# Mirror Writing and Hand Dominance in Children: A New Perspective on Motor and Perceptual Theories

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Mirror writing in nursery and school-aged children was investigated using a novel approach. The motor hypothesis of mirror writing, which proposes that the non-dominant hand may be more adept at mirror writing, was assessed with dominant and non-dominant hand writing using a digitizing tablet. A measure of perceptual discrimination was used to investigate the relationship between mirror writing and the perceptual hypothesis, which states that unintentional mirror writing may be attributable to a form of perceptual confusion. Findings demonstrated a significant positive correlation between mirror writing and perceptual confusion, indicating that perception is the predominant driving factor in the majority of young children. Mirror writing was shown to decrease with age and as children grow older, motor factors gradually take over as a foundation for mirror writing. As children mature, these motor mechanisms gradually become governed by cognitive control strategies. In certain cases, brain damage may occur that disrupts these control strategies, producing unintentional mirror writing in adults. This developmental perspective of mirror writing considers it to be an inherent phenomenon and a normal part of writing development in children.

*Keywords:* mirror writing, children, perceptual, motor, dominant, non-dominant

Mirror writing is defined as the production of individual letters or whole words in reversed form, such that they become easily legible when viewed with a mirror. Mirror writing is most commonly characteristic of young children who are in the early stages of language acquisition (Schott, 2007), and has also been identified in certain cases of brain damage in adults (Paradowski & Ginzburg, 1971). Despite there being a few famous cases of adults practicing mirror writing intentionally (Schott, 1999), for most individuals it constitutes a complex, unnatural and cognitively demanding task. In light of this fact, it is intriguing that the vast majority of children have a tendency to mirror reverse words, letters and digits at some point during their writing development (Cornell, 1985).

Several researchers have proposed theories regarding the behavioral basis of mirror writing, with the debate centered on whether mirror writing can be considered a predominantly perceptual or motor phenomenon.

*Perceptual Explanations* Perceptual theories of mirror writing attribute unintentional mirror writing in children to perceptual confusions of the letters. One such theory is the mirror engram hypothesis (Orton, 1928). This theory states that visual representations (engrams) of stimuli such as letters and words are stored in the dominant hemisphere for language (usually left), while the corresponding mirrored engram is stored in the alternate hemisphere. These mirrored engrams are normally suppressed unless hemispheric dominance has yet to be established (as is the case in young children), or if damage occurs to the mechanism involved in such suppression (as may be the case in brain damaged adults). Confusion over the internal representation of letters would therefore elicit mirror writing with both the dominant and non-dominant hands. A perceptual foundation may also explain the large concurrence of mirror writing with mirror reading.

Orton's mirror engram hypothesis has found support from case studies of adults with brain damage (e.g. Gottfried, Sancar & Chatterjee, 2003; Heilman, Howell, Valenstein, & Rothi, 1980) and experimental studies with normally functioning adults (Tucha, Aschenbrenner, & Lange, 2000; Tankle & Heilman, 1983). Tankle and Heilman (1983) focused on whether the left

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hand was more adept at mirror writing and investigated the basis for this superiority. Participants were asked to mirror write words and sentences with both their dominant and non-dominant hands and errors were counted as instances when the writing was not correctly mirror reversed. It was found that when writing with the dominant hand, left handers mirror wrote with fewer errors ($p < .01$) and at a faster pace ($p = .04$) than right handers. There was no difference detected between right and left handers' speed when writing in normal direction ($p > .20$). Building on the work of Tankle and Heilman (1983), Tucha et al. (2000) instructed left- and right- handed subjects to mirror write with both hands using the touch screen of a digitizing tablet, making it easier to write with the non-dominant hand. This study also stressed the role of left handed superiority in mirror writing, as left handers were found to make significantly fewer errors than right handers when writing with their dominant hand ($p < .01$).

An alternative model of mirror writing was devised by Dehaene, Nakamura, Jobert, Kuroki, Ogawa and Cohen (2010) in an effort to explain the neural substrate of spontaneous mirror writing in children. Their fMRI study with adults found the human perceptual system to be inherently dichotomous, presenting evidence of an 'unlearned' capacity for recognizing mirrored forms of writing in adults. They propose that this mechanism is still intact in children who are in the early stages of language acquisition and can thus account for the readily available mirrored representation of letters and words, which in turn produces mirror reading and writing.

There exists a relatively sparse body of literature on mirror writing in normal children. Due to the misinterpretation of mirror writing as a dysfunction in children, older studies tended to focus on learning and other developmental difficulties (Orton, 1928). Recent research has dispelled such myths and has shown there to be little or no relationship between mirror writing and learning difficulties or intelligence in children (Cubelli & Della Sala, 2009).

An early study with normally developing children used a simple technique to induce mirror writing in those aged between 3 and 14 years old (Cornell, 1985). Children were asked to write their names on a sheet of paper that was bisected by a line. When instructed to write on the left side of the line, there was insufficient space for the child to write his or her name and to do so in a correct direction would require the child to write over the line. Children aged 8 years or older (n = 54) all successfully wrote their names in a left-right direction across the line. The younger group of children, however, did not always successfully write their names across the line, and instead tended to mirror write their names in a right-left direction (n = 99). The proportion of mirror writing dropped off as a function of age, ranging from 82% of 5 year olds to 13% of 7 year olds.

