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Character reversal in children: the prominent role of writing direction

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Abstract Recent research has established that 5- to 6-year-old typically developing children in a left–right writing culture spontaneously reverse left-oriented characters (e.g., they write Ⴑ instead of J) when they write single characters. Thus, children seem to implicitly apply a right-writing rule (RWR: see Fischer & Koch, 2016a). In Study 1, the reversal of all asymmetrical digits and capital letters by 356 children was modeled with a simple Rasch model, which describes reversal as the outcome of two competing responses, correct writing and writing in the cultural direction of writing. It accounts for the high frequency of reversals of the left-oriented characters (3, Z, J, 1, 2, 7, 9), as predicted by the RWR. Study 2 investigated letter reversals when children spontaneously write their name from right to left. Most of the 204 children in the study radically changed the direction of the RWR by reversing mainly the right-oriented letters (B, C, D, E, F, G, K, L, N, P, R, S). Hence, a more universal formulation of the RWR would be as an implicit rule orienting characters in the writing direction. This reformulated rule is consistent with the "spatial agency bias" model (Suitner & Maas, 2016), according to which writing direction affects thoughts and actions. Visual and motoric statistical learning may favor bootstrapping of the rule. Taken together, these data demonstrate the prominent role of culture in a phenomenon—character reversal or mirror writing—which has often been presented uniquely as biologically determined.

Keywords Mirror writing · Writing direction · Capital letter reversal · Digit reversal · Rasch model

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The present research investigated the tendency of 5- to 6-year-old typically developing children to mirror-reverse some characters, at least occasionally, when they are learning to write. Our interest in this topic was triggered by the fact that the mirror-reversal phenomenon has intrigued neuropsychologists and developmental psychologists for more than a century and by the importance of learning to write within primary school curricula. In addition, because learning to write has a major impact on language learning, elucidating the mechanism(s) underlying character reversal could provide further insight into both the language-learning process and some of the difficulties associated with it. Most notably, the results of studies into the character reversal phenomenon may help refine contemporary theories of language acquisition, such as the cognitive theories of implicit statistical language learning (e.g., Erickson & Thiessen, 2015) and of language acquisition through bootstrapping (e.g., Christophe, Millotte, Bernal, & Lidz, 2008). Data on character reversal could also provide a further test for the psychosocial model of "spatial agency bias" (Suitner & Maass, 2016).

Single-letter or single-digit reversal is sometimes called fragmentary or partial mirror writing, as the reversed characters appear normally written when held in front of a mirror. This phenomenon is particularly intriguing in 5- to 6-year-old typically developing children because these children spontaneously write characters (letters or digits) they have never seen written in this fashion (see Fig. 1). Where does this ability come from?

For a long time, mirror-reversed writings were attributed to a child's individual characteristics, most notably writing with the left hand. For example, Ireland (1881) wrote of "a physiological tendency with left-handed children to fall into mirror-writing" (p. 364). In fact, emphasis on writing with the left hand was so great that Scheidemann (1936) found the reversal of characters by a six-year-old boy who had no left-handed tendencies to be "noteworthy since all cases of mirror writing thus far reported have been encountered with left-handed children, and only with extremely left-handed ones" (p. 492). The primacy of the left-handedness explanation of mirror reversal continued until the end of the twentieth century, when Lebrun, Devreux, and Leleux (1989) wrote: "In countries where script normally runs from left to right, young children who spontaneously produce mirror-writing are generally left-handers" (p. 356).

However, despite its predominance, left-handedness was not the only causal explanation of mirror reversal in young children. Gordon (1921) concluded his empirical research by noting: It is "evident that mirror writing is very closely associated with mental deficiency" (pp. 342–343). Hildreth (1950) subsequently combined these two views when she stated: "The strongest tendency to mirror write occurs when left-handedness and mental defect coincide" (p. 74). Gender is also

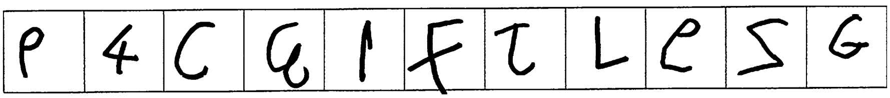


Fig. 1 Writing of the series P, 4, C, 3, 1, 7, J, L, 9, Z and G (dictated characters) by a 6-year 2-month old girl, using her preferred hand (*right*), in an experiment by Fischer and Tazouti (2012)

sometimes mentioned as a factor in mirror reversal. In the same review of research into mirror writing, Hildreth concluded: “Most observers find mirror writing more common among boys than girls in proportion greater than three to one” (p. 69, but see Fischer, 2010, p. 231).

In contrast with explanations of mirror reversal based on children’s individual characteristics, recent research has uncovered a quite different source of character reversals in typically developing young children. Both Fischer and coworkers (Fischer, 2013; Fischer & Koch, 2014; Fischer & Tazouti, 2012) and Treiman and co-workers (Treiman & Kessler, 2011; Treiman, Gordon, Boada, Peterson, & Pennington, 2014) have proposed a link between the reversal of characters and their shape. They noted that several letters in the Latin alphabet have a vertical or semi-vertical stem and one or more appendages attached to the right (e.g., b, P, R), which gives the impression that these letters face right. Furthermore, because writing has a motor component, Fischer and coworkers emphasized the need to take into account the dynamics of writing in the cultural environment in which children learn to write. For example, 5- to 6-year-old French children generally write N by producing an upward vertical stroke, followed by a right-trending downward stroke, and then another vertical upward stroke. Given this writing dynamic, N may be categorized as right-oriented, even though the static form of the finished letter cannot be said to have any specific orientation. Viewed in this way, all the asymmetrical characters (digits and capital letters) can be classified as either left-oriented (1, 2, 3, 7, 9, J, and Z) or right-oriented (all the others).

