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| Jean-Paul Fischer. Children's Mirror Writing: A Comprehensive Story. 2022. <hal-03897628>

HAL Id: hal-03897628

<https://hal.science/hal-03897628v1>

Preprint submitted on 14 Dec 2022

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Children's Mirror Writing:

A Comprehensive Story

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December, 2022

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Presentation

The current piece of work is a translation from French of “L’écriture en miroir des enfants” published in open science (HAL), in October, 2022. In French, I have subtitled it "une histoire complète" (a complete story). However, I know from my experience in research that any scientific work may never be fully achieved. Indeed, it would not be adequate to consider that a debate or scientific research is finished or reaching a dead end. Therefore, the English subtitle refers to "a comprehensive story", which can also be interpreted as a detailed story, yet incomplete.

Mirror writing in children (with typical development) has received growing interest for 145 years. I believe this is the right time to synthesise the scientific literature. My motivations for publishing this essay go beyond personal interests and agedness. Indeed, the first quarter of the 21st century seems an especially appropriate time for two main reasons. Firstly, handwriting is in the process of regression, or even disappearance, especially cursive-attached writing. Secondly, contemporary developments in neuroscience and cognitive developmental psychology have considerably modified and clarified our understanding of the phenomenon.

Yet, I would like to mention some other more personal reasons motivating the current work. Along with co-authors, I have published many articles on the topic (see the references). Bringing my research together in a single document seems rather practical if, by adventure, someone is interested in it. Another motivational aspect of this publication may be self-esteem. Indeed, I can see authors posting statistical observations on the Internet without indicating, or maybe even knowing their source. For example, Dr Kruti Mehta-Dhiwani, who founded three clinics in Mumbai, informed parents¹ through a blog post that two frequently reversed characters are 3 and J. However, the author fails to mention the source of the reported finding (see Section 6.1).

Although I have avoided sharing details usually reported in scientific articles (e.g., significance levels, standard errors), this book is meant to be scientific. Thus, I have kept minimal numbering to facilitate cross-referencing and argumentation. Moreover, I provide exhaustive references with, in most cases, the DOI (digital object identifier). The English translation of the French document, contains necessary adaptations for English readers but also some corrections or improvements to the original. If most modifications are rather minor, one important change is the addition of Section 7.8, which is absent from the French version. This section could not be included in the French publication because of the publication date and is aimed to avoid a potential pedagogical aberration.

To facilitate understanding, the reader must consider the formulation and labelling of key concepts which remain consistent throughout the document:

(1) Differentiating an inversed (or inverted) character (digit or letter) from a reversed character. For example, **Я** is the reversed uppercase letter R (horizontally mirrored), whereas **Ɔ** is the inversed R (vertically mirrored). This distinction is usual.

(2) Differentiating a reversable character from and a reversible character. For example, the lowercase letter h is reversable, but is not a reversible letter because the reversed h, that is **h**, is

¹ On <https://magicofmom.com/the-phenomenon-of-mirror-writing/> in 2019, but still retrievable in November 2022.

Presentation

not a conventional lower case letter; the lowercase letter p is both a reversable and a reversible letter, because its reversal, that is q, is an accepted letter in the alphabet; the uppercase letter T is not reversable because it cannot be distinguished from its horizontal mirror. This distinction—by the use of the qualifying “reversable”—is idiosyncratic.

(3) Designating of the Great Section of the French *école maternelle* as GS kindergarten.

(4) Designating of the intermediate or Middle Section of the French *école maternelle* as MS kindergarten.

Finally, I must acknowledge (with the risk of forgetting some), for the precious help of everyone who contributed in some way to this comprehensive story of mirror writing in children. First, my long-time friend Marie-Bénédicte Parisot who often volunteered as a judge in the coding of the writing, and also offered me some free time for the writing. Then, I thank my co-authors (on the subject), Anne-Marie Koch, Christophe Luxembourger, Youssef Tazouti and Xavier Thierry; those who helped me materially (Jérôme Dinet, Director of the 2LPN; Carolane Hélin) or stimulated me scientifically (Michael Corballis†, Jean-Noël Foulin, Robert McIntosh, Thomas Lachmann, Marine Portex). Furthermore, I thank all my students. A special thought goes to Anne-Marie Koch, whom I unfortunately did not manage to bring to the end of her thesis although her results were and remain fundamental and unique, and all the others who conducted observations in schools (and whom I often lost sight of): Olivier Bartlett, Audrey Breton, Gaële Chaloppé, Gaëlle Chevalier, Jennifer Collignon, Valentin Descharnes, Laura Durey, Chloé Hess, Stéphanie Grandemange, Caroline Hasbi, Pauline Husson, Adeline Jacque, Estelle Martin-Jouan, C. Martignon, Emy Mockels, Audrey Moschini, C. Petit, Michaël Pierrel, Justine Traina, M. Traore, Noémie Werbicki.

