and age group as a between-subject factor also with three levels (1st graders, 4th graders, adults). The test was based on 5000 permutations. The results showed a significant main effect of grade, $F(2, 60)=89.33$, permuted $p=.0002$[1], $\eta^2_p=0.75$, and letter shape, $F(2, 120)=24.15$,

[1] $p=.0002$ corresponds to the smallest possible value which can be obtained after performing 5000 permutations (1/5000=0.0002). Parametric $p<.001$, for comparison.

permuted $p = .0002$[2], $\eta^2_p = 0.29$. The interaction of these two factors did not reach significance, $F < 1.0$, permuted $p > .56$[3].

In the next step, we aimed to address more directly our research question regarding advantage of culture-consistent letter orientation. To do so, we run permutation tests for planned contrasts for the factor letter shape, with 5000 permutations (function *contrastmeans* from the Predictmeans package in R, Luo et al., 2022). The analyses showed that letters oriented canonically to the right (in line with script direction) were reacted to faster than letters oriented canonically to the left (against script direction), $t(120) = 4.61$, permuted $p = .0002$. Symmetrical letters also triggered faster reactions as compared to asymmetrical ones, $t(120) = 5.20$, permuted $p = .0002$. As can be seen in Fig. 1, this pattern was clearly repeated across all age groups. This is also reflected in the lack of significant interaction.

Since we were not primarily interested in the main effect of Age group, we did not run contrast analysis for this factor. However, as can be inferred from Fig. 1, there is a clear pattern of decrease in reaction times: 1st graders responded slowest in our task, adults responded fastest, with 4th graders' response times being in the middle.

We also looked at response times to individual letters, which were selected to represent our three orientation categories. As can be seen in Table 1, both single letters within each category produced very similar reaction times, which differed however

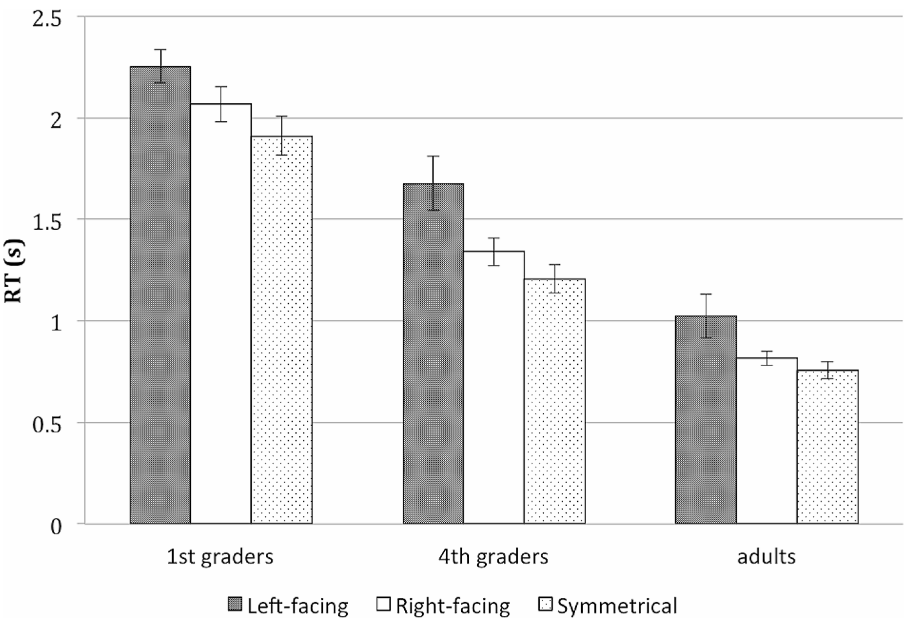

Fig. 1 Mean reaction times (+-SE) for orientation judgment of canonically left-facing (a,j), right-facing (h,k) and symmetrical (x,i) letters, in three groups of subjects: 1st graders, 4th graders and adults

[2] parametric $p < .001$, for comparison.

[3] parametric $p > .55$, for comparison.