Reversal of the characters is easy to explain via Fischer and Koch’s (2016a, b) proposed right-writing rule (RWR), which could be acquired by statistical learning (Treiman & Kessler, 2011; Treiman et al., 2014). Due to mirror generalization by the brain (Corballis & Beale, 1976; Dehaene, 2010), 4- to 5-year-old typically developing children know only the shape of the characters but not their horizontal (left–right) orientation. Consequently, in our left-to-right oriented culture, the RWR predicts that children should prefer to orient their writing rightwards when writing the characters from memory; therefore, they reverse mainly the left-oriented characters (see Fig. 1).

Our Study 1 used a simple Rasch mathematical model to confirm the reversal of left-oriented characters. However, the dependence of reversal on the left–right direction of writing in the children’s culture raises another question: What happens when children write from right to left? Study 2 attempted to answer this question by using, for the first time, a within-subject design.

Study 1: Character reversal when writing from left to right

Introduction: a Rasch model of reversal

In order to fully discuss character reversal, it is necessary to analyze both the characteristics of participants and the properties of the items. The logistic item-response (Rasch) model allows the participant and item locations to be placed in a directly linear relationship on a single oriented line. Therefore, it appears well suited to modeling data on character reversal by children.

The Rasch model is a standard method for modeling success, coded 1, and failure, coded 0, in test situations. The basic model begins by postulating that $\ln[\frac{p_{pi}}{(1-p_{pi})}] = \theta_p - \beta_i$, where p_{pi} is the probability of a participant, *p,* giving a 1-response. In the present research, we attributed a 1-response to a correct writing of a character and a 0-response to a mirror reversal of a character. Therefore, θ_p can be considered the writing competency of a participant, *p,* and β_i the attraction towards mirror reversal of an item (character), *i*. Applying elementary mathematics to the basic equation shows that (a) if a participant's competency, θ_p, is greater than an item's attraction, β_i, the chance of the participant writing that item correctly is better than even; (b) if θ_p is less than β_i, the chance of the participant reversing that item is better than even; and (c) if $\theta_p = \beta_i$, the two chances are the same.

Method

Because Fischer and Tazouti (2012, Expt 2) involved suitable numbers of both items ($n = 23$) and participants ($N = 356$), we used data from this experiment for our Rasch analysis. The items were the 15 asymmetric capital letters (all but A, H, I, M, O, T, U, V, W, X, Y) and the 8 asymmetrical digits (all but 0 and 8). The children ($M_{age} = 5.71$ years, $SD = 0.36$, range: 5.00–6.41, 175 girls, 181 boys) were recruited from "upper section classes" at 18 *écoles maternelles* (kindergarten) in France. The other features of the participants, materials, procedure, and data coding can be found in the original paper, so we describe here the only important change we made. In the original experiment, each child wrote each character one time only, with the exception of 3, 9, J, and Z, each of which they wrote three times. In order to homogenize the items, the present analysis includes only the first writing of each of these four items. Therefore the datasheet contained $23 \times 356 = 8188$ responses, coded 1 (correct writing), 0 (left–right mirror reversal), or NA (not available).

The main weakness of these data is the large number of missing data (NA), mainly due to an absence of writing (10.2 %)—children who did not know how to write a character were instructed to put a cross in the response box corresponding to that character. Fortunately, these missing data do not rule out a Rasch analysis for two reasons. First, the Rasch functions implemented in the recent R-TAM-package (Kiefer, Robitzsch, & Wu, 2016; R-Core Team, 2015) process the missing data and, second, the non-available data were distributed in such a way that all the items and all the participants could be included in the analysis. This second point is important because excluding some items or some participants is not without risk (Flieller, 1994), especially when the aim is (as was the case here) to produce an ecologically valid analysis.

Results

Goodness-of-fit

Because inferences drawn from a poorly fitting model may be invalid (Maydeu-Olivares, 2013), it is essential to evaluate how well the data fit the model. A basic idea of the Rasch model is that consistent item parameter estimates can be obtained from any subgroup of a population where the model holds, so it is important to verify that no specific items depend on the subgroup being examined. Possible differences in the functioning of items across subgroups (DIF) can be examined both on subgroups based on extraneous participant characteristics (e.g., boys vs. girls) and on subgroups based on raw experimental data (e.g., children with good writing skills vs. children with poorer writing skills). We tested the 23 items for possible DIF in subgroups defined by writing hand, gender, and age (subgroups determined by median split in the latter case). A Fisher exact test on the two subgroups defined by each of these three participant characteristics indicated 2, 1, and 3 significant differences (at the .05 level), respectively. However, at the .01 level and, a fortiori, at a level corrected for multiple comparisons (i.e., .05/23 = .0022), there were no significant differences between the subgroups (out of 23 characteristics × 3 subgroups = 69 possible differences).