By contrast, Fischer and Tazouti (2012) rationalized that the perceptual explanation of mirror writing could be split into two facets: errors in the direct perception of letters (assessed by means of a copying task) and errors in the internal representation of those letters (assessed by writing from memory). A large sample of children (n = approximately 300) aged between 5 and 6 years was recruited. Under the memory condition, mirror writing was relatively frequent (> 20%); while in the copying condition the prevalence of mirror writing was negated (< 0.5%). Referring to previous results of Fischer (2010, 2011), the authors here reiterate that in the absence of a defined direction of letters, children use their implicit knowledge of orientation of characters when writing. Research has found that those letters and digits that are mirror written most often are those that end in strokes facing leftwards (e.g. J, Z, 3). As English is a predominantly rightward facing language, both in terms of the individual letters and the overall direction of script, it is assumed that children may over-apply this 'right writing rule' (Fischer, 2011).

*Motor Explanations* An alternative set of explanations attributes mirror writing not to perceptual factors, but rather to motor factors. According to one motor hypothesis, as first proposed by Erlenmeyer in 1879 (as cited in Critchley, 1928), the motor sequence for writing with the dominant hand is stored in the contralateral hemisphere. It is hypothesized that when writing is undertaken with the non-dominant hand, the motor sequence must be transferred to the alternate hemisphere and becomes mirrored in the process (Noble, 1968). Another motor hypothesis is related to the popularized perception that mirror writing is the natural script of the left hander. The basis for this is that adductive movements tend to be more comfortable than abductive movements (Brown, Knauft & Rosenbaum, 1948). This would suggest that when right handers undertake writing with their left hand, it may be more natural to start from the midline and write in a right-left (adductive) direction. As a consequence of this theory, it could plausibly be predicted that left handers are better able to overcome the left-right directional bias (Tankle & Heilman, 1983).

There is a growing body of research supporting motor hypotheses (Angelilo, De Lucia, Trojano & Grossi, 2010; Rodriguez, 1991; Rodriguez, Aguilar & Gonzalez, 1989). Evidence for motor mechanisms has been observed in cases of brain damaged adults (Balfour, Borthwick, Cubelli & Della Sala, 2009; Buxbaum, Coslett, Schall, MacNally & Goldberg, 1993) and in more recent studies with children (Della Sala & Cubelli, 2007; Wang, 1992). The motor hypothesis would be testable in younger children if they were to write with their non-dominant hand, as such age groups may lack the conscious awareness to override the basic mirrored motor output.

The term 'directional apraxia' was used by Della Sala and Cubelli (2007) to explain unintentional mirror writing. Directional apraxia refers to the unavailability of the correct direction of movement. Their investigation into mirror writing concerned both patients with left hemisphere stroke and normally developing children. The authors argued that our motor systems are inherently dichotomous and in young children, an appropriate writing direction has yet to be encoded due to inexperience with writing. Concerning adults with brain damage, the theory is that the acquired writing direction is lost due to infarction. Della Sala and Cubelli argued against a perceptual explanation of mirror writing as they failed to find a relationship between mirror writing and performance on perceptual and orientation tasks in children. This study provides an interesting perspective on mirror writing by considering the two populations alongside one another. Overall, this approach succeeds in unifying the theoretical underpinnings of mirror writing across different populations. The findings were later upheld by Cubelli and Della Sala (2009) when they tested the same sample of children. A caveat should be applied to these methods, however, in that odd-one-out picture tasks were used as a measure of perception and orientation. A more appropriate task would have been a perceptual confusion task with written stimuli, as discrimination of mirrored images and letters are different processes (Pedago, Nakamura, Cohen & Dehaene, 2011).

To the best of our knowledge, only one study has explored the motor hypothesis in children by asking them to write with their non-dominant hand (Wang, 1992). Writing with the dominant and non-dominant hand was examined in normally developing children and adults. Overall, Wang found a higher prevalence of mirror writing with the left hand (45.8%) compared to the right hand (22.2%) in preschool children (n = 72). There was a significant drop off of mirror writing with the left hand (10%) in school children (n = 40), and no mirror writing was observed with the right hand. Given that right handedness is more common than left handedness, we assume these results to be indicative of non-dominant (left) and dominant (right) hands. Wang also found a relationship between left/right spatial disorientation and mirror writing in preschool children (67.6%). Writing with the non-dominant in adults did not elicit mirror writing except in one case (n = 40). This suggests a greater effect of motor driven mechanisms in children that gradually drops off with age.

*The Present Study* Much research in this area has focused on mirror writing in brain-damaged adults and much current thinking stems from such work. Our study, by contrast, is concerned with the prevalence of mirror writing in children. Given the relatively small body of literature on mirror writing in children and in the absence of satisfactory contradictory evidence, it is reasonable to assume that the mechanisms driving involuntary mirror writing in brain damaged adults and young children may share a common underlying neural substrate.

In light of the evidence discussed above, we propose an investigation into dominant and non-dominant hand effects on children's mirror writing. In cases where mirror reading is reported alongside mirror writing, motor hypotheses cannot account for both. It would seem, therefore, that mirror writing is not a unitary disturbance; rather it is likely that multiple processes are at work. For this reason, we accounted for the possibility of both motor and perceptual foundations in our study. There are numerous shortcomings in the research that are rectifiable by a simple experimental approach. The method pioneered by Wang (1992) has proven to be an unusually effective method of assessing the motor hypothesis in young children. The use of a tablet (Tucha et al., 2000) will eliminate any potential confounds to holding a pen with the non-dominant hand. A more concrete approach to assessing children's perceptual abilities would be by means of a letter perceptual discrimination task, as opposed to an odd-one-out task (Della Sala & Cubelli, 2007).