Table 1 Mean reaction times (+-SE) for each letter representing each orientation category

Condition (letter orientation)	Left-facing		Right-facing		Symmetrical	
Item (letter)	a	j	k	h	i	x
Mean RT in sec.	1.64	1.60	1.40	1.40	1.26	1.28
SE in sec.	0.10	0.10	0.09	0.07	0.08	0.08

Table 2 Average accuracy rate for orientation judgment of canonically left-facing (a,j), right-facing (h,k) and symmetrical (x,i) letters, in three groups of subjects: 1st graders, 4th graders and adults

	Canonical orientation of a letter		
	Left	Right	Symmetrical
1st graders	0.68	0.87	0.96
4th graders	0.86	0.96	0.99
Adults	0.90	0.99	0.48

between the categories. So, at this descriptive level, there is no indication that the results were driven by any individual letter.

To complement our RT analyses, we also looked at accuracy rates across the three letter shape conditions and age groups. As can be seen in Table 2, the pattern obtained for RTs is approximately repeated by the accuracy rates. We did not test the effect with any inferential statistics for two reasons: First, adults performed nearly at ceiling level. That is, they made very few errors (in both asymmetrical shape conditions), which renders meaningful statistical analysis difficult. This also corresponds to the rationale of our experiment, as we intended to search for more implicit indices of mirror letter confusion than accuracy rates, especially in subjects who judge letter orientation most of the times correct. Second, in contrast to both groups of children, adults produced relatively more errors in the symmetrical condition (close to chance level)[4]. Still, the pattern of a right-facing letter advantage could also be seen in accuracy rates, especially in children of the youngest group, who produced relatively more errors.

A high level of mistakes found in adults in the symmetrical condition could have influenced the analysis of the second contrast (symmetrical vs. asymmetrical conditions). Therefore, we checked the contrast estimate (weighted sum of marginal means for RTs in the symmetrical and asymmetrical conditions) for all the subjects and for the children only. The value of the contrast changed only slightly from 0.238 (all groups together) to 0.275 (children groups only), thus maintaining the advantage of the symmetrical condition.

Finally, we looked at whether the speed advantage for right-facing letters, which we found in our data, was related to children's reading fluency. As indices of reading skills, we used the number of correctly read words and pseudowords from the results of the SLRT-2 test (Moll & Landerl, 2010). As an index of letter orientation effect, we subtracted the mean RTs to right-facing letters from the mean RTs to left-facing letters.

[4] Notably, such high error rate was neither present in other (asymmetrical) conditions nor in the children groups. Therefore, it is not very likely that our subjects failed to follow the task's instruction. This surprising observation could indicate that adults (who were expert readers) were mistakenly assuming that even symmetrical letters were sometimes wrongly written, so they were searching for non-existing deviations.

A positive value of such index would thus indicate the culture-consistent advantage of letters facing to the right, whereas a negative value would indicate the culture-inconsistent pattern, i.e. advantage of letters facing to the left. Due to non-normal distribution of the data, we calculated the Spearman rank correlations between each measure of reading skills and the orientation effect. Both correlations were small and insignificant. The correlation between the number of correctly read words and the orientation effect was $r(38)=-0.008$, $p=.963$. The correlation between the number of correctly read pseudo-words and the orientation effect was $r(38)=0.001$, $p=.994$. Therefore, there was no indication in our data that both phenomena are related.

Discussion

Previous studies have shown that preliterate children go through a phase of mirror letter confusion, i.e. they mix up letters with their mirror counterparts (Cubelli & Della Sala, 2009; Fischer & Tazouti, 2012; McIntosh et al., 2018). The pattern of mistakes made by such children suggests that letter orientation is processed in close relation to the directionality of text: those letters which are incongruent with text direction (e.g., left-facing in left-to-right Latin script) are more often mirror-reversed than those letters congruent with text direction. In this study, we examined whether the relation between text direction and letter orientation still remains when formal literacy training begins, and how it changes with an increasing expertise in literacy. We used a speeded-judgment task, where subjects - at different stages of their literacy experience - had to judge under time pressure whether a letter was oriented in a correct (canonical) or incorrect (mirrored) way. This procedure allowed us to search for more explicit orientation biases in processing letter shapes, rather than subtle biases emerging at the subconscious level of processing masked primes (e.g., Soares et al., 2019, 2021). However, such biases would still be relatively implicit, as compared to those occurring in preschool children during writing behavior.

Our results showed that mirror letter biases indeed existed in our literate sample: participants responded faster to letters oriented rightwards (i.e. in line with left-to-right reading direction) than to those oriented leftwards (i.e. against reading direction) or to symmetrical letters (i.e. neutral as regards reading direction). Interestingly, this pattern was evident in the whole sample, with no significant differences between age groups.