The children's academic performance and their parents' socio-economic status (SES) were not included in Fischer and Tazouti's (2012) data, so for this particular comparison we used analogous data from Fischer and Koch (2014), which indicated these characteristics. For academic performance, we used the mean to split the sample into two subgroups. For SES, we compared the subgroup of children whose parents had low SES with the complementary subgroup of children whose parents had intermediate or high SES (according to a French categorization reported in Fischer and Koch). For the two subgroups defined by each of these two participant characteristics, a Fisher exact test led to 0 and 2 significant differences (at the .05 level), respectively. Again, there were no significant differences (out of 23 × 2 = 46) at the .01 level.

We used the likelihood ratio global test (LR-test: see Andersen, 1973), as implemented in the eRm package (Mair & Hatzinger, 2007), to compare the subgroups determined by the results of the experiment. As well as being able to detect DIF, this test is a powerful tool for checking sufficiency and monotonicity, two other conditions determining the applicability of the Rasch model. The test yielded a LR-value of 28.39; therefore, a Chi-square test with 22 degrees of freedom was not significant ($p = .163$).

In addition, the eRm package includes a graphical procedure that can be used to detect, a posteriori, a DIF between children with good writing skills and children with poorer writing skills (dichotomization through the mean). The 23 items were relatively well aligned around the diagonal of the first quadrant (continuous black line) and only 2 items (the letters B and N) clearly lie outside the confidence band shown by the dotted lines (Fig. 2).

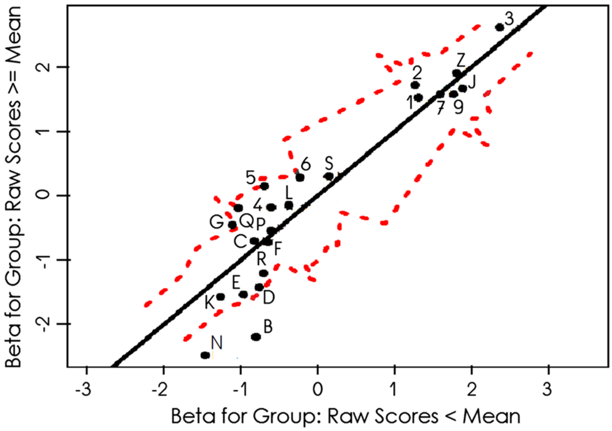


Fig. 2 Graphical check of a possible differential functioning of the items between children with good writing skills and children with poorer writing skills (the *dotted lines* indicate the confidence band)

Items parameter

Table 1 (column 2) shows the beta estimates for all 23 items. These estimates range from −3.893 (the letter N) to +0.611 (the digit 3). Column 4 in Table 1 shows the recorded frequency of mirror reversals for each character. As would be expected if the item difficulty is mainly due to the attraction towards mirror reversal, the correlation between the betas and the reversal frequencies is very high: $r(22) = 0.976$, $p < .001$ ($r_S = 0.999$ with Spearman's rho).

Depiction on a common scale

Figure 3 shows item attractions as points along a straight vertical line (or band) on the left (higher values are towards the top). There were too many children in the sample to show each child's writing competency as a point on the scale, so the right-hand column in Fig. 3 shows their distribution in intervals of length of .50.

Figure 3 shows the children are shifted upwards compared with the items, which indicates that the items were relatively easy for the children. This is mainly due to the fact that only two letters (J and Z) attracted the children to write them in the wrong direction (because of their left orientation).

Discussion

As a general rule, data never fit a Rasch model perfectly and this was the case for the present study. Because the model's underlying hypotheses—unidimensionality and local independence—are both difficult to satisfy and hard to verify (Flieller, 1994), it was important to assess how well our data fit the model before applying the model to the participant's scores. The results of the checks we carried out did not suggest the model should not be applied.

Table 1 Beta parameter estimates (with SE) and empirical reversal frequencies for the 23 Items

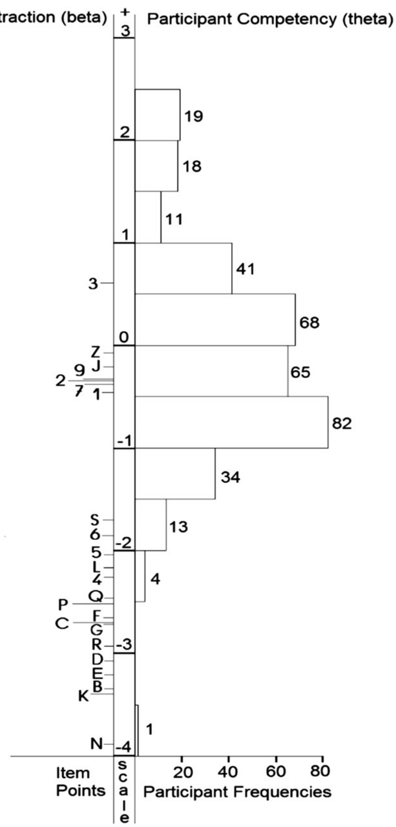
Item (character)	Beta		Reversal frequency (%)
	Estimate	Standard error	
1	−0.454	0.116	40.06
2	−0.340	0.119	42.64
3	0.611	0.121	63.25
4	−2.262	0.177	11.38
5	−2.042	0.170	13.69
6	−1.861	0.166	15.44
7	−0.371	0.123	41.42
9	−0.321	0.132	42.11
B	−3.351	0.298	4.17
C	−2.710	0.217	7.60
D	−3.076	0.261	5.42
E	−3.212	0.252	4.93
F	−2.663	0.227	7.80
G	−2.727	0.265	7.21
J	−0.212	0.126	45.14
K	−3.397	0.344	3.91
L	−2.174	0.176	12.19
N	−3.893	0.361	2.56
P	−2.530	0.203	8.86
Q	−2.463	0.215	9.29
R	−2.939	0.241	6.21
S	−1.704	0.153	17.56
Z	−0.079	0.122	47.86

Once we had run the Rasch analysis, we verified the consistency of the results with our reversal theory. As predicted, the item coefficients (see Table 1; Fig. 3) clearly separated the left-oriented characters from the others. This result supports the validity of the present Rasch analysis and of a reversal theory based on the left–right orientation of the characters (Fischer, 2013; Treiman & Kessler, 2011).