To test for motor factors, we had subjects write their names and a selection of letters with both their dominant and non-dominant hands. Bimanual tasks such as these allow us to see how much conscious control children are exerting on their writing direction and are thus effective in determining whether mirror writing is due to motor factors. To test for perceptual factors, we chose to use an alphabetic directional discrimination task. This allowed us to gauge the extent to which perceptual confusions impacted children's mirror writing. Using these methods meant that we could conduct straightforward correlational analyses on the data collected, resulting in discernible relationships between motor factors, perceptual factors and age. These tests also allowed us to record a single data point for each of the letters analyzed, allowing us to test Fischer's (2011) theory of the 'right writing rule'.

We predict that perceptual factors will play an overriding role in spontaneous mirror writing in younger children, while motor influences are likely to impact increasingly as the child grows older and perceptual confusions fade. We predict that we will find consistent mirror writing of certain letters across both dominant and non-dominant hands in younger children. In older children, we expect to observe less mirror writing with the dominant hand and more mirror writing with the non-dominant hand, in accordance with Critchley (1928). As a separate hypothesis, we expect to find more mirror writing of less common, leftward-facing letters, as predicted by Fischer (2011).

## METHOD

Writing with both dominant and non-dominant hands was assessed among pre-school and school-going children in order to analyze spontaneous occurrences of mirror reversals. These instances were recorded alongside literacy and perceptual measures as a means to determining the possible underlying causes of mirror writing in children.

*Participant Characteristics* The sample consisted of 51 normally developing children (28 boys, 23 girls; aged 48 - 124 months, mean 79.33, SD 18.38) recruited from local nurseries and after-school clubs. Only 5 children were considered to be left-handed and they were all male. Children were selected to participate on the basis that they could spontaneously write their name and had a basic knowledge of the alphabet. We relied on reports from both parents and teachers as an accurate assessment of this ability. Consent forms were sent to the participating nursery or after school club and these were forwarded to parents. Those children who had obtained consent were then asked if they would like to participate in our study.

Age, gender, handedness and literacy were recorded for each child alongside spontaneous written productions of their names and letters of the alphabet. These were sampled using both the dominant and non-dominant hands. A perceptual measure of letter orientation discrimination was also included.

## PROCEDURE

The children completed a set of writing tasks in which productions were recorded on a digitizing tablet. Children were seated at a desk with the touch screen tablet placed squarely in front of them. They were asked to write with both their dominant and non-dominant hands using their index finger, and stickers were used to help the children identify each hand. By requesting children to use their finger as opposed to a stylus, we were able eliminate any difficulty in holding a pen with the non-dominant hand. It was not always possible to keep the testing environment quiet or free from distraction and the location of testing also differed, but for the most part the testing environment was kept relatively constant.

Subjects were tested one at a time and consistent testing order was maintained across all participants. Testing of each subject took fifteen minutes to complete and was administered in the following order:

As a preliminary test to establish handedness, the children were asked to pick up the stylus and draw a circle on the tablet. The hand that they chose to draw with was considered to be their preferred, and therefore dominant, hand. The children were then asked to write their name spontaneously using the index finger of their dominant hand. This aspect of the procedure doubled as an initial literacy test. If the child could not spontaneously produce their name, they were excluded from the study. Children were then asked to write their name using their non-dominant hand. As a third preliminary measure, we administered a simple literacy test which comprised all 15 asymmetrical capital letters of the alphabet (B, C, D, E, F, G, J, K, L, N, P, Q, R, S, Z) printed on white A5 cards in 250 point size Times New Roman black font. The asymmetrical capital letters were presented to the child one at a time in alphabetical order and the subjects were asked to name each letter. For the younger children, making the noise of the letter was sufficient.

We carried out two experimental tasks, the first being the bimanual motor task, and the second the directional discrimination task. To investigate whether mirror writing could be attributed to motor factors, subjects were asked to write the asymmetrical letters that they could name, all initially with their dominant hand and then all with their non-dominant hand. They were asked to write both the upper and lower case of the letter if possible. Finally, to test the prominence of perceptual factors in mirror writing, subjects completed a perceptual task in which letters were presented in normal and mirrored form and the subjects had to indicate which orientation of each letter was correct. The same 15 asymmetrical letters were presented on the tablet using a specialized computer program. The letters were printed in black uppercase Arial font against a white background. The experimenters selected the asymmetrical capital letters that were known by the child, of a possible 15, and these were displayed in a randomized order, one at a time in the center of the screen. For the children who recognized 10 or more, each letter was presented in both a normal and mirrored orientation. For children who recognized less than 10, the letters were reused until a 10-letter list had been completed. There were therefore between 20 and 30 trials per child. Participant responses were recorded by the experimenters by pressing a button corresponding to either correct or incorrect direction.

*Data Recording* All written productions were recorded as bitmap images and saved to the digitizing tablet. The perceptual test responses were saved as text documents. A separate paper record of all production errors as well as perceptual errors was kept for all participants as a backup in case of a computer fault.