Our search for mirror letter biases in literate subjects was inspired by a large scope of evidence that experience with reading and writing in a particular direction exerts strong influences on human cognition and behavior (e.g., Chokron & Imbert, 1993; Dehaene et al., 1993; Maass & Russo, 2003; Shaki, 2013; Vaid, 1995; for recent review see Faghihi & Vaid, 2023). According to this line of research, mental representation of a horizontal, directionally oriented continuum is utilized by the human brain as a mapping medium to enhance processing of certain sorts of information, like magnitude (Dehaene et al., 1993), agency (Maass & Russo, 2003), temporal orders (Fuhrman & Boroditsky, 2010), etc. In our study, participants responded to characters with different facing arrangement. Thus, we assumed that the compatibility of facing direction with the direction of script would facilitate processing of a stimulus, whereas incompatibility would impede it. This was indeed the case, (i) even though we used letters – objects that have a certain, pre-defined canonical orientation; (ii) even though we tested literates – subjects who already possess knowledge about such canonical orientation; and (iii) even though we presented letters at the level of conscious perception, thus extending the previous results of Soares et al. (2019, 2021) to other paradigms than masked priming. Apparently, neither explicit knowledge on how to write down a particular letter, nor a conscious perception of that letter, exclude implicit tendencies to mentally represent and process its shape as it would follow the direction of script.

First, we will discuss possible mechanisms, which might have led to the above-described spatial bias in literate subjects. Second, we will discuss to what extent these findings can be generalized to other languages using Latin script. At the end, we will briefly refer to the finding of the null results for the relation between the effect and age/reading fluency.

How the left-right bias in processing mirror letters may arise

Much discussion in recent years focused on how the literate brain overcomes the tendency to generalize over mirror and canonical letters (e.g., Ahr et al., 2016; Duñabeitia et al., 2011; Fernandes et al., 2024; Perea et al., 2011). Ahr et al. (2016) called the mirror invariance *a neuronal heuristic* – a shortcut strategy used by the visual system to quickly identify objects. The heuristic proves itself in the majority of cases, but is not reliable in case of letters. Thus, this heuristic needs to be replaced by an *alphabetic algorithm*, which defines how a particular letter needs to be written. Probably, such an algorithm enabled the literate subjects in our study to correctly evaluate orientation of each letter at the end of the decision process.

However, the right-facing bias found in our data makes us suppose that the way towards an application of the alphabetic algorithm may not be straightforward. Following the terminology of Ahr et al. (2016), we suppose that the algorithm was preceded by another, this time *culturally acquired heuristic*, which utilizes directionality of script. An activation of script directionality might be an interim strategy of the literate mind to process mirror images of letters, at least in certain situations. As Treiman et al. (Treiman & Kessler, 2011; Treiman et al., 2014) suggested, preliterate children, who do not have yet full access to alphabetic rules, may pick up statistical prevalence of right-facing letters in the Latin script and generalize it to all other letters. Analogically, Fischer et al. (Fischer, 2017; Fischer & Koch, 2016a) pointed out that children may decide about the letter orientation based on its compatibility with the writing direction. A similar situation could happen in literate subjects, when for some reason the full activation of an alphabetic algorithm is not achievable.

One strategy that participants might have used in the present experiment, let us call it the *computational-statistical* one, might allow them to roughly assess the chance of each orientation feature to appear. Statistically, the chance that an asymmetrical letter in the Latin alphabet is oriented to the left is much lower (6/26) than the chance that this letter is oriented to the right (14/26). It is then more profitable to expect that the letter should be oriented to the right as a default, and then eventually revise the response. The crucial question arises whether a strategy based on general statistical regularities would fit our particular design in which we equalized the numbers of letters in each orientation condition. In this case, we might consider that either the computational statistical strategy is automatically applied (i.e. even if it does not aid in a given task) or that our task, with 30 test trials, was too short to realize that the chance for all orientations to appear is equal.