Does the model describe the data well? Take the case of the 34 children within the [−1.5, −1] interval on the scale in Fig. 3. According to the model, the mean probability the children will correctly write each of the 23 characters is greater than .50 for all the characters except for 3 ($p = .142$), Z ($p = .248$), J ($p = .273$), 9 ($p = .295$), 2 ($p = .299$), 7 ($p = .306$), and 1 ($p = .324$). These estimated probabilities are a good reflection of the data, as more than 50 % of the 34 children's writings of each character were correct for all the characters except 3 (17 %), Z (31 %), J (25 %), 9 (29 %), 2 (30 %), 7 (15 %), and 1 (19 %).

Because the Rasch model's common scale is an interval scale, it does not show only whether different values are bigger or smaller, it also indicates how much

Fig. 3 Item distribution (*left side*) and histogram of children's writing competencies (*right side*) on a common scale



bigger or smaller they are. As an illustration, the distance between the group of 68 children and the item K is greater than the distance between the group of 34 children and the item P. Accordingly, the model estimates that the mean probability the group of 68 children will correctly write K ($p = .974$) will be greater than the mean probability the group of 34 children will correctly write P ($p = .791$). The corresponding empirical frequencies, 100 and 79 %, were in line with the model's estimates.

However, the value of a model also resides in its ability to make predictions. Analogous data compiled by Fischer and Koch (2014) allowed us to verify many of the present Rasch model's predictions. First, the beta estimates reported in Table 1 should correlate with the percentage of reversals in Fischer and Koch. This prediction was clearly confirmed, as $r(21) = .923$, $p < .001$. Second, because the items {3, Z, J, 9, 2, 7, 1} are clearly the most attractive (see Fig. 3), these seven items should be the seven most frequently reversed items in Fischer and Koch's data. This was the case. Third, because the model's estimates clearly placed the digit 3 at the top of the scale and the letter N at the bottom of the scale, we expected them to occupy the same positions in Fischer and Koch's data. Again, this was the case. However, one prediction was not confirmed. Because the digit 3 exerts the greatest attraction, we predicted that children who reversed just one character would reverse the digit 3. This was not the case in Fischer and Koch's data, as the most common character reversed by the 19 children who reversed only one character was the letter L. The rarity of character reversals by these 19 children suggests that they were further advanced in learning to write than most of the other children. This observation led us to hypothesize that many of these 19 children had confused the letters L and J, as these letters tend to be better (but not totally) consolidated in the declarative memory of more advanced learners, compared with less advanced learners.

Because the data from Fischer and Koch (2014) that we used to verify some of the model's predictions were compiled by the same research group as the data used to compute the beta estimates, we felt it was important to test the model's predictions on data compiled by an independent research group. Unfortunately, no recent data on both digit and capital-letter reversals by 5-year-old children are available. However, Ritchey's (2008, Fig. 1)[1] graphical data allowed us to test the predictions for the 15 asymmetrical capital letters. The correlation we obtained was positive and highly significant, $r(13) = .72$, $p < .005$, although it was slightly lower than the correlation obtained using Fischer and Koch's (2014) data.

In summary, the Rasch model simply describes the curious phenomenon of character reversal in writings by 5- to 6-year-old typically developing children. We used the Rasch model approach in order to describe character reversal as a result of competition between two possible responses to a lack of knowledge about the direction in which characters are oriented (Wilson & De Boeck, 2004). The first response arises from a child's ability to write correctly. However, the standard direction of writing in the cultural environmental also exerts an attraction over a child's writing. Thus, in a left–right writing culture this second response competes with the first in the case of the left-oriented characters. The sign and value of the basic difference $\theta_p - \beta_i$ in the Rasch model, where θ_p is a child's writing competency and β_i is the attraction of the item in a false direction, provide a probabilistic solution to the conflict.[2]

Study 2: Letter reversal when writing from right to left

Introduction

The Rasch model adequately describes and accounts for reversals of characters when children write normally, that is, from left to right in a left–right (L–R) culture. But what happens when the writing direction changes radically, that is, when children write from right to left?

[1] The percentages of reversed and correct writings were manifestly inverted in Ritchey's (2008, p. 37) graph (or in the legend). For comparison, we estimated the percentage of reversals by measuring on the graph the number of reversals and the absence of writings (correct or reversed) for each of the 15 asymmetrical capital letters.

[2] The probability of a participant, p, reversing an item, i, can be derived from the basic formula given at the beginning of Study 1: $p_{pi} = [\exp(\theta_p - \beta_i)]/[1 + \exp(\theta_p - \beta_i)]$.