*Data Analysis* The data for each child was coded as follows: every mirror reversal of a letter was denoted by '1' for error; all correctly written letters were denoted by '0' (for both name and writing task). Similarly, every error made on the perceptual task (if a mirrored letter was said to be correct or vice versa) was denoted by '1', and again '0' represented a correct response. The literacy score was calculated as a proportion of the letters known by the child (of a possible 15). The proportion of mirror writing per child was calculated from the number of mirror reversals with respect to the number of letters written by that child. Perceptual error was scored in the same way.

## RESULTS

*Preliminary Analysis* In order to assess the relationship between age, mirror writing and perceptual errors, the children were split into a mirror writing group and a non-mirror writing group. Those who did not produce any mirror writing in their written productions were excluded from the analysis (n = 15). The final analysis for mirror writing among children was carried out on 36 participants. Total proportionate mirror writing was calculated for each child, along with the proportion of mirror writing carried out with the dominant hand, non-dominant hand, lowercase letters and uppercase letters. 5 children did not complete the perceptual task. The proportion of perceptual errors was calculated for each of the remaining children (n = 46).

We conducted a similar analysis with respect to letters. For this, the proportion of mirror writing with the dominant hand and non-dominant hand was calculated for each letter. A motor score was derived from the average number of times that a letter was mirror written with both hands. A perceptual error score for each forward and backward facing letter was also calculated, and the total perceptual error score was derived from the average number of times each letter was confused. We assessed the relationship between these scores and included the direction of the letters as a grouping variable.

As there were only 7 instances of mirror written names, this variable was not considered pertinent to our investigation and was therefore excluded from the analyses.

The majority of children performed at ceiling level in the literacy test; therefore, this was not considered to be a practical assessment of language development and age was used instead for comparative purposes in tracking the progression of mirror writing and perceptual confusion.

Normality plots and Shapiro-Wilk tests indicated that all data was significantly non-normal, positively skewed and leptokurtic. This non-normality could not be rectified by an arcsine transformation and therefore non-parametric methods were used to analyze the data.

*Statistical Analysis*

*Descriptive Statistics.* The mean mirror writing per child gradually decreased with age (Table 1). A significant proportion of 4 year olds' writing was mirrored (24.4%); however, this was representative of a very small sample (n = 5). Less than 2% of writing was mirrored in children aged 8 years and older (n = 9). The proportion of perceptual errors for different age groups corresponded to the values of mirror writing, 4 year olds were inclined to make more perceptual errors than other age groups (38%) and this error rate gradually decreased with age, reducing to only 1.4% for ages 8 and over.

*Research Question 1: Is there a relationship between age and mirror writing?* Age was found to correlate significantly and negatively with both perceptual error [$r_s$ = -.69, *df* = 46, $p$ < .001] and mirror writing [$r_s$ = -.47, *df* = 51, $p$ < .001].
There was no significant effect of gender on either proportion of mirror writing ($U$ = 308.5; exact $p$ = .4) or proportion of perceptual errors ($U$ = 261.5; exact $p$ = .494). Girls had an average rank of 26.59 for mirror writing and 23.45 for perceptual error. Boys had an average rank of 25.52 and 23.54 for mirror writing and perceptual error respectively.

TABLE 1. Average rate of mirror writing (MW) and perceptual error (PE) per child, grouped by age

| Age (Yrs) | Av. MW (n) | Av. PE (n) |
|---|---|---|
| 4 | 24.4% (5) | 38% (2) |
| 5 | 17.7% (16) | 23.2% (15) |
| 6 | 11.4% (13) | 13.7% (12) |
| 7 | 9.2% (8) | 5.5% (8) |
| > 8 | 1.7% (9) | 1.4% (9) |

*Research Question 2: Is mirror writing attributable to perceptual confusion?* In order to determine the association between mirror writing and perceptual errors, the proportion of mirror writing per child was compared to the average perceptual error for that child. Analysis by Spearman's rho showed a significantly positive correlation [$r_s$ = .667, *df* = 46, $p$ < .001], demonstrating that mirror errors increased with perceptual confusion. Given that the perceptual task consisted of only uppercase letters, we also correlated perceptual error with percentage of mirror written uppercase letters for each child to obtain a more accurate picture. These scores were again shown to be significantly positively related, $r_s$ = .677, $p$ < .001.

*Research Question 3: Does directionality of letters predict mirror writing?* Further to the evidence reported by Fischer (2011), we investigated whether left-facing letters of the alphabet were likely to be mirror reversed more often than right-facing letters. The letter J was mirrored a total of 37 times, while Z was mirror written 42 times. Both of these values were significantly above average (Table 2).

Similarly, the rate of mirror writing among letters was significantly positively correlated with the rate of perceptual confusion for that letter, $r_s$ = .786, *df* = 15, $p$ = .001.

When the perceptual confusion scores for letters were plotted against the proportion of mirror writing for that letter, a clear picture of Fischer's 'right writing rule' emerged (Figure 1).

A Mann Whitney U showed that mirroring and confusion of left (*M rank* = 14.5) and right (*M rank* = 7) facing letters was significantly different, *U* = .000, exact *p*(one tailed) = .01; $r_g$ = .1, a 'large' effect by Cohen's (1988) classification. We can conclude from this that the left-facing letters J and Z were mirror written and perceptually confused considerably more often than the other 13 asymmetrical capital letters (Figure 2).