Another strategy that participants might have used in the present experiment, which will be called here *embodied-based* one, could be to activate the sensory channel. In their model, Pegado and colleagues (2014) proposed that unlearning of mirror generalization could take place via the top-down input that the VWFA receives from other circuits involved in language processing. In particular, the areas involved in handwriting may provide salient cues for the VWFA by activating specific motor program for steering hand movement while writing a particular letter. Some studies confirm such relation showing that handwriting better supports mirror letter discrimination than typing training (Longcamp et al., 2006, 2008). Based on this model, we suppose several senso-motoric experiences that might provide top-down information on canonical letter orientation. These experiences do not only include fine movement pattern while writing single letters, but also general motor training while writing whole texts, as well as oculomotor attentional training while reading consistently in one (e.g., left-to-right) direction. Altogether, these experiences may provide some relevant information for the VWFA, guiding the process of overcoming mirror generalization. Hence, the directionality feature of texts, well internalized by repetitive reading and writing experience, may be automatically transferred to individual letters for an initial, rough decision about their orientation, and then corrected by an appropriate algorithm based on more detailed knowledge on how to write a particular letter.

Similar to our results, Soares and colleagues (2019, 2021) reported an influence of script directionality on processing mirror letters in literate subjects, in a special experimental situation of masked priming (i.e. when letters were presented below the threshold of consciousness: very shortly and followed by a mask stimulus). Kinoshita and Liong (2023) attributed this asymmetry to a noisy perception of a letter presented below the threshold of consciousness. Our data are not compatible with this interpretation. In our experiment, participants had to decide about correctness of a clearly visible letter orientation, under time pressure. What is common for both experimental designs is a certain limitation of resources, either visual (masked primes) or cognitive (decisions under time pressure), which may disrupt fast access to an exact alphabetic algorithm. An activation of a short-cut though less accurate cultural heuristic could be then more useful to make an initial rough judgment about letter orientation. Analyzing every single letter orientation from scratch may be more effortful than to activate one dominant orientation pattern (congruent with script direction) and eventually correct any potential deviation from it.

Altogether, the presence of right-facing biases in letter processing does not testify the lack of alphabetic knowledge or immaturity of orthographic processing, since they are also found in expert readers. One may consider whether it shows greater stability of script-compatible letter representation in the brain (cf. Soares et al., 2019). So far, the biases were found in special situations of uncertainty, i.e. in preliterate children while trying to write (e.g., Fischer & Koch, 2016a, b; Treiman & Kessler, 2011), in literates under limited perception conditions (e.g., Soares et al., 2019), and in our study under time pressure. Thus, we find it well conceivable that the rightward biases emerge because the human brain tries to optimize processing of alphabetic information in such situations by switching to more economical way of functioning.

Notably, such “economical way of functioning” is not only evident in the explicit writing behavior of children or implicit biases in literate adults. Fischer (2022) refers to archeological evidence which suggests that shapes of letters were probably adapted to the direction of reading and writing by our ancestors, in the course of evolution of writing systems. The Latin alphabet originally consisted of left-facing letters, which were re-oriented to the right once the direction of script was finally established as left-to-right. This shows that the inclination towards directional congruity between letters and script is much more than just being a temporary stage is children’s literacy development.

Implications for other languages

We have studied the effect in users of the German language. German is not only based on the Latin alphabet, which is written from left to right, but has many specific features on its own. Some of them may make the directionality of text and orientation of letters more transparent than features of other languages. We shortly discuss some of them, since this may open the discussion to what extent our finding can be generalized to other languages adopting a left-to-right script.

Even though most letters are oriented to the right side in the Latin script, one should acknowledge differences between particular languages, as to how often a given letter appears in written texts. In German, the most frequent lower-case letter is “e”, which is right-oriented (thus in line with script direction). The first most frequent left-facing letter (“a”) comes only at the 7th place in the frequency ranking of all the letters, after right-facing “n”, “r”, “t”, “s” and symmetrical “i” (Heister et al., 2011). There are however other languages, like Portuguese, in which left-facing “a” (against script direction) appears as the most frequent letter (e.g., Grigas & Juškevičienė, 2018). This example shows us that users of different languages may have different experiences with left- and right-facing letters. In fact, German readers could benefit from larger exposure to letters that are compatible with the general orientation of the Latin script.