One way of approaching this question would be to carry out a comparative analysis of writings by children from two different reading/writing cultures (L–R and R–L). However, it is very difficult, if not impossible, to establish a systematic and comparative statistic on reversals of single (capital) letters. Indeed, the letters in R–L writing cultures generally have very different shapes to those in Western, L–R writing cultures, and these shapes can vary across both geographic areas and time (Suitner & Maass, 2016). In addition, participants who write different scripts (e.g., in two different countries) cannot be randomly assigned to groups, which makes it difficult to explore the causality of the writing direction effect.

Two recent studies have examined the influence of mirror reading on adults. In an experiment by Casasanto and Bottini (2014), Dutch speakers were asked to perform space–time congruity tasks with the instructions and stimuli written in standard, mirror-reversed, or rotated orthography. In one block, they were instructed to press a button if the stimulus-phrase referred to an interval of time in the past and another button if it referred to an interval of time in the future. In the other block, the mapping between the two buttons and past/future phrases was reversed. In fact, when participants judged temporal phrases written in standard orthography, their reaction times were consistent with a rightward-directed mental timeline, but after brief exposure to mirror-reversed orthography, their mental timelines were reversed. In another experiment, Román, Flumini, Lizano, Escobar, and Santiago (2015) asked Spanish students to draw the contents of auditory descriptions such as “the square is between the cross and the triangle” immediately after reading a short text. The text in one condition was mirror written. The directionality of the drawings in the mirror-reading condition clearly showed a reduction in the standard L–R bias found in the normal reading condition.

Although these experiments on adult participants show the considerable impact of writing/reading direction on the spatial bias, they do not clarify the influence of writing direction on letter reversals when young children write spontaneously. There are at least three major reasons for this. First, in these experiments mirror writing had a contextual function and its influence was studied only on tasks not related to writing. Second, unlike adults, 5- to 6-year-old children have not automatized writing and reading. Third, with respect to letter reversal, writing differs considerably from reading because when reading children see the letters’ orientations. To the best of our knowledge, no experiments have been conducted to investigate the influence of writing direction on letter reversal by children. Maass, Suitner, and Deconchy (2014) also commented on this curious lack of research, noting that “the role of writing direction in writing/reading errors among non-clinical populations is at the moment at best under-investigated and further studies are needed to clarify the role of writing direction in mirror writing and letter inversion phenomena” (p. 83).

The data compiled by Fischer and coworkers (Fischer & Koch, 2014, 2016a; Fischer & Tazouti, 2012) provide interesting material that has not yet been exploited for examining this issue. These data were gathered in naturalistic situations, as attending school is an almost universal part of growing up in France, the culture in which the data were collected. More than 500 5-year-old children were asked to carry out both a character-writing task, in which they had to write all the asymmetrical capital letters and digits under dictation, and a name-writing task. The name-writing task included a condition (adapted from Cornell, 1985) in which the children were encouraged by spatial constraints to write their name from right to left and a condition inducing normal writing. Hence, the role of writing direction in the capital-letter reversal process can be studied, at least in the children who reversed the L–R direction of writing, by comparing the writing of the asymmetrical letters in the character-writing task and in the name-writing task.

Method

Participants

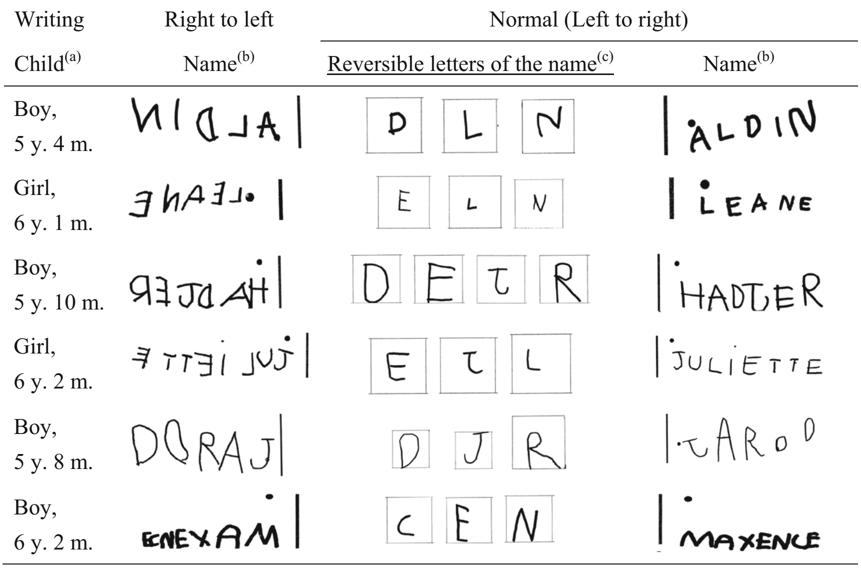
Encouraging R–L writing by applying spatial constraints, but without explicitly telling children to write from right to left, is far from always being productive. In order to obtain a sufficiently large sample, we combined data from three experiments (Fischer & Koch, 2014, 2016a; Fischer & Tazouti, 2012, Expt 2) in which children were encouraged to write their name from right to left. These three experiments involved 579 children, 349 of who wrote their name from right to left (generally in the condition encouraging R–L writing) and who were, therefore, potentially eligible for inclusion in our analysis sample. However, as Fig. 4 shows (first column of name writings), some of these children reversed all the reversible letters in their name (e.g., ALDIN and LEANE), some reversed some of the reversible letters but not all (e.g., HADJER and JULIETTE), and some did not reverse any of the reversible letters (e.g., JAROD and MAXENCE).

Because the aim of the study was to compare within-participant letter reversals during right-to-left spontaneous name writing and during normal (L–R) writing of single letters and words, all the children included in the sample had to have written their name in both directions and in capital letters. In addition, each child's name had to contain at least one reversible capital letter. Consequently, our final sample comprised 204 children (M_{age} = 5.60 years, *SD* = 0.35, range 5.00–6.35, 70 girls, 134 boys) who fulfilled all these conditions. Thirty of these children wrote with the left hand. Most of the children were attending "upper section" classes in *écoles maternelles* (kindergarten) in northeast France.

Material

The children had to write (in capital letters) three series of nine or ten dictated characters. The characters were written in squares (one character per square) on one side of a sheet of paper (half A4 format), moving from left to right (see Fig. 1). The precise series and details of the procedures are described in Fischer and Tazouti (2012, Expt 2) and Fischer and Koch (2014). What is important here is that all 15 asymmetrical capital letters (B, C, D, E, F, G, J, K, L, N, P, Q, R, S, and Z) were dictated once.[3] The children wrote their name on the other side of the sheet of paper,

[3] The letters (J and Z) were dictated three times: only the first writing was included in the data. The digit writings are not analyzed in this study.



(a) All these children wrote with their (preferred) right hand.
(b) Informed written consent for the publication of the name writings was obtained from each child's legal guardian.
(c) The single letter writings were extracted from the character-writing task.

Fig. 4 Name writings as a function of direction of writing and normal writings of the single reversible letters included in their name by six of the children in our sample. The *dot* described in the Material section can be seen to the left (*first column* of name writings) or to the right (*last column*) of the vertical line

either before or after writing a series of characters. This side of the paper was bisected into two boxes by an ink line. Two name-writing conditions were used. On the first and third sheets of paper, an ink dot was positioned about 1 cm to the left of the median line (dot-left condition: see first column of name writings in Fig. 4). On the second sheet of paper, this dot was about 1 cm to the right of the median line (dot-right condition: see the last column of Fig. 4).

Procedure

In both conditions of the name-writing task children were instructed to write their (first) name "as beautifully as possible", beginning at the ink dot. In order to get reasonably spontaneous writings from the children, even if their writings were not truly spontaneous, the experimenter did not correct children who took the starting dot as the finishing point for their writing (or who crossed the bisecting line). Consequently, because the dot-left condition implicitly encouraged R–L writing, the children had two main opportunities to momentarily change the normal direction of writing.

Details of how the writings were coded are provided in Fischer and Tazouti (2012, Expt 2) and Fischer and Koch (2014). The sample of writings shown in Fig. 4 shows that reversal judgments of capital letters were unambiguous.

Operationalized predictions

We used the three writings—single characters, R–L names, and L–R names—to compute three correlations: (1) between individual letter reversals in normal writing of single characters and in R–L writing of the name; (2) between individual letter reversals in normal writing of single characters and in L–R writing of the name; and (3) between individual letter reversals in R–L name writing and in L–R name writing. These correlations are not independent but because of the non-transitivity of correlations all three are reported.

If statistical learning (e.g., Erickson & Thiessen, 2015; Spencer, Kaschak, Jones, & Lonigan, 2015; Treiman et al., 2014) results in children retaining in their implicit memory that the letters face right, they should reverse the same letters (mainly J and Z) irrespective of the writing direction. Therefore, letter reversals should positively and strongly correlate between any pair of writings. Thus, this statistical learning (fundamentally visual) predicts that correlations 1, 2, and 3 should be positive and strong.

However, if statistical learning results in children memorizing that the letters face the writing direction, they should reverse the right-oriented letters when writing from right to left. Such statistical learning would lead to a negative correlation 1, with letter reversals in the single-character writing task correlating negatively with letter reversals in R–L name writing, a positive correlation 2, with letter reversals in the single-character writing task correlating positively with L–R name writing, and a negative correlation 3. The level of activation of Fischer's (2013) postulated implicit RWR is a function of the individual and of the context. Therefore, activation of the rule should be weaker when children write from right to left. In fact, as Fischer and Koch (2016a, p. 115) noted, "the rule may disappear or the child may even transform it into an implicit left-writing rule". The correlations predicted by such an adaptation of the rule to the direction of writing are the same as those predicted by statistical learning of the letter's orientation in the direction of writing.

If children turn the letters in the direction of writing, they should reverse the right-oriented letters more frequently than the left-oriented letters (J and Z) when they write their name from right to left. In contrast, when they write the single letters (in their name) or their whole name in the "normal" direction (L–R), they should reverse the left-oriented letters more frequently than the right-oriented letters.

Because the debate between perceptual and motor explanations of mirror-writing is omnipresent in the literature (see McIntosh & Della Sala, 2012), it should be emphasized that assuming children orient the letters in the direction of writing does not mean that learning is based only on a child's motor movements. In fact, many lines of evidence in adults point to close links between the perceptual and motoric representations of actions in the brain (Oosterhof, Wiggett, Diedrichsen, Tipper, & Downing, 2010). When parents or teachers (at least in France's *écoles maternelles*) in a L–R writing culture "read" picture books to 3- or 4-year-old children, they usually point to the pictures, moving their finger from left to right (even if they just point to the pictures on the left-hand page before the pictures on the right-hand page). Whether or not the accompanying text is read (and tracked with the finger), this practice gives the child an opportunity to see (and therefore implicitly learn) that the letters of the text are generally oriented in the direction in which their parent's or teacher's finger moves.