TABLE 2. Proportion of mirror writing instances for each letter

| **Letter** | **Average Instances of MW (%)** |
|---|---|
| B | 8 |
| C | 10 |
| D | 19 |
| E | 5 |
| F | 5 |
| G | 4 |
| **J** | **29** |
| K | 6 |
| L | 13 |
| N | 16 |
| P | 8 |
| Q | 0 |
| R | 9 |
| S | 10 |
| **Z** | **36** |

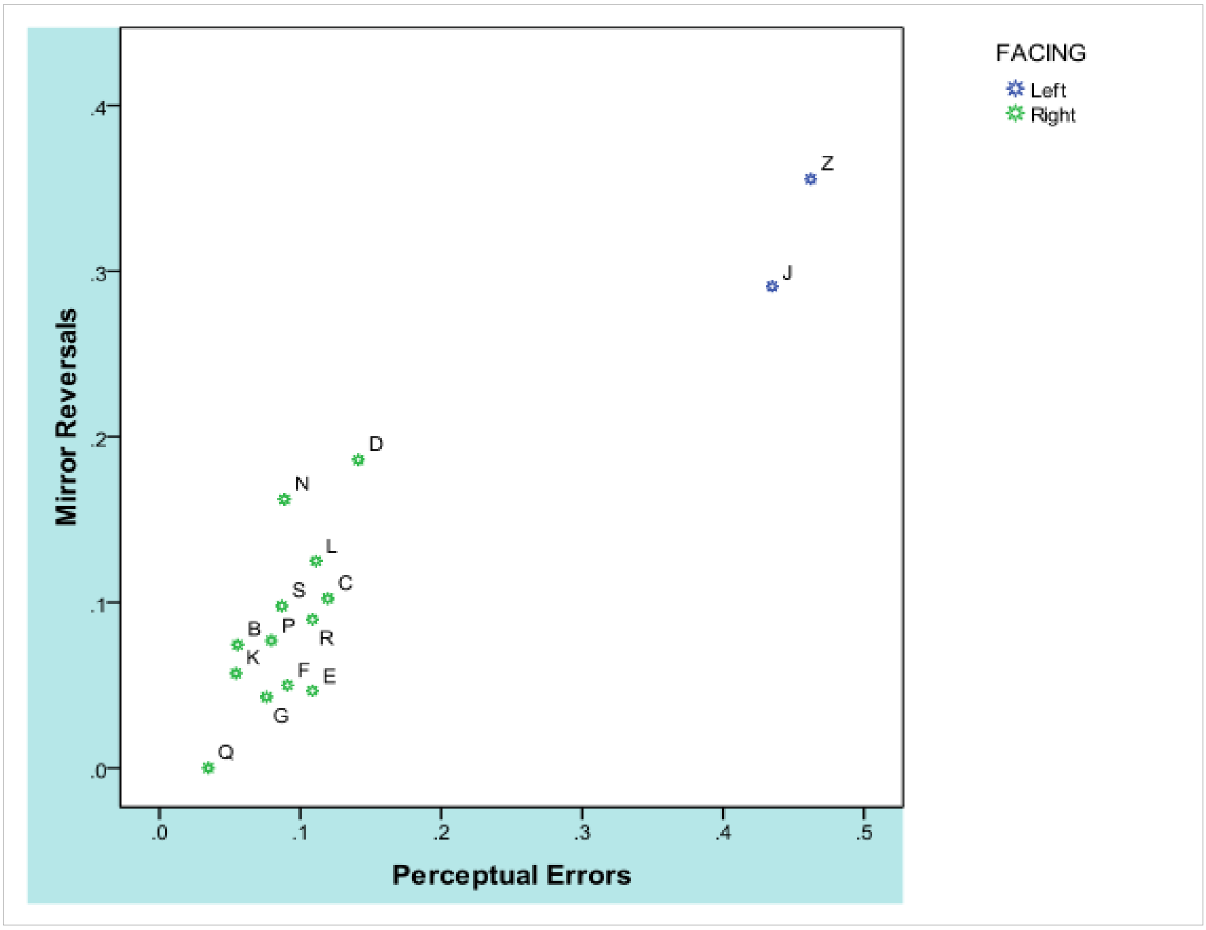


FIGURE 1. Mirror writing compared to perceptual errors for each letter, grouped by direction.

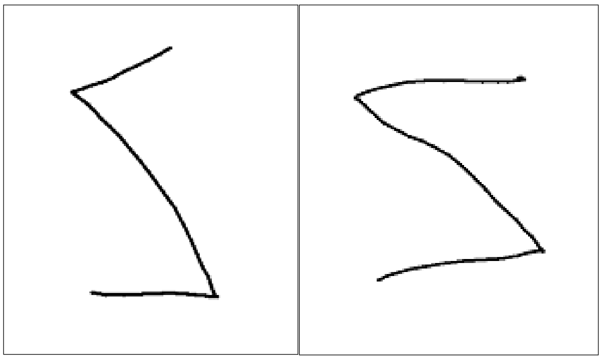

FIGURE 2. An example of perceptually driven mirror writing of Z by a child aged 81 months.