Beyond the level of individual letters, there are also more “global” language features which may enhance acquisition and processing of the directionality of script. For instance, German has a unique capitalization pattern where all nouns start with an upper case. This forms a visual asymmetry between the beginning (capital on the left side) and the rest of the word (lower case to the right), which can potentially boost acquisition of the directional rule in children. German words are also on average longer as compared to most other languages like English or Spanish (e.g., Marian et al., 2012; Siegelman et al., 2022). Kuperman (2022) demonstrated that users of Latin script whose languages contain longer words (e.g. users of Finnish or German) produced longer saccades and less re-fixations during reading than users of Latin script whose languages contain shorter words (e.g. users of English or Spanish). This could imply that the eye movement pattern associated with reading follows the canonical script direction more consistently and smoothly in a written language with longer words than in a written language with shorter words. Finally, the orthography of the German language is quite consistent in the way graphemes are mapped onto phonemes (i.e. one grapheme is spelled the same way most of the time). Such orthographic structure allows for more systematic decoding of the reading material based on smaller (grapheme-phoneme) units rather than decoding based on whole syllables or whole words (Rau et al., 2015; Ziegler & Goswami, 2005). This might again make the reading process more sequential (and more directional) in German than in languages with less consistent orthographies like English or French (cf. Bahnmueller et al., 2016).

In sum, studying script and letter related directional biases may not only be affected by a general directional rule functioning in a given writing system. Such biases may also depend on how such rules are incorporated at the level of reading and writing practice, and this may depend on more specific features of a particular language.

No evidence for developmental change of the effect?

According to our hypotheses, we expected either an increasing delay of processing left-sided letters with age and literacy experience (if directionality of script was the major factor affecting letter shape representation) or a decrease in the effect (if letter knowledge had a major influence). None of these hypotheses was confirmed by our data. However, one should keep in mind that the null effect may result from not sufficient power. In particular, our sample of 40 children might not have been large enough to detect a potential correlation between the left-sided bias and literacy. Another limitation of our study, which could be relevant here, was the restricted number of letter items per each orientation category. On the one hand, representing each category with more than two letters could potentially allow obtaining more accurate picture of the right-facing bias within each age group. On the other hand, since there are only few lower-case left-facing letters in the Latin alphabet, it is also hard to achieve larger variation within the category. Considering all these limitations, our results should be interpreted with caution: they cannot be fully conclusive regarding the lack of developmental change in the effect.

Nevertheless, the general pattern that emerged from the data, which is roughly repeated in all age groups, may encourage us to at least consider the possible scenario of the stability of the effect. Thus, we might ask why the left-sided bias could potentially stay the same despite differences in age and literacy experience.

We cannot rule out that there is interplay between different skills or processes, which might develop in parallel and cause counter-effects. The effect of reading direction may indeed be a primary cause of the speed advantage for right-facing letters; but at the same time, this advantage may not increase so much with age, because it is hindered by the development of letter knowledge. To give an example: accepting left-facing “j” (or rejecting its right-facing version) may become more difficult with age as it contradicts culture-consistent directionality of information processing. However, the older the child is, the more he/she should be able to activate the canonical representation of letter shape (i.e. left-facing “j”) to replace that primary tendency towards left-to-right mapping. Fernandes et al. (2024) reported that mirror discrimination skills become automatized only by the 6th grade, which is even later than the older group tested in our study. Thus, although mirror writing is supposed to disappear in school children, the first years of school education are still a time of extensive training of different directionalities and orientations encountered in a script. Children train not only the fluency of reading and writing (in one canonical direction) but also the discrimination over different letter orientations, even though mirror mistakes may no longer be observable in their writing. During this period, children also develop inhibitory control mechanisms, which may allow them to suppress the incorrect image of the letter, according to their alphabetic knowledge (Ahr et al., 2016). All in all, although developmental aspect of our result should be interpreted with caution, it may at least point to the need of future studies examining the specific role of such different factors changing with age and education, to understand better the exact developmental trajectory of right-facing biases in letter processing.

Final conclusions

In this study, we presented evidence that literate subjects using Latin script process orientation of individual letters in close relation to reading direction. They reacted faster to letters oriented to the right (i.e. in line with the left-to-right reading direction) than to letters oriented to the left.

These data may suggest that processing and internally representing letter shapes by literate subjects does not work like a pure algorithmic process, with strictly defined orientation rules for each single letter. It seems that at the root of this process there might be certain short-cut heuristics or strategies, which the literate mind may use to facilitate the decision on how to orient a particular letter. One such heuristic could be based on the expected correspondence between letter orientation and directionality of script.

Notably, in the Latin script, the dominant orientation of letters follows the direction of script. Perhaps, this cultural peculiarity of the alphabet is a manifestation of the economical functioning of the human visual system, which tries to maintain compatibility between letters and text orientations, to find a way to deal with mirror confusions. While script directionality seems to be extracted much easier in individual development, and is constant within a language, it may indeed serve as a good cue for preliminary dissolution of the mirror letter conflict.

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Declarations

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