Results

Percentages of reversals for the 15 individual letters

Table 2 shows the percentages of reversals for each of the 15 asymmetrical capital letters in the character-writing and name-writing tasks. Because occurrences of each letter in the children's names differ greatly, Table 2 also reports the number of opportunities for writing each of these letters in the name-writing task. Some letters (e.g., E) occurred frequently in the children's names; others were much rarer. For example, the letter Q occurred in only two children's names and was therefore excluded from our correlation coefficient computations. The number of relevant writings of each letter is indicated in the last column of Table 2. These numbers are much greater than the numbers of occurrence of the letters in the children's name, although the children appear to have had difficulties writing the letter G, resulting in this letter having the lowest number of relevant (correct or reversed) writings.

Table 2 Comparison between reversals of individual letters in normal (L–R) writing of the single letters and writings of the same letters in a R–L or L–R writing of the child's name

Percentage reversal	Name		Number of opportunities[a]	Letter (normal writing)	Number relevant[b]
	Right–left	Left–right			
B	100.0	0.0	8	7.2	152
C	92.9	0.0	28	13.6	162
D	68.4	0.0	19	5.6	160
E	84.4	0.8	122	8.8	194
F	66.7	0.0	6	10.4	144
G	60.0	20.0	5	9.5	95
J	33.3	33.3	18	51.0	153
K	66.7	0.0	6	1.9	107
L	95.8	1.4	72	9.0	167
N	74.2	0.0	95	3.5	170
P	75.0	0.0	8	10.1	168
Q	0.0	0.0	2	14.5	131
R	77.6	0.0	49	7.6	172
S	36.3	5.9	51	20.8	173
Z	0.0	16.7	6	55.6	162

[a] The number of opportunities was the same for both R–L and L–R name writing

[b] All 204 children were asked to do the character-writing task, but some of them could not write certain letters or produced a writing other than the correct or reversed form of the capital letter in question

Correlational analyses

Correlation 1, between single letter reversals in the character-writing and R–L name-writing tasks, was significant and negative, $r(12) = -.82$, $p < .001$. Although we excluded the letter Q from the computation (which only slightly diminished the strength of the correlation), many other letters we did include were poorly represented in the children's names. Consequently, we computed the same correlation on the 253 children who had completed these two tasks adequately. This slightly more representative sample confirmed the strong negative correlation, $r(12) = -.84$, $p < .001$.

Correlation 2, between single letter reversals in the character-writing and L–R name-writing tasks, was significant and positive, $r(12) = .78$, $p < .001$. The large number of null percentages (8 out of 14) indicates a probable floor effect for this measure, so we also computed a point-biserial correlation after coding all non-zero percentages "1", $r_{pb} = .56$, $p < .05$.

Correlation 3, between letter reversals when the name was written from left to right and letter reversals when the name was written from right to left, was significant and negative, $r(12) = -.67$, $p < .01$. For the same reason as in correlation 2, we also computed a point-biserial correlation, $r_{pb} = -.49$, $p < .10$.

Global analyses

On a more global level, we compared the weighted mean percentage of reversals of the right-oriented capital letters (B, C, D, E, F, G, K, L N, P Q, R, and S) with the weighted mean percentage of reversals of the left-oriented capital letters (J and Z). The first percentage was greater than the second percentage (77 vs. 25 %) when the children wrote their name from right to left, but when the children wrote their name normally (L–R) and when they wrote the single letters of their name, the first percentage was smaller than the second percentage (1 vs. 29 and 4 vs. 53 %, respectively).

Discussion

Data gathered by Fischer and coworkers (Fischer & Koch, 2014, 2016a; Fischer & Tazouti, 2012) offered an opportunity to examine, for the first time, which (capital) letters children in a L–R writing culture tend to reverse when they spontaneously write from R–L. The findings were very clear.

First, R–L name writing leads to a considerable number of reversals, whereas L–R writing of the same names leads to very few reversals (Table 2, first column of name writings). The letter E, which occurred in most of the 204 children's names, was reversed on more than 84 % of occasions (i.e., less than 16 % correct Es) when it was included in a R–L name writing, but on only 0.8 % of occasions (i.e., more than 99 % correct Es) when it was included in a L–R name writing.

Second, if the children orient the letters in the writing direction, the three correlations we obtained conform perfectly to our predictions. These correlations were both significant (in the predicted direction) and strong. This was especially true for the negative correlation (correlation 1, $r = -.82$) between reversals of single characters when written in the normal (L–R) direction and their reversals when included in a R–L writing. This correlation, which can be considered "very large" according to the nomenclature introduced by Cohen (1988), seems to considerably weaken the hypothesis that children implicitly memorize (mostly visually) letters as facing right, and then use this implicit knowledge when writing. Indeed, children who do not know a letter's orientation generally write that letter so its orientation coincides with the direction of writing. Such behavior could be favored by the motor dynamics of writing. Transforming the right-orienting/right-writing rule into a writing-direction-orienting rule reveals the RWR to be a special case of the more universal rule that applies to L–R writing cultures. Although most of the digits are turned towards the left (the opposite direction to our writing direction), the primacy of reading picture books (with the help of parents or teachers) means it is possible for children to assimilate the rule by statistical learning (Treiman et al., 2014).