*Research Question 4: Can mirror writing also be considered a motor phenomenon?* In addition to the role of perception in mirror writing, we wanted to investigate if there are also motor processes involved. The mean number of children in whom dominant mirror writing occurred more frequently than non-dominant mirror writing ($M$ = 15) was higher than those in whom non-dominant mirror writing occurred more than dominant mirror writing ($M$ = 11.25). However, this difference did not reach statistical significance so it was not possible to conclude a motor aspect to mirror writing from this analysis alone, ($p$ = .402). The sums of ranks were 120 and 180 for negative and positive ranks respectively, therefore $W$ = 120.

With respect to dominant and non-dominant hand mirror writing, there was a lower negative correlation between age and non-dominant hand mirror writing [$r_s$ = -.405, $df$ = 51, $p$ < .01], compared to dominant hand mirror writing [$r_s$ = -.519, $df$ = 51, $p$ < .001]. This indicates that non-dominant hand mirror writing may persist longer than dominant hand mirror writing as children grow older.

This non-dominant bias may be illustrative of a motor aspect of mirror writing. To probe this theory, the age range was split into two groups along the median age (75.5 months among mirror writers). Mirror writing in the younger group (n = 18) was shown to be biased towards the dominant hand, while in the older group (n = 18), it was biased towards the non-dominant hand (Figure 3). Our index of bias was calculated by subtracting the mirror writing scores of the dominant hand from those of the non-dominant hand. Therefore, a positive value indicates a non-dominant bias and a negative value indicates a dominant hand bias. To test the statistical significance of this pattern, the two groups were compared against their hand bias for mirror writing. The data was not normally distributed and was therefore analyzed by means of a Mann Whitney U test. The average rank of the older age group (22.14) was greater than the average rank of the younger age group (14.86). This difference was shown to be significant, U = 97; exact $p$ (one-tailed) = .017; $r_g$ = .4, a "medium" effect (Cohen, 1988). This shows that mirror writing in older children was biased to their non-dominant hand and is indicative of a gradual transference from perceptual to motor processes in mirror writing as children grow older.

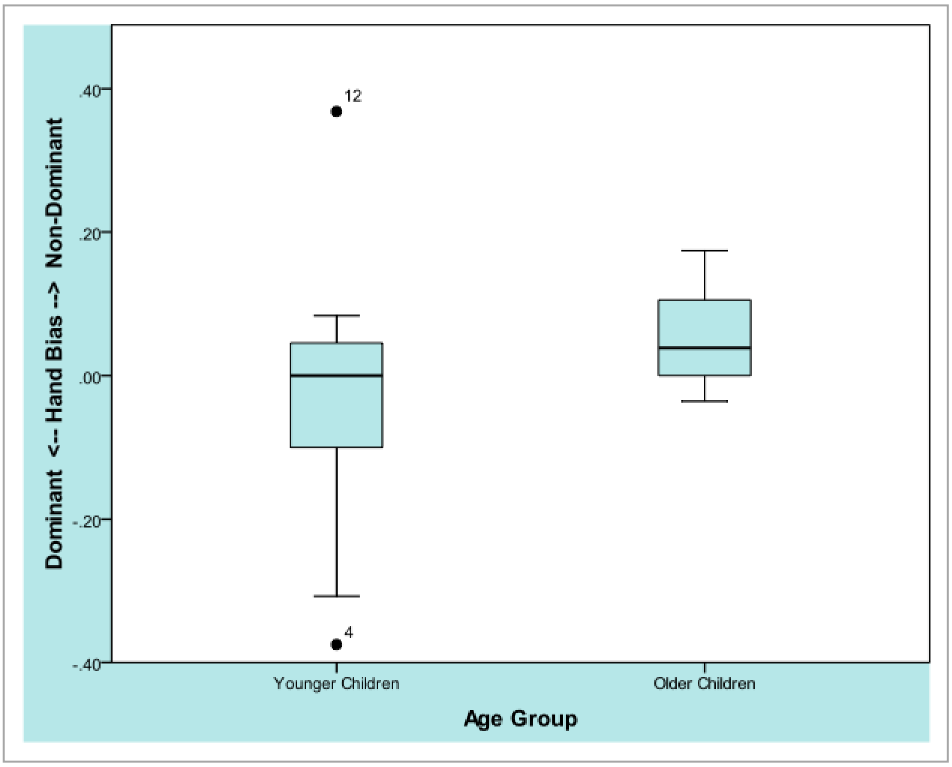


FIGURE 3. Hand bias for younger and older age groups.

## DISCUSSION

Deciphering the behavioral basis of mirror writing has posed a significant challenge for researchers for over a century. Given the ongoing debate over perceptual and motor accounts of mirror writing, and with considerable evidence supporting each side of the argument, we posited a role for both a perceptual and motor foundation of mirror writing in children.

Our study provides compelling evidence for a perceptual basis to mirror writing. Perceptual errors were shown to significantly increase with the rate of mirror writing ($p < .001$). This finding is at odds with studies that have posited a primarily motor basis to this phenomenon in children (Della Sala & Cubelli, 2007). Della Sala and Cubelli found no relationship between perceptual error and mirror writing; however their measure of perception was an odd-one-out picture task. Our task of letter discrimination may be a better predictor of perceptual confusions with written stimuli and may explain this disparity in the results. Our findings are supportive of previous research with brain-damaged adults (Gottfried et al., 2003; Heilman et al., 1980) and control samples (Yang, 1997; Tankle & Heilman, 1983). However, despite the compelling evidence for a perceptual foundation to mirror writing, it only represents half of the story.

We found that perceptual errors and mirror writing both significantly decrease with age ($p < .001$). This is in support of Cornell's (1985) findings. A distinct parallel can be drawn across Cornell's findings and our own, with respect to the prevalence of mirror writing among different age groups. Cornell found that 82% of 5 year olds mirror wrote, while we found an 81% prevalence of mirror writing among 4 and 5 year olds. The high prevalence of mirror writing in recent studies such as this is at odds with older studies which reported mirror writing as extremely rare among children (Orton, 1928). These reports of low incidence rates led to the perception of mirror writing as an abnormality and a developmental dysfunction. In another similarity to this study, Cornell also found no effect of gender on mirror writing. Despite the high occurrence of mirror writing in younger children, Cornell found that only 13% of 7 year olds mirror wrote, while 76% of our 6 and 7 year olds produced mirror reversals. In fact, the prevalence of mirror writing in our study only dropped as low as 33% for children aged between 8 and 10 years. This discrepancy may be best explained by the different methods used. In Cornell's study, a spatial constraint was used to induce mirror writing in children. The persistence of mirror writing in our experiment may be attributable to the fact that we used a motor technique to elicit mirror writing as opposed to a perceptual one.

We also established that perceptual errors in mirror writing gradually dissipate with age and are replaced by a motor mechanism. This transition from perceptually-dominated to motor-driven mirror writing is illustrated as occurring between the ages of 6 and 7 years. The basis of mirror writing before this age differs significantly with the motor patterns of older children ($p = .017$). This development is at odds with Della Sala and Cubelli's (2007) suggestion of directional apraxia. In our study, experience with language in young children seems to initially shift the causes of mirror writing from perceptual to motor factors, rather than abetting the acquisition of a correct motor direction. Although the theory of directional apraxia may apply to dominant hand mirror writing, non-dominant hand mirror writing almost certainly seems to be the execution of a learned motor program in mirrored form. This finding lends substantial support to the motor hypothesis and corroborates evidence from pathological cases of mirror writing (Balfour et al., 2009; Buxbaum et al., 1993). This motor mechanism is not directly observable in adults as sufficient cognitive control strategies are assumed to be in place to override such a phenomenon.

This study also substantiated claims made by Fischer (2010, 2011) in that the direction of letters is a major factor in relation to both mirror writing and perceptual confusion. We found that the leftward facing letters J and Z were mirrored and confused significantly more often than rightward facing letters ($p = .01$).

Two children stand out as good illustrations of each of these processes, one exhibiting a near perfect perceptual pattern (aged 78 months) and the other a near perfect motor pattern (aged 64 months). In isolation, the ages of these children conflict with our finding that mirror writing is increasingly influenced by motor factors as children grow older, however, these children attended different schools and as such, this discrepancy is probably attributable to individual differences in their experience with writing.

In the case of the younger child, the majority of capital letters were written in the correct direction with the dominant hand, with the exception of J, R and S. A large proportion of the letters that were written correctly with the dominant hand were then mirrored with the non-dominant hand, with the exception of N, P, Q and Z, which were written correctly with both hands, and R and S which were written mirrored with both hands. An interesting observation is that J was mirrored with the dominant hand and then written correctly with the non-dominant hand (Figure 4). This indicates that perceptual and motor influences are operating simultaneously. It seems that J may have been perceptually confused to begin with but the mirrored motor program unintentionally rectified this confusion. The perceptual error score for this child was 63%

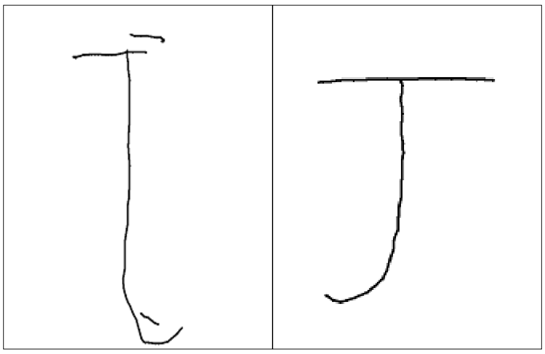

FIGURE 4. Child's mirror written Js with dominant hand (left) and non-dominant hand (right).

which may show that the child was on the verge of overcoming perceptual confusion and was still vulnerable to motor reversals for most letters. It is likely that perceptual factors are still impacting the letter J as it is a leftward facing letter and therefore has a higher perceptual confusion rate. Another interesting observation is that Z was written correctly with both hands, demonstrating that perceptual confusions were diminishing.

The second interesting case exhibited a predominantly perceptual pattern. Although this child was 14 months older, she seemed to have persistent perceptual confusion in writing, as all letters with the exception of B, C, J, Q and Z were mirrored consistently with both hands (Figure 5).

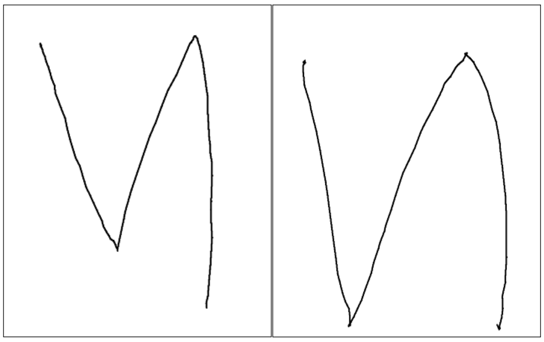

FIGURE 5. Example of mirror written Ns with dominant (left) and non-dominant hand (right).

This is interesting as her correct writing of J and Z violate the frequency with which these letters are usually mirrored relative to right facing letters. A noteworthy factor of this case was that the child had a relatively low perceptual error score of 33%. This may highlight a possible discrepancy in the development of perceptual mechanisms governing mirror writing and mirror reading. It is possible that mirror discrimination abilities may mature slightly faster than writing abilities in certain children. This theory would only be testable by means of a longitudinal study.

Previous studies in this area have generally lacked a cohesive approach to examining the fundamentals of mirror writing. The literature has largely focused on satisfying one side of the perceptual/motor debate or the other, which has limited the more exploratory stance of considering both mechanisms simultaneously. Despite the spontaneous occurrence of mirror writing in children, the majority of research in this area has concerned pathological cases of mirror writing or intentional mirror writing in adults. These studies are highly repetitive with regards to both the methods and participant sample used.

The study of mirror writing over the past few decades has been restricted by previous assumptions and has only recently received renewed attention. New perspectives on the phenomenon in children have been introduced in recent times using brain imaging technology (Dehaene et al., 2010) and novel theories (Fischer & Tazouti, 2012; Della Sala & Cubelli, 2007). Concerning the theory of directional apraxia, the conclusions reached from these studies were inferred from inconclusive methods. As discussed above, the perceptual task devised by Della Sala and Cubelli (2007) perhaps failed to accurately assess perception of mirrored letters, and the use of inappropriate stimuli led to perceptual theories of mirror writing being discounted. This study appears to lack a comprehensive approach to assessing motor influences of the non-dominant hand on mirror writing in children.

Our approach adopted a more exploratory technique and addressed some of the gaps in the literature. Up to this, no study had explored the impact of non-dominant hand writing in children and this process was made easier by allowing children to write with their fingers on the tablet. This novel approach meant that children did not have to concentrate on holding a pen with an unfamiliar hand and may have resulted in a more natural writing output with the non-dominant hand. Assuming that this natural script is mirrored, this technique is therefore the best measure of the motor hypothesis. This study has also contributed significantly to the literature by the use of a letter perceptual discrimination task. The use of both normally oriented and mirrored letters in this task allowed us to thoroughly gauge the child's reactions to both forms of letters and it was noted that children showed equal levels of confusion with both correctly oriented and mirrored letters.

These results contribute a great deal to the current debate surrounding mirror writing. Despite this, our study was limited in that our sample was relatively small and the participants recruited were from similar backgrounds and education systems. It would be valuable to test these findings not only with bigger samples, but also in different cultures or with left facing languages, to determine the universality of our findings. Our approach would also be furthered by replication with a larger sample of left handers (n = 5 in the present study) to fully assess the implications of the motor hypothesis. This may succeed in corroborating the evidence stated here, but such a study may also undermine our findings if the motor hypothesis is demonstrated to be specific to the left hand as opposed to the non-dominant hand.

More specific limitations of our study stem from aspects of our design that would benefit from modification. A more thorough measure of literacy is essential for assessing different stages of language acquisition in children and would provide a more suitable measure for tracking the development of mirror writing, rather than age. Our perceptual task ought to include lower case letters as these were written in conjunction with upper case letters during the writing tasks. There is also a need for consistency with the fonts used for both the literacy and perceptual tasks. The discrepancy between the *serif* Times New Roman and the *sans-serif* Arial fonts sometimes created confusion, particularly with upper case mirrored J. In Arial font, this letter is ambiguous as it also resembles lower case L and during the perceptual task, we had to reiterate to the children that this letter was a J. Our findings added credence to Fischer's "right writing rule" with respect to letters. However, it may also be beneficial to include digits in future mirror writing studies to gain a more comprehensive view of this mechanism (Fischer, 2011).

There is also room for improvement with our assessment of handedness. It was noted that some children seemed equally comfortable using both hands to write and would sometimes attempt to switch between their preferred and non-preferred hands during testing. One child, who preferentially wrote with his right hand initially, reported that it was "more comfortable" to write with his left hand during testing. We also noted that difficulties with the use of the tablet as on some occasions the children had to make several attempts before the tablet registered their writing. As a result, when writing with the non-dominant hand, some of the children's original productions were traced in a mirrored direction. When writing was disrupted, leading to them having to concentrate harder, some children corrected their direction and wrote the letter normally. We only included the final production of the letter; thus, samples of mirror writing were lost due to this difficulty.

It is evident that mirror writing may be more common and may persist longer in older groups of children than previously thought. As such, future studies may wish to track this phenomenon in children as they progress into adolescence. Replica studies by longitudinal analysis are needed to determine the robustness of our findings. This method would be paramount in tracing the progression of mirror writing throughout childhood. Age and literacy cannot fully account for the development of mirror writing as children mature at different rates as language and writing skills are impacted by a large number of contributing factors, including influences from the home environment, schooling, parents and siblings. Continued convergence of neuropsychological evidence, experimental studies with children and development of new methods of analysis, such as brain imaging techniques as well as longitudinal research, is necessary to gain a comprehensive understanding of the impact of these factors. Only then will we be able to fully grasp the basis of this intriguing phenomenon.

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