1. A long history

The concept and name of "mirror writing" appeared in the scientific literature in 1878 in an article in a Berliner clinical journal (Buchwald, 1878). Critchley (1927) mentions that a case of mirror writing in an epileptic patient had already been described by Leutilius in 1688. Since Critchley does not provide further details about this case, Buchwald's article is generally considered to be the first to define and label mirror writing with its German label "*Spiegelschrift*". The German origin of the name is due (in part) to the fact that the city of Breslau, where Buchwald worked as a physician's assistant, was then the sixth largest city in a newly unified Germany. It is only after World War II that the city became Polish and was named Wrocław. History perhaps saved or deprived us of having an originally Polish name for mirror writing ("*pismo lustrzane*" according to my computer translator)! The German name was then translated literally into French ("*écriture en miroir*") as well as into English ("mirror writing").

Buchwald's article was quickly commented on by Erlenmeyer (1879) and cited many times (e.g., Figuera, 1902), often as a secondary or false source. For example, Canzano et al. (2011) cite a definition of mirror writing, by Critchley, attributing it to Buchwald! Such confusion could result from Schott's contiguous reference to Buchwald and Critchley. Canzano et al.'s fault would have been to indicate a false reference (to Buchwald) instead of the real one (Critchley, as cited by Schott).

1.1. His first name was Alfred

Although his article was often quoted, Buchwald's first name remained a mystery for a long time. It was even unknown, not only to Critchley (1927), but even much later to Schott (2007). The latter had a copy of the article, but since the article does not specify the first name, Schott referenced Buchwald without the initial of his first name in the list of references. Obviously, articles citing Buchwald as a secondary source would not reveal Buchwald's first name or at least his initial. It is only in 2012 that the German journal "*Gehirn und Geist*" (Fischer, 2012b) introduced Buchwald's first name—Alfred—when adapting and translating an article from the French journal *Cerveau et psychologie* (Fischer, 2012a).

While Buchwald's first name is only anecdotal, his contribution to the direction of research on mirror writing is major. First of all, he gave a definition of mirror writing which is culturally shaped: it is a right-to-left writing that only resembles our usual writing when viewed in a mirror. It should be noted that if Buchwald defines a complete mirror writing in this way, he does not reject the simple reversal of characters (letters or digits). Indeed the first patient he describes, aged 45, produced, in the course of remission, the digits in Figure 1, most probably by writing from left to right.

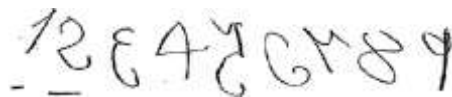


Figure 1. Buchwald's (1878, p. 7) first patient's writing of digits during remission. Writing with the left hand, as a result of right hemiplegia.

Buchwald greatly contributed to the development of the hypotheses that mirror writing (1) concerns mainly pathological cases, and, (2) arises only with the left hand. He mainly described three adult patients with right hemiplegia who were forced to write with the left hand, and opened the way to the observation of mirror writing in children. Indeed, at the end of his article,

he reports observations on children who mirror wrote with their non-dominant left hand, apparently without being aware of their mirror writing. To further support hypothesis (2) and to suggest that mirror writing is the natural writing of the left hand, Buchwald then reports precisely the case of an 11-year-old girl. She wrote her name with her non-dominant left hand correctly, slowly and with great care, yet fiddly. However, when she was asked to write faster, she began to mirror write much more beautifully.

Hypothesis (2), which came out of Buchwald's article, became a success on a scale that is hard to imagine at a time when communication was not yet facilitated by the Internet. The year after Buchwald's founding article, Erlenmeyer (1879), in a more general book on writing, referred to it at length. He indeed had a good reason to refer to it since he thought he had the explanation for this type of writing: it is abductive writing that would lead to mirror writing. This notion of abduction—a centrifugal movement that starts from the body and goes outwards—opposed to adduction, is the basis of Erlenmeyer's analysis of writing. Erlenmeyer did not hesitate to criticize the designation of mirror writing (*Spiegelschrift*), introduced by Buchwald. He suggested that “left-handed abductive writing” (*linkshändige Abductionsschrift*) would have been a more appropriate label. This explanation was later adopted as the "motor hypothesis" of mirror writing (Eager & Fisher, 1932). In agreement with Erlenmeyer's suggestion, Figuera (1902) established it as a definition of mirror writing: "This name is used, as is well known, to designate the special way of writing with the left hand, which graphically constitutes a copy of normal writing, when it is presented to a mirror and its image is looked at" (p. 147).

1.2. A tsunami of left-hand writing

Amazingly, Buchwald's hypothesis (2), and its relays, led to numerous observations of students in their schools. These students were simply asked to write, on a purely experimental basis, with their left hand. It also led to the comparison of left- and right-handed students. But even for such comparisons the test was on their left-hand writing since the researchers were convinced that it was the only hand that produces mirror writing.

Ireland (1881) was probably one of the first to publish such a comparative observation. He begins by citing Buchwald (and Erlenmeyer), and then describes some cases of children or adolescents with right hemiplegia who write with the left hand, or left-handed children. Most interestingly, he reported statistics from two teachers showing "that there is a physiological tendency with left-handed children to fall into mirror-writing" (p. 364). In both observations, the students (presumably from Stirling, Scotland) were asked to write with their left hands. The results are remarkably clear: not only does the Fisher exact probability test calculated on the data in Table 1 confirm that the difference between left- and right-handed students is highly significant in both observations, but even mirror writing logically implies being left-handed!

Table 1. Ireland's data attributing mirror writing (with the left hand) to left-handed children only. [Table based on Ireland's (1881) verbal description].

Laterality	Mirror Writing		Mirror Writing	
	Yes	No	Yes	No
Left	5	0	3	3
Right	0	55	0	128
Participants	60 elementary pupils		134 students in grades 4-6	

In 1893 in Germany, Cahen-Brach was a medical doctor, especially for children, in Frankfurt/Main. Cahen-Brach and his wife had a tragic destiny since they died in the Theresienstadt concentration camp at the end of 1942. Furthermore, one of their twin sons was deported and exterminated in 1943 in the Majdanek camp (according to Hock, 2021). He seemed not particularly concerned by mirror writing, since the previous year he had published an article on gonorrhoea in young girls. However, the subject did arouse the curiosity of pediatricians. Therefore he observed mirror writing on 649 public school students. In order for these students to concentrate on writing with the left hand, their names, as well as the digits from 1 to 9, had been previously written by the experimenter on the blackboard. The results of the investigation are reported in Table 2.

Table 2. Mirror writing of names and digits with the left hand observed by Cahen-Brach. [Table based on Hildreth (1950a), p. 69].

Age	Class	Boys		Girls	
		N	%	N	%
7	I	20	43	29	43
	II	7	11	11	22
10	III	7	14	4	8
	IV	3	6	4	8
13	V	5	9	3	7
	VI	8	13	6	10
Total Mirrors		50	15.3	57	17.7
Total in all classes		327		322	

The approximately 600 students tested by Cahen-Brach, however, represent only a small number compared to the more than 3000 students involved in of Doctor Lochte's (1896) research. In this observation, students were asked to write their name and age with their left hand, starting in the middle of the paper to allow them to write to the right as well as to the left. Since the youngest students, aged 6-7, could not yet write them, Lochte asked them to write a few known words or letters, and digits, again with their left hand. The results are from 2804 students tested in Berlin, and another 421 tested in Zehlendorf, a district of Berlin. The only clear result of this observation on 3225 pupils is the decrease in mirror writing as the level of education increases. In addition, from the Berlin school data, Lochte observed that only 12 of 69 left-handed students mirror wrote. He concluded that "this is clear evidence that by no means all left-handed children have a particular tendency to mirror writing" (p. 389). In other words, the reciprocal—(being left-handed) \Rightarrow (mirror writing)—of the implication drawn on Ireland's data, namely (mirror writing) \Rightarrow (being left-handed), is not valid. Further statistical analysis of these data, however, allowed us to verify that left-handed students still mirror wrote more than right-handed students: the percentage of mirror writing of left-handed students ($12/69 \approx 17\%$) differs significantly from that of right-handed students (between 5 and 7%, depending on whether we consider completely or partially mirror writing).

1.3. The first flaws in the left-handedness hypothesis

While it is now known that all children produce at least partial mirror writing (i.e., of certain characters, especially digits), it may seem curious that it took so long to realize this! In fact, some researchers had quickly and clearly pointed it out. For a long time, I thought that it was

A long history

the physiologist, psychologist and chemist William Preyer who, in 1882, in the first edition of his book, "The soul of the child" (translated title), was the first to report this reversal of writing by a right-handed child. In a long and cumbersome German sentence, he wrote in effect: "The fact that my boy, when I let him write ordinary numbers, which I was drawing, in his fifth year, always reproduced most of the digits—most of the time the 1 and the 4—with mirror writing, the latter often also reversed, while the 5 was always correct, is not due to a defect of sight, but to an imperfect transposition of the visual representation into the motor representation necessary to write." (Preyer, 1895, p. 41). Yet, this anecdotal report by Preyer about his son does not appear in the first two editions of the book! Preyer, presumably having got wind of this curious discovery of children being able to mirror write, included the anecdote in a section of his book, added in its third edition, in 1890. Preyer is therefore less likely to be the first to have reported, at least verbally because he does not reproduce any of his son's writing, the mirror writing of a typical right-handed child! But he still stands a chance of being the first because the only other case mentioned by Hale and Kuh (1901) dates from 1900.

Ten or 20 years after Preyer, Figuera (1902), in a note to the 4th Brazilian Congress of Medicine and Surgery, reported the observation of 107 children and one adult. The Brazilian children were observed by professionals of the pediatric clinic of the Faculty of Rio de Janeiro for a part (they are from 9 to 16 years old according to the reported cases), and in municipal schools of Fuiz de Fova (Minas-Geraes State) for the other part. The adult included in the observation accompanied his son to the clinic and, asked to write successively with the right hand and the left hand, produced with the latter reversed writing. In the introduction, Figuera notes—probably because he knew the results of his observations—that Ireland's result (see above), of rare clarity, is not infallible. And, in fact, he notes that the two times when reverse writing was shown (1 child and the adult), it was in non-left-handed individuals. Figuera concludes that "if mirror writing can occur in neuropathic children and mainly in left-handed individuals, it also occurs in healthy children, who are not left-handed, and lack in many cases of nervous affections of young age" (p. 154).

Around the time of Figuera's article, Hale and Kuh (1901) reproduced the handwriting of typically developing right-handed children who spontaneously produced mirror writings, including a boy of 5 years and 6 months (see Fig. 2). Hale and Kuh, whose observations are inconsistent with Erlenmeyer's mechanical theory, write that most of Erlenmeyer's statements about right- and left-hand writing are completely false. As far back as 1901, they stated without the slightest hesitation that "almost every child, at a certain period of its development, will be found to produce spontaneous mirror-writing, and that, too, also with its right hand" (p. 1382). This assertion was later taken up by Fuller (1916), with reference to these two authors. But Fuller's own observations of 18 "normal" children who had just learned letters are too succinct to provide much support.



Figure 2. Mirror writing of the digits 2, 3, 7 and the numbers 21 and 16², perhaps the first reproduced from a right-handed child. [Figure reproduced from Hale and Kuh (1901), Fig. 1, p. 1381].

Having rejected Erlenmeyer's thesis, Hale and Kuh, clinical assistants in ophthalmology and neurology respectively, then suggested an explanation of mirror writing by retinal image inversion: "The outer world is impressed upon the retina in an inverted image. It is only by experience laboriously acquired that we learn to interpret this image and to produce upright writing" (p. 1383). They rule out the immediate objection that the inverted retinal image should also lead to an up-down inversion. They suggest that the left-right reversal explanation is corrected last because it is the most difficult to overcome³.

At the adult level, serious reservations about the quality of left-hand mirror writing came from Downey's (1914) research on 25 female students aged 17 to 24 at the University of Wyoming. She presented a table of inter-correlations between different writing/reading, mirror or not: reading mirror-script, writing mirror script with the right hand, writing mirror script with the left hand, reading inverted script, