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Developmental mirror-writing is paralleled by orientation recognition errors

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Abstract

The writing attempts of children often feature mirror-reversals of individual letters. These reversals are thought to arise from an adaptive tendency to mirror-generalise. However, it is unclear whether mirror-writing is driven by mirror-generalisation of the visual letter forms, or of the actions for writing them. We report two studies of the relationship between mirror-writing, and the ability to recognise whether a visually-presented letter is in the correct orientation, amongst primary and preschool children learning to read and write in English. Children who produced more mirror-writing also made more orientation recognition errors, for uppercase (Study 1, n =44) and lowercase letters (Study 2, n = 98), and these relationships remained significant when controlling for age. In both studies, the letters more often reversed in writing were also more prone to orientation recognition errors. Moreover, the rates of mirror-writing of different uppercase letters were closely similar between the dominant and non-dominant hands (Study 1). We also note that, in the recognition tasks, children were more likely to accept reversed letters as correct, than to reject correctly-oriented letters, consistent with a tendency to mirror-generalise the visual letter forms. In every aspect, these results support a major role for visual representations in developmental mirror-writing.

Keywords: mirror-writing; mirror-generalisation; orientation recognition; statistical learning.

Introduction

Mirror writing faces opposite to the normal direction. In its complete form, all letters and the script direction are reversed, like normal writing seen in a mirror. In its more common, partial form, individual characters may be reversed within a normally oriented script. Mirror writing is often seen in children, from aged three upwards, decreasing in frequency with age, and all-but disappearing beyond about eight years (Schott, 2007). Although once viewed as a sign of low intelligence, and/or left-handedness (Fuller, 1916; Gordon, 1921; Schiller, 1932), the modern consensus is that mirror-writing is a normal part of literacy development, with no preferential association with left-handedness (Cornell, 1985; Della Sala & Cubelli, 2007; Fischer, 2011; Fischer & Koch, 2016b; Fischer & Tazouti, 2012). Mirror-writing can also emerge later in life, following brain-damage, dementia, or at times of great anxiety (Balfour, Borthwick, Cubelli, & Della Sala, 2007; Critchley, 1927, 1928; Della Sala, Calia, De Caro, & McIntosh, 2015; Della Sala & Cubelli, 2007). These pathological errors *are* preferentially associated with the use of the left hand, though not with left-handedness. A typical case of involuntary mirror-writing would be a right-handed adult who has suffered a left-hemisphere stroke and who, due to weakness of the dominant hand, is forced to write with the non-dominant left. Finally, some adults show an aptitude for deliberate mirror-writing, and this is usually most fluent with the non-dominant hand (Allen, 1896; McIntosh, De Lucia, & Della Sala, 2014; Schott, 1999, 2007; Smetacek, 1992). Only children seem to have a facility for writing in the wrong direction with the dominant hand, and only as a transient stage.

Whilst involuntary mirror-writing in adults seems pathological, the untutored production of mirrored letters during development is more plausibly a neat feat of mirror-generalisation. Very few natural objects or actions have an invariant horizontal orientation, and so it may be adaptive for the brain to disregard the particular orientation in which they are encountered, in order to abstract to the general form: a tiger is the same predator when viewed from the other side, and the direction of the gesture needed to warn another person of its presence should be equally reversible (Corballis & Beale, 1976). It may take longer to learn that certain objects or actions, such as those of written language, have a direction that is critical to their identity. On the perceptual side, it is argued that the visual representation of letter shape is subject to an automatic mirror-generalisation, which must be suppressed before a child will infallibly write that letter forward (Ahr, Houdé, & Borst, 2016; Corballis & Beale, 1976; Dehaene, 2010; Dehaene et al., 2010; Duñabeitia, Molinaro, & Carreiras, 2011; Pegado, Nakamura, Cohen, & Dehaene, 2011). On the motor side, it has been proposed that

that the direction of the action for writing a letter is learned separately from, and later than, its shape (Cubelli & Della Sala, 2009; Della Sala & Cubelli, 2007). Spontaneous mirror-writing may reflect a developmental phase during which the child represents both orientations of the letter, and both directions of action, as equivalent.

Della Sala & Cubelli (2007; see also Cubelli & Della Sala, 2009) have argued that mirror-writing does not stem from a general insensitivity to mirror orientation. This conclusion was based chiefly on data from 109 Italian nursery and primary school children. Those children who made mirror-writing errors did not perform poorly in a perceptual odd-one-out task, in which one of three otherwise identical drawings of an animal was mirror-reversed, thus showing that they could match and discriminate by mirror-orientation. This is consistent with the fact that mirror-writing error rates are greatly reduced when children are given a visible model to copy, rather than being required to write to dictation (Fischer & Tazouti, 2012). Some potentially discrepant data were provided by Wang (1992), who reported that children who failed to identify left and right for their own body parts were (marginally) more likely to mirror-write. The reporting of data for that study was minimal, however, and the laterality discrimination required was of indirect relevance to the handedness of visual forms such as letters. So, the weight of evidence suggests that mirror-writing is not driven by an inability to perceive mirror-orientation. But it may still be related to the automatic mirror-generalisation of visual forms in memory, so that children will be prone to mirror-write asymmetrical letters until their mirrored forms are *unlearned* (Ahr, Houdé, & Borst, 2016; Corballis & Beale, 1976; Dehaene, 2010; Dehaene et al., 2010; Duñabeitia, Molinaro, & Carreiras, 2011; Pegado et al, 2011). The main purpose of the present study is to examine the relation between mirror-writing and visual representations, by testing children's ability to recognise whether individual asymmetrical letters are shown in the correct orientation or not. If visual representations are implicated in mirror-writing, then orientation recognition errors should be predictive of the tendency to mirror-write, independent of the child's age.

We would further predict that variations in mirror-writing errors for specific *letters* should be paralleled by orientation recognition errors for those same letters. This is highly testable, because there are pronounced variations in the tendency to mirror-write different letters: reversals are more common for letters that are 'left-facing' (Fischer, 2011; Simner, 1984; Treiman & Kessler, 2011; Watt, 1983). Most left-facing characters have their distinctive features on the left (although this is not true for all; e.g. Z), and literate adults show good agreement about character facing direction (Fischer, 2017b; Treiman, Gordon, Boada, Peterson, & Pennington, 2014). Within the uppercase Latin alphabet, the letters J and Z face left, whilst many more letters face right (B, C, D, E, F, G, K, L, N, P, Q, R, S), or are symmetrical (A, H, I, M, O, T, U, V, W, X, Y). Left-facing letters are less rare in lowercase (a, d, g, j, q, y, z), but still less common than right-facing letters (b, c, e, f, h, k, l, p, r, s) (Treiman et al., 2014). Initially, it was suggested that children learn through repeated exposure that the majority of letters face to the right, then over-apply this rule, promoting correct writing of right-facing letters (such as B and C), and mirror-writing for left-facing letters (such as J and Z) (Fischer, 2011; Treiman et al., 2014). However, Fischer (2017a) has recently demonstrated that, if children are encouraged (by spatial constraints) to adopt a right-to-left writing direction, then right-facing letters become most often reversed, and left-facing letters the least. This implies that the internalised rule may actually be that letters face in the direction of writing. Nonetheless, in the absence of specific manipulations to encourage right-to-left writing, the typical bias will be the greater reversal of left-facing characters amongst children learning a left-to-right language. And if children who mirror-write apply the same heuristic when judging whether a letter is correctly oriented, they should tend to endorse right-facing stimuli, and to reject left-facing stimuli, so there should be more recognition errors for letters for which the correct form faces left.

This paper reports two studies of the relationship between mirror-writing and orientation recognition errors, across children and across letters, to examine the role of visual representations in spontaneous mirror-writing. Study 1 compared mirror-writing and orientation recognition for uppercase letters, and Study 2 applied a similar strategy for lowercase letters.[1] Study 1 also incorporated a motor manipulation, requiring children to write each letter with the dominant (preferred) hand, and then separately with the non-dominant hand. In adults, a strong association with the non-dominant hand, coupled with the fact that mirror-writing is rarely accompanied by an enhanced ability for reading mirrored script, has provided evidence for motor accounts of the phenomenon (Balfour et al., 2007; Critchley, 1927, 1928; Della Sala & Cubelli, 2007; McIntosh et al., 2014; McIntosh & Della Sala, 2012). The influence of hand used has been much less well studied in children (see later for discussion of: Fischer & Koch, 2016b; Wang, 1986, 1992). However, any systematic influence of writing hand on the rates of mirror-reversal, or on the pattern of reversals between left- and right-facing characters, would indicate a causal or moderating role for motor factors in developmental mirror-writing.

Methods: Study 1, uppercase letters

Participants

Fifty-one children, aged from 4.0-10.3 years, were recruited from pre-school nurseries and after-school clubs in Edinburgh. Five of the children did not complete the orientation recognition task, and were excluded from further consideration. Forty-six children provided full data, two of whom formed no left-facing characters correctly during the writing assessment, and were excluded at the data analysis stage. The final sample comprised 44 children, ranging in age from 4.6-10.3 years (mean 6.82, SD 1.49), 23 of whom were male and 21 female. Hand dominance was inferred from the child's spontaneous use of a stylus to draw on a tablet at the start of the test session (see *Procedure*). The right hand was judged to be dominant in 41 children, and the left hand in three.

Written informed consent was obtained from a parent or guardian for every child, and the research protocol was approved by the University of Edinburgh Psychology Research Ethics Committee, and the City of Edinburgh Council.

Procedure

Children were tested individually, with a digitizing tablet computer (Toshiba Portégé) flat on the table in front of them, and the experimenter seated opposite. Whenever possible, children were tested in a quiet location, away from other children. A sticker was placed on the back of the child's non-dominant hand, as an aid when instructing them to write with one or other hand. The tests were completed in a fixed order, and took less than fifteen minutes to complete.

The child was initially asked to pick up a stylus placed in front of their midline, and to use it to draw a circle on the tablet. The hand that they chose to draw with was considered to be dominant. The experimenter then removed the stylus, and all further writing was done directly onto the tablet with the index finger of one or other hand. To accustom the child to writing directly with the fingertip, and to confirm basic writing skills, the child was asked to write their name on the tablet, first using the index finger of the dominant hand, and then the index finger of the non-dominant hand. These writings were not formally analysed.

The child was then shown the 15 asymmetrical letters of the uppercase alphabet (B, C, D, E, F, G, J, K, L, N, P, Q, R, S, Z), printed individually in black 250 point Times New Roman font, on white A5 cards. The letters were shown sequentially in alphabetical order, and the child was asked to name each. The appropriate letter name or sound was accepted as correct, and the experimenter recorded a list of the letters named correctly.

The child was then prompted to write each of the named letters individually on the digitizing tablet, first with the dominant hand, and then with the non-dominant hand. For each hand, the child was asked to draw the 'big' (uppercase) letter, and subsequently also the 'small' (lowercase) form if they knew it. The writing of lowercase forms was not a part of the main study, but was encouraged at the time of testing for exploratory purposes, though children almost always drew an incomplete set of lowercase letters, and the perceptual tests were restricted to uppercase forms. Lowercase writings were thus not formally analysed, but are included in the supplementary data file for Study 1. Each letter was drawn individually onto a white screen, with a black trail left by the finger, and each drawing was saved as a bitmap for later scoring.

Finally, the child completed a visual orientation recognition task. Each uppercase letter that had been correctly identified was presented individually on the tablet, in black Arial font, against a white background, once in the correct orientation and once mirror-reversed, with the order of presentation shuffled. The child was informed that some of the letters would be shown the right way round, and some the wrong way round. They were asked to state, for each letter shown, whether they thought it was the right way round or not. Forty-one of the children had initially named all 15 letters and so completed 30 trials (one for each orientation of each letter). The other three children had named 10, 11 and 14 letters, and so completed 20, 22 and 28 trials respectively.

Scoring and screening

Each letter drawn in the letter-writing task was judged first for its general form, independent of horizontal orientation (forward or reversed); letters that were not unambiguously recognizable were excluded as invalid forms. The validly-formed letters were then coded according to whether they were drawn in a forward orientation (0) or mirror-reversed (1). An initial sample of drawings was screened by two experimenters, and judgements were closely concordant, so double-coding was not deemed necessary for the full dataset.

Each of the 15 letters was named correctly by at least 42 of the 44 children (median 43), and formed validly during the writing task by at least 31 children (median 38). The left-facing characters J and Z, although infrequent in English, were not unfamiliar to the children, being named correctly by all 44 children, and formed validly by 40 and 42 children respectively. Two children formed neither of the left facing characters (J or Z) correctly during the writing task. Because character facing direction is an important dependent variable, these two children were excluded from subsequent analyses. All other children drew valid forms for at least five letters (median 14), all of which were drawn correctly with both the dominant and non-dominant hand. The orientation recognition response on each trial was coded as correct (0), or as incorrect (1), where an incorrect response means that the child accepted a reversed letter as correct, or rejected a correctly-oriented letter as incorrect.

Results, Study 1, uppercase letters

Mirror writing and orientation recognition by child

For each child, a *mirror-writing* score was calculated, for each hand, as the proportion of valid forms that were mirror-reversed. An *orientation recognition error* score was calculated per child as the proportion of incorrect responses on the recognition task. As expected, both mirror-writing and orientation recognition errors declined with age, and were very infrequent beyond eight years of age (Figure 1a and 1b). The overall relationship between mirror-writing and orientation recognition errors, as shown in Figure 1c, was strong, Spearman's $\rho = .69$, $p < .005$, and persisted when the effect of age was controlled for, Spearman's partial $\rho = .59$, $p < .005$. That is, independent of age, children who produced more mirror-writing also made more orientation recognition errors. Finally, Figure 1d shows a strong relationship between rates of mirror-writing with the dominant and non-dominant hands, Spearman's $\rho = .74$, $p < .005$.

Mirror writing and orientation recognition by uppercase letter

For each letter, a *mirror-writing* score was calculated, for the dominant and non-dominant hands, as the proportion of valid forms that were mirror-written. An *orientation recognition error* score was calculated per letter as the proportion of incorrect recognition responses. Figure 2a shows that the likelihood of mirror-writing was elevated for the left-facing characters (J and Z), as expected, and that similar patterns arose with the dominant and non-dominant hands, $r = .96$; Spearman's $\rho = .83$, $p < .005$. Figure 2b shows a positive relationship between rates of mirror-writing and orientation recognition errors across the 15 letters, Spearman's $\rho = .67$, $p < .01$, confirming that the letters more often mirror-written were also more prone to orientation recognition errors (most notably the left-facing letters, J and Z).

Binary logistic regression

Mirror-writing and orientation recognition are binary outcomes per trial, so we used binary logistic regression to formally analyse the likelihood of errors under different task conditions.

For the writing task, we assessed fixed effects of character facing direction (right, left) and hand used (dominant, non-dominant), with a random intercept for child to control for individual differences in overall reversal rates. Character direction had a significant effect on the likelihood of mirror-writing, $\beta = 2.04$, $z = 7.84$, $p < .005$, but hand did not, $\beta = 0.27$, $z = 1.21$, $p = .23$. To get an intuitive estimate of the effect size for character direction, we converted the logodds β (2.04) to relative risk, by the method of Zhang & Yu (1998), taking the marginal mean reversal rate for right-facing letters as the baseline risk (8.23%). Children were thereby estimated to be 4.95 times more likely to mirror write a left-facing than a right-facing uppercase letter, 95% CIs [3.55, 6.49].

For the orientation recognition task, we assessed fixed effects of character facing direction (right, left) and orientation of presentation (forward, reversed), with a random intercept for child. Character direction had a significant effect on the error rate, $\beta = 2.88$, $z = 11.33$, $p < .005$. Taking the marginal mean error rate for right-facing letters as the baseline risk (8.88%), children were estimated to be approximately 7.14 times more likely to make an orientation recognition error for left-facing than right-facing letters, 95% CIs [5.78, 8.34]. Children were also more likely to make an error for letters shown in reversed orientation than for those shown in the correct, forward orientation, $\beta = 0.53$, $z = 2.65$, $p = .008$. Taking the marginal mean error rate for letters shown forward as the baseline risk (22.97%), children were estimated to be 1.47 times more likely to make an orientation recognition error for letters shown in the reversed orientation, 95% CIs [1.11, 1.87]. This overall positive response bias would be consistent with a tendency to mirror-generalise the representation of letter forms, so that a letter seen in either orientation would match the representation in memory.

Discussion, Study 1, uppercase letters

The patterns observed in Study 1 were clear. Mirror-writing and orientation recognition errors were related across children, and across (asymmetrical) uppercase letters. The correlations were surprisingly strong ($\rho = .69$ across children; $\rho = .67$ across letters), considering that each child made only two writing attempts and two recognition judgements per letter. Mirror-writing and orientation recognition errors were both linked to age, but their inter-correlation was only slightly lessened when shared variance with age was partialled out ($\rho = .59$). Even if age had completely accounted for the correlation between mirror-writing and orientation recognition errors across children, this would not lessen the potential importance of the relationship; it would just indicate that they share a developmental trajectory bound to chronological age. However, our result suggests that mirror-writing and orientation recognition are more specifically yoked, either because they are each related to some other aspect of literacy development, or because they are functionally related directly. Parsimony, and *a priori* likelihood, suggest that a direct functional relationship is likely, and that children do not use separate representations for recognising letters and for writing them.

Mirror-writing rates were similar, across children and across letters, regardless of whether the child used the dominant or non-dominant hand. The non-dominant hand was almost always the left (in 41 of 44 children), so our data do not distinguish dominance from hand laterality *per se*. However, Fischer & Koch (2016b) compared character writing with the dominant hand between 59 left handed and 59 right handed children, finding equivalent rates of mirror-writing in each group, and similar patterns across characters (more errors for left-facing characters). Together with the present study, this suggests that mirror-writing is not associated with use of the left hand. This contradicts the classical suggestion that mirror-writing is the natural script of the left hand (Buchwald, 1878; Erlenmeyer, 1879). It also differs from the prevailing pattern for adults, in whom an association with the non-dominant (left) hand has been taken as evidence for a motor account, according to which actions learned with the dominant hand are naturally executed in mirror-reversal by the non-dominant hand (Balfour et al., 2007; Critchley, 1927, 1928; McIntosh et al., 2014; McIntosh & Della Sala, 2012). The absence of a similar hand bias in children would suggest that developmental mirror-writing instead reflects a general lack of knowledge of letter orientation, with writing guided by the same representations of letter shape that inform letter recognition. The adult, motoric pattern would not be possible until the letter orientations were securely learned, so that the action patterns for writing them had become ingrained.

One other study seems to be at odds with these results. Wang (1992) reported that, of 112 five to eight year old Chinese preschool and school children, around twice as many reversed at least some characters in writing their name, age and dictated numerals, with the left hand rather than the right (33% vs. 14%). The asymmetry was even greater (43% vs 0%) amongst 60 'mentally retarded' children aged from nine to fifteen. Assuming that Wang's findings would not be culturally-specific to Chinese children, then, contrary to the present data, they suggest that children are indeed more prone to mirror-write with the non-dominant hand. One tentative account of the divergence between these studies could be related to the specific writing task: the present study used single isolated characters, but Wang's task involved name writing. It seems possible that, for this practiced task, there is an ingrained action for the dominant hand, which may tend to be executed automatically in mirror-reversal by the non-dominant hand. However, this is not supported by an informal analysis of name-writing in the present study, which was included to accustom the children to writing with a finger on the tablet. Mirror-writing within names for this preliminary task was quite rare, but equally common with the dominant and non-dominant hand (four and three names respectively, from 51, contained mirror-reversals). More comprehensive studies are needed to clarify the possible influence of writing hand, separate from handedness, on mirror-writing in children. Our method of writing directly with the finger onto a tablet, may be useful for this purpose, by making the task accessible to children who may lack pen skills, especially with the non-dominant hand.

As with most other studies on this topic, Study 1 used uppercase letters, which are often the earliest letter forms to be taught to children (Fischer, 2011, 2017a, Fischer & Koch, 2016a, 2016b; Fischer & Tazouti, 2012). Unlike some previous studies, we did not include digit writing, so we were able to sample very few left-facing characters. Only two uppercase letters face left, which also happen to be two of the least frequent letters in English (J and Z).

All 44 children recognised both of these letters, but it is possible that they were *relatively* unfamiliar with them, which could have biased error rates upward. In any case, the sample of behaviour was much smaller for the (two) left-facing characters than that for the (13) right-facing characters, which could make the estimates of relative risk of reversal for left- and right-facing letters unreliable. In Study 2, we sought to extend the scope of investigation to a new sample of children, within the Irish pre-school and primary education system, in which lowercase letters are taught from the earliest stages. Left-facing characters are better represented amongst the lowercase letters, though still less common than right-facing characters. One study of childhood mirror-writing has included lowercase letters, but they were not analysed separately from uppercase letters, and orientation recognition was not tested (Treiman, et al, 2014). If visual representations are critical to mirror-writing, then we would expect to replicate a correlation between mirror-writing and orientation recognition, across children and across lowercase letters.

Methods: Study 2, lowercase letters

Participants

One hundred and twenty-three children, aged from 3.1 to 8.4 years, were recruited from an Irish primary school and preschool. Twenty-three children identified fewer than ten (of 18) letters, and were excluded from consideration; a further two children were excluded because they produced fewer than ten recognisable forms in the writing task. The final sample comprised 98 children, ranging in age from 4.08 to 8.42 years (mean 6.56, SD 0.92), 58 of whom were female and 40 male. Hand dominance was inferred from the child's spontaneous use of a pencil to write their name at the start of the test session (see Procedure). The right hand was judged to be dominant in 83 children, and the left hand in 15.

Written informed consent was obtained from a parent or guardian for every child, and the research protocol was approved by the University of Edinburgh Psychology Research Ethics Committee, and the governance of the participating school and preschool.

Procedure

Children were tested individually in a quiet area of the classroom, or in a separate room, with the examiner sitting across a table from them. The tests were completed in a fixed order, and took less than 15 minutes to complete.

The child was initially asked to pick up a pencil placed in front of their midline and to write their name on a piece of paper. These writings were not analysed formally, but the hand that they chose to write with was considered to be dominant. The child was then shown 18 asymmetrical letters of the lowercase alphabet, presented individually in large black Comic Sans font (commonly used in the participating school) in the centre of a white screen on a tablet computer (Toshiba Portégé). The letters were shown in shuffled order and the child was asked to name each letter. Either the appropriate name or the letter sound were accepted as correct. At the stage of experimental design, each letter had been classed as a left-facing letter (a, g, j, q, u, y, z), or a right-facing letter (c, e, f, h, k, l, m, n, r, s, t).[2] Subsequent to data collection, more objectively-determined measures of letter facing-direction became available, based on ratings from American college students (Treiman et al., 2014). According to these ratings, the letters m, n and u do not face strongly in one direction. For consistency with our original design, and to retain all of our data, our analysis will follow our *a priori* classification, but note that no important conclusions would be altered by using Treiman and colleagues' scheme.

The child was then given a blank sheet of A4 paper, and a pencil, and was asked to write each of the letters that they had named correctly. The experimenter spoke each of the letter names or sounds (as given by the child), one at a time, in alphabetical order, and the child was asked to write the 'small' (lowercase) letter somewhere on the sheet.

Finally, the child completed an orientation recognition task. Each lowercase letter that had been correctly identified in the letter-naming task was presented individually on the tablet, in black Comic Sans font, against a white background, once in the correct orientation and once horizontally mirror-reversed, with the order of presentation shuffled. The child was informed that some of the letters would be shown the right way round, and some the wrong way round. They were asked to state, for each letter shown, whether they thought it was the right way round or not. Since each letter was shown in forward and reversed orientations, there were 36 trials for any child that had named all 18 letters correctly (n = 84), 34 for any child that had named 17 letters (n = 10), and 32 for one child who had named 16 letters. The other three children had named fewer than 15 letters (14, 14, and 13), so one or two of the available letters were randomly selected and re-used, to pad the task up to 30 trials.

Scoring and screening

The scoring system was as in Study 1. Each form produced in the letter-writing task that was not unambiguously recognizable was excluded as invalid, and the validly formed letters were classed as being in a forward orientation (0) or mirror-reversed (1). An initial sample of drawings was checked by a colleague of the experimenter, and judgements were closely concordant, so double-coding was not deemed necessary for the full dataset. All children produced valid forms for at least three of the seven left-facing characters (median 7) and at least four of the eleven right-facing characters (median 11). The response on each trial of the orientation recognition task was coded as correct (0), or incorrect (1).

Each of the seven left-facing letters was named correctly by at least 91 of the 98 children (median 96), and formed correctly in the writing task by at least 84 children (median 93), whilst each of the 11 right-facing characters was named correctly by at least 96 children (median 98), and formed correctly by at least 84 children (median 94). The left-facing characters did not therefore seem to be generally more difficult than the right-facing characters.

Results: Study 2, lowercase letters

Mirror writing and orientation recognition by child

For each child, a *mirror-writing* score was calculated as the proportion of valid forms that were mirror-reversed. For the orientation recognition task, an *orientation recognition error* score was calculated per child as the proportion of incorrect responses.

Both mirror-writing and orientation recognition errors declined with age (Figure 3a and 3b). As shown in Figure 3c, mirror-writing and orientation recognition errors were moderately correlated across children, Spearman's $\rho = .46$, $p < .005$. This relationship remained significant when age was controlled for, Spearman's partial $\rho = .30$, $p < .005$. Thus, independent of age, children that made more orientation recognition errors for lowercase letters also mirror-wrote them more often.

Mirror-writing and orientation recognition by lowercase letter

For each letter, a *mirror-writing* score was calculated as the proportion of valid forms that were mirror-written, and an *orientation recognition error* score was calculated as the proportion of incorrect recognition responses. Figure 3d shows a clear relationship between rates of mirror-writing and orientation recognition errors across the 18 lowercase letters, Spearman's $\rho = .58$, $p < .05$. As expected, left-facing characters were more prone to error. Notably, the overall rate of mirror-writing was not elevated for the left-facing letters a or y, nor for the letter u (which was not classed as strongly directional by Treiman et al., 2014).

Binary logistic regression

For the writing task, we assessed a fixed effect of character facing direction (right, left), with a random intercept for child to control for individual differences in overall reversal rates. Character direction had a significant effect on the likelihood of mirror-writing, $\beta = 5.60$, $z = -5.60$, $p < .005$. Converted to relative risk, by the method of Zhang & Yu (1998), taking the marginal mean reversal rate for right-facing letters as the baseline risk (2.98%), children were estimated to be 3.51 times more likely to mirror write a left-facing than a right-facing lowercase letter, 95% CIs [2.29, 5.29].

For the orientation recognition task, we assessed fixed effects of character facing direction (right, left) and orientation of presentation (forward, reversed), with a random intercept for child. Character direction had a significant effect on the likelihood of recognition error, $\beta = 1.10$, $z = 10.45$, $p < .005$. Taking the marginal mean error rate for right-facing letters as the baseline risk (10.60%), children were estimated to be 2.47 times more likely to make an orientation recognition error for left-facing than right-facing letters, 95% CIs [2.12, 2.87]. They were also more likely to accept a reversed letter as correct, than to reject a correctly-oriented letter, $\beta = 1.02$, $z = 9.46$, $p < .005$. Taking the marginal mean error rate for letters shown forward as the baseline risk (10.63%), children were estimated to be 2.34 times more likely to make an orientation recognition error for letters shown in the reversed orientation, 95% CIs [1.99, 2.73]. As in Study 1, this positive response bias would be consistent with a tendency to mirror-generalise the representation of letter forms, so that a letter seen in either orientation would match the representation in memory.

Discussion, Study 2, lowercase letters

Study 2 replicated the correspondence between mirror-writing and orientation recognition errors seen in Study 1, although the correspondence was less strong (ρ = .46 across children in Study 2 vs .69 in Study 1; ρ = .58 across letters in Study 2 vs .67 in Study 1). One reason for the more muted relationship may be that each child made only one writing attempt per letter in Study 2, as opposed to one attempt with each hand in Study 1. The estimates of mirror-writing rates were thus based on half as many observations per letter, and likely to be noisier. Moreover, this is the first study of childhood mirror-writing that has used lowercase letters only, and it appears that the distinction between left- and right-facing letters is overall less pronounced than for the uppercase forms (compare Figure 2b and Figure 3d). For uppercase letters, the difference between reversal rates for left- and right-facing letters may be exaggerated by the fact that the only two left-facing uppercase letters (J and Z) are two of the least frequent letters in English (and in French). Relative rarity may make J and Z less likely to be known securely, and render them more prone to reversal.

On the other hand, previous studies that have included digits, as well as letters, have generally found that left facing numbers (1, 2, 3, 7, 9) are also very likely to be mirror-reversed, especially the number 3 (Fischer, 2011, 2017a, Fischer & Koch, 2016a, 2016b; Fischer & Tazouti, 2012). This would not be explicable in terms of the relative rarity of the numbers, unless perhaps children have less experience writing numbers than letters *in general*. One could speculate that the number 3 could be especially prone to reversal because its reflected form resembles a familiar uppercase E. It might be similarly possible to suggest plausible reasons why some of the left-facing lowercase letters were mirror-written less often in the present study (e.g. the letters a and y). All such accounts would be ad-hoc, however, because the characters of natural languages and number systems vary in diverse ways that could potentially affect the likelihood of reversal: for instance, in the frequency of the character in the child's experience, the frequency of exposure with different neighbouring characters, the complexity of the shape, the similarity to other shapes, the pedagogical instructions for forming the character, and so on.

This inherent lack of experimental control over natural letters and numbers led McIntosh, Anderson & Henderson (2018) to adopt a more experimental approach to testing the influence of character facing direction on the likelihood of mirror-writing. We created a novel set of artificial letter-like characters, half of which were left-facing and half of which were right-facing, and we taught children (aged 4.8-5.8 years) to write them. Alternate groups of children learned identical but mirror-reflected character sets, so that all possible influences on the likelihood of error were counterbalanced. Children were three times more likely to mirror-write a novel character learned in a left-facing format, than one learned in a right-facing format. This is broadly compatible with the estimates from the present Study 2, of the increased likelihood of mirror-writing (3.51) for left-facing over right-facing letters. Given that the present studies show a correspondence between mirror-writing and orientation recognition, a valuable further step would be to confirm the influence of facing direction on orientation recognition errors experimentally, using artificial letter-like characters.

General discussion

The general patterns from these two studies are clear and consistent. Children who made more reversals when writing were more likely to make errors in judging whether letters are correctly oriented, and letters that were more often mirror-written were also more prone to orientation recognition errors. Moreover, mirror-writing rates were closely similar, across children and across letters, regardless of whether the dominant or non-dominant hand was used (Study 1). This effector-independence departs from the prevailing pattern for adults, and suggests that children's writing is guided by a high-level representation of the letter form, rather than an effector-specific motor pattern (cf. Balfour et al., 2007; Critchley, 1927, 1928; McIntosh et al., 2014; McIntosh & Della Sala, 2012). In both studies, we replicated the expected tendency for left-facing characters to be more often mirror-written than right-facing characters, and we extended this pattern to orientation recognition judgements. Moreover, we note that children were more likely to accept reversed letters as correct, than to reject correctly-oriented letters, consistent with a tendency to mirror-generalise the representation of letter forms (Ahr, Houdé, & Borst, 2016; Corballis & Beale, 1976; Dehaene, 2010; Dehaene et al., 2010; Duñabeitia, Molinaro, & Carreiras, 2011; Pegado et al, 2011).

Our results therefore disprove a prior conjecture that children mirror-write principally because they are ambivalent about the direction of the writing action, not because they are ambivalent about how the letter should look (McIntosh & Della Sala, 2012). The present results instead imply a major role for visual representations, though this does not mean that motor factors are irrelevant. Indeed, the emerging representation of letters is likely to encompass associated visual and motor aspects, which co-develop, and which influence one another. A tight interplay of perceptual and motor factors is suggested by Fischer's (2017a) recent demonstration that a manipulation causing children to reverse their writing direction, thus writing from right-to-left, also flips the pattern of character reversals, so that right-facing characters become more often reversed than left-facing characters. This implies that the heuristic that children apply is not that most letters face rightward, but that most letters face in the direction of writing (and reading). Children may derive this expectation from exposure to written language, via a process of statistical learning (Treiman & Kessler, 2011; Treiman et al., 2014), but the stimulus driving this learning would not be just the visual form of the letters, but the higher-order relation between the orientation of letters and the direction of action. In other words, the orientation of letters that children initially learn may not be defined by a left-right reference frame, but by a comparison of letter orientation with the direction of action. This seems plausible, given that primary-age children may not distinguish left from right in representing visual forms, but can detect by direct comparison whether left-right orientations match (e.g. Cubelli & Della Sala, 2007; Della Sala & Cubelli, 2009).

Considering our own results alongside Fischer's insights, a more nuanced account of childhood mirror-writing can be advanced. The developing brain is pre-disposed to mirror-generalisation, so a child will initially accept the correct or reflected version as equivalent, and fail to notice or amend their own mirror-writing errors. Once the child learns a consistent direction of approach to written language (left-to-right in a dextrad writing culture), they may statistically learn the prevailing regularity that most (Latin) characters face in the direction of action. This biases their writing, so that a child taking a left-to-right approach will mirror-write left-facing characters disproportionately often. This tendency can be modulated by situational and spatial constraints, and is largely independent of individual characteristics such as sex and handedness. During this period, the child knows the general direction of writing better than the orientation of the specific letters, but further practice and experience allows them to learn those specific orientations, and mirror-writing is eventually eliminated. Letters are now formed consistently, and the movements for forming them with the dominant hand eventually become ingrained, creating the potential for unthinking reversals when using the non-dominant hand, as in the adult 'motor' pattern of mirror-writing (Balfour et al., 2007; Critchley, 1927, 1928; Della Sala & Cubelli, 2007; McIntosh et al., 2014; McIntosh & Della Sala, 2012). The development and resolution of mirror-writing in children is thus a complex interaction of perceptual and motor learning.

Footnotes

[1] Study 1 was conducted as an undergraduate research dissertation by AB and ML (Brennan, 2012), and Study 2 as part of a postgraduate research dissertation by KH (Hillary, 2012).

[2] The letters q and t were modified for inclusion by adding short rightward ‘tails’ to the bottom of the spine. The letters i, o, v, w and x were excluded as being symmetrical or near-symmetrical, and the letters b, d and p were excluded because the mirror image of each is closely similar to the correct form of another letter.

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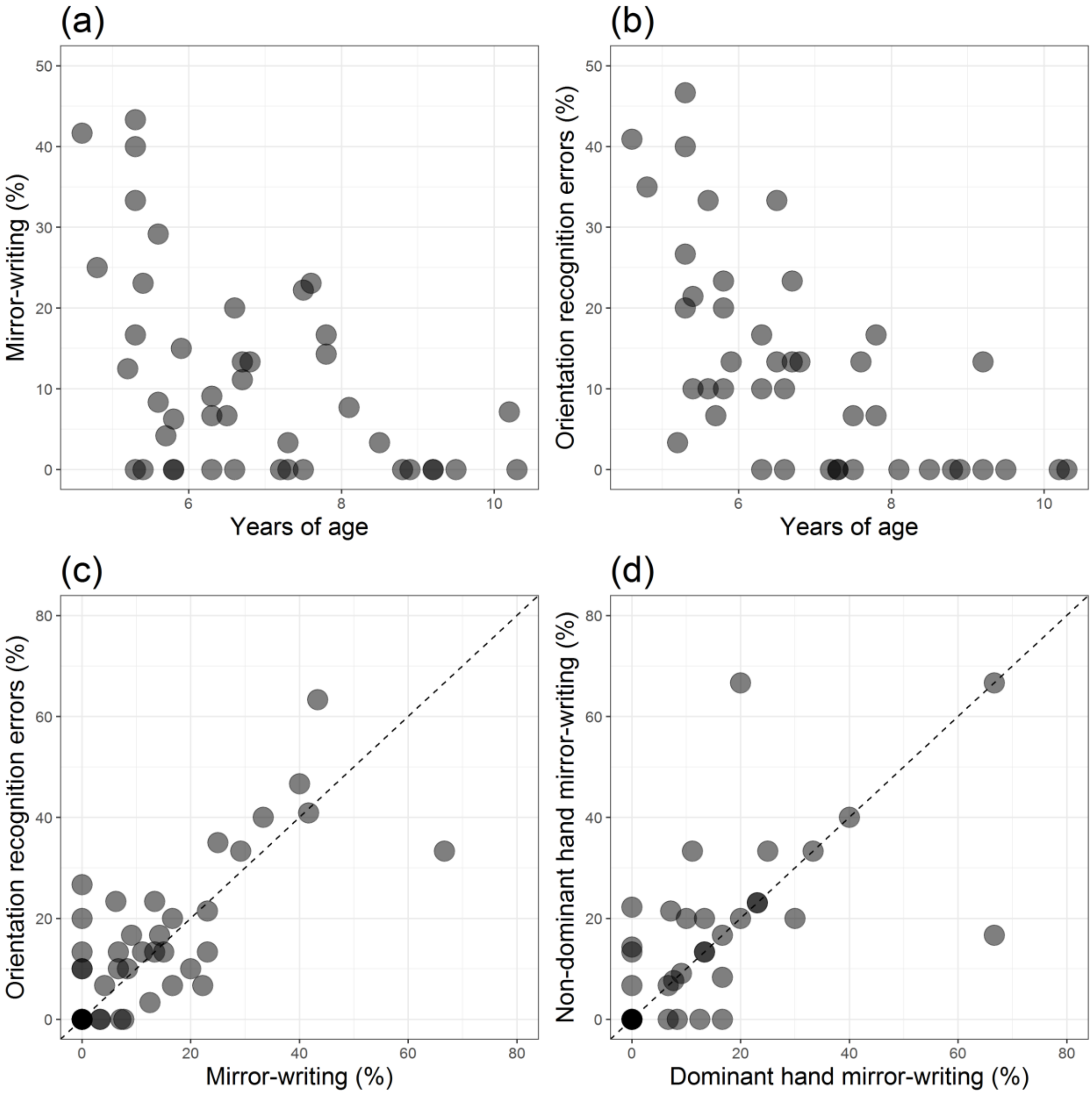

Figure 1. (a) The tendency to mirror-write uppercase letters declines with age (ρ = -.45). **(b)** The tendency to orientation recognition errors for uppercase letters also declines with age (ρ = -.69). **(c)** Across children, there is a positive relationship between mirror-writing and orientation recognition errors (ρ = .69. **(d)** The tendency to mirror-write is positively related between the dominant and non-dominant hand (ρ = .74). Dashed lines show lines of identity.

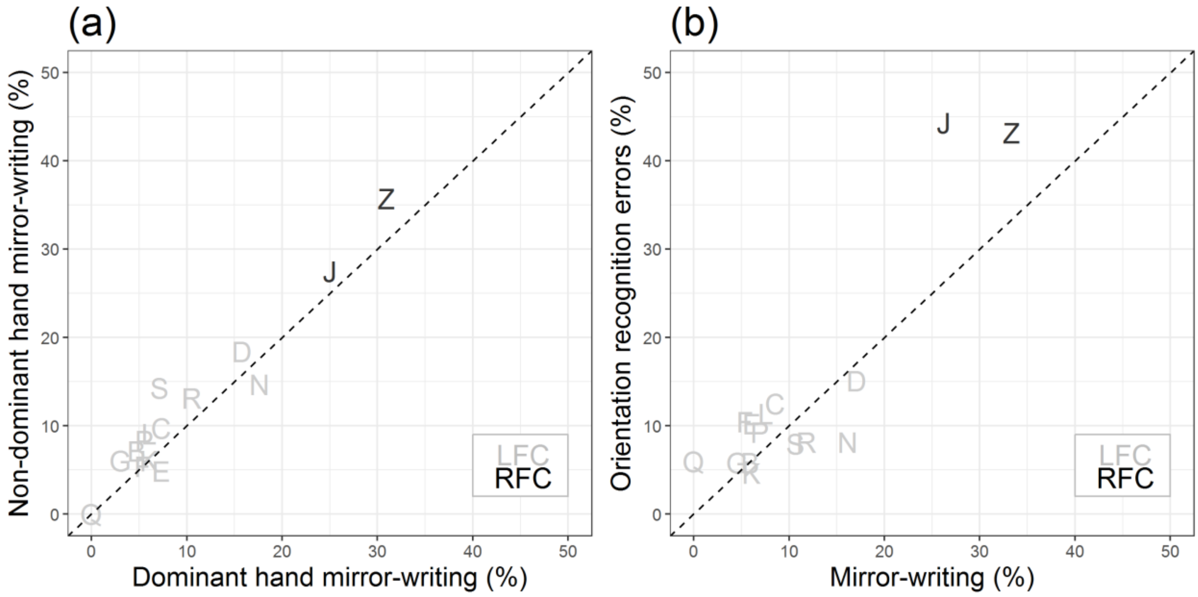

Figure 2. (a) The rates of mirror-writing of different uppercase letters is similar between dominant and non-dominant hands (r = .96, ρ = .83), with left-facing characters (LFC) more likely to be mirror-written than right-facing characters (RFC). **(b)** Across uppercase letters, there is a positive relationship between mirror-writing and orientation recognition errors (ρ = .67). Dashed lines show lines of identity.

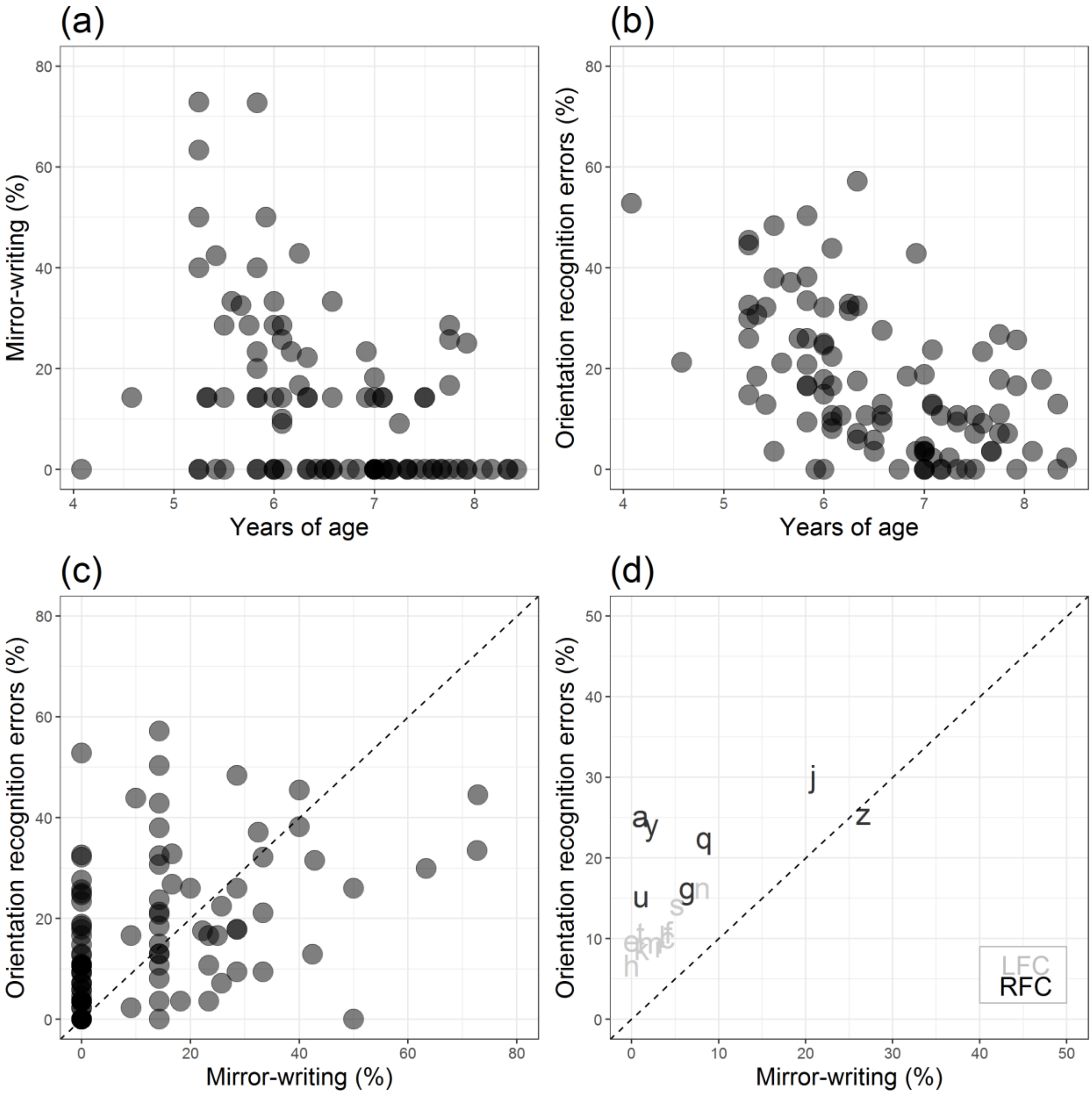

Figure 3. **(a)** The tendency to mirror-write lowercase letters declines with age (ρ = -.43). **(b)** The tendency to orientation recognition errors for lowercase letters also declines with age (ρ = -.54). **(c)** Across children, there is a positive relationship between mirror-writing and orientation recognition errors (ρ = .46). **(d)** Across lowercase letters, there is a positive relationship between mirror-writing and orientation recognition errors (ρ = .58). Dashed lines show lines of identity.