Even though the left-oriented capital letters (J and Z) provide only a small amount of material for studying the comparison between reversals of the left- and right-oriented characters, they confirm the result of a similar comparison with the digits. In fact, there are more left-oriented digits (1, 2, 3, 7, and 9) than right-oriented digits (6, 5, and 4, if one takes into account writing dynamics), and all the left-oriented digits were reversed more frequently than the right-oriented digits in a normal (L–R) writing task (in our Study 1 and in Fischer, 2013).

In addition to the small number of left-oriented letters, our study has a number of other limitations. First, it was based, essentially, on children's writings of their name. Two inconvenient consequences of this are that (a) some letters (notably the letter Q) are under-represented and that (b) the percentage reported for each of the 15 asymmetrical letters is based on a (partially) different (and often small) sub-sample of children. Avoiding this problem would be difficult because at the developmental age at which children spontaneously mirror write, the only word most children can write from memory is their name.

The second limitation comes from the difficulty of obtaining spontaneous mirror writings. The "spontaneous" mirror writings in our sample were not truly spontaneous, as they were prompted by a spatial constraint. However, as shown by the number of children excluded from the initial sample, the children were never "forced" or explicitly instructed to write from right to left.

A third limitation arises from our decision to focus entirely on capital letters. We did this because French children are quickly taught to write in a cursive style, using connected, lower-case letters. Hence, many children mirror wrote their name in this way (see, for example, Fischer & Tazouti, 2012, Fig. 3). Because cursive mirror writing implies reversing all the letters, it made no sense to study reversals of individual letters in names written using this style of writing. As a result, many children who wrote their name in this way were excluded from the initial sample.

General discussion

Before concluding, we discuss how our present findings may relate to, and thereby contribute to the discussion of three more general ideas or theories. Our results indicate that children in a western culture tend to orient the characters, correctly or erroneously, toward the right (Study 1). This raises the question of the historical origins of this choice of preferred direction. Interestingly, the results of our Study 2 suggest a partial answer to this epistemological question, as the analysis was based on data from single experimental sessions involving two conditions in which children were encouraged to write their names from L–R and from R–L. In the dot-right condition (encouraging L–R writing), many children wrote their name from left to right while orienting all the letters toward the right, whereas in the dot-left condition (encouraging R–L writing), they wrote their name from right to left while turning all the letters toward the left. If "ontogeny recapitulates phylogeny", as postulated by Haeckel (quoted in Shuttleworth, 2010, p. 40), the genesis of an individual's knowledge would be expected to follow the same course as the genesis of human knowledge. Hence, the alternating behavior shown by children should be found in early human writings. This is, in fact, the case for the Boustrophedon writing system, which was used in ancient Greece around the 6^{th} century BC. In this system, successive lines of text run in opposite directions, left to right, then right to left, then left to right, etc., with the orientation of the individual characters also being reversed from one line to the next.

Second, the recent spatial agency bias (SAB) model (Suitner & Maass, 2016) postulates that human agency follows the script direction prevalent in a given cultural context. Writing direction is the first moderator and "plays a founding role in defining both the direction and the intensity of the SAB" (p. 280). A possible explanation is that, in cultures in which text is written from left to right, reading and writing encourage a scanning habit that also runs from left to right. The SAB model postulates that this left to right habit generalizes to a much larger spectrum of actions than just reading and writing. For example, if an individual is asked to depict an actor (i.e., the agentic person) performing an action on an object, the SAB model predicts that the actor is likely to be depicted to the left of the object. Nevertheless, the SAB is also sensitive to short-lived changes in writing direction (Suitner, 2009) and is therefore compatible with both reversal of the left-oriented characters and reversal of the right-oriented characters when momentarily writing from right to left in a L–R writing culture. The compatibility of the present findings with the SAB model appears to extend the domain of application of this model because all prior observations of the influence of SAB have been in tasks unrelated to writing.[4] Furthermore, an essential feature of agency, that is, acting autonomously in a given environment, holds for our observations: When children do not know which way a letter is oriented, they use a self-initiating process, with no apparent help, to

[4] For example, in visual motion drawing (e.g., Maass, Suitner, & Nadhmi, 2014), aesthetic preference (Chokron & De Agostini, 2000; but see Treiman & Allaith, 2013), and line bisection (Chokron, Bartolomeo, Perenin, Helft, & Imbert, 1998).

improvise its orientation (see Fischer & Koch, 2016b, note 5). These improvisations may be rooted in implicit statistical learning (Treiman et al., 2014).

Third, our empirical studies contribute to the central debate in the cognitive sciences over the nativist hypothesis, according to which the universal features of behavior reflect a biologically determined cognitive substrate. Indeed, the ease with which many children reverse the right spatial bias when they write from right to left shows that a weak, culturally induced bias is easily defeasible, as Thompson, Kirby, and Smith (2016) suggested for cognition in general.

In summary, our first study used a basic Rasch model to investigate character reversal as the outcome of two competing responses: correct writing and writing in the cultural direction of writing. The model confirmed that 5- to 6-year-old children reverse mainly the left-oriented characters in a L–R writing culture, when orientation is defined taking into account the dynamics of writing. A partial explanation for these reversals is provided by children's implicit knowledge (obtained by visual learning) that the asymmetrical capital letters face right.

However, this memorized learning cannot account for the fact that, in a second study, the children reversed mainly the right-oriented letters when they wrote from right to left. These reversals show that the implicit right writing rule (Fischer & Koch, 2016a), which accounts for the reversal of the left-oriented characters in a L–R writing culture, should be more universally seen as an orienting in the writing direction rule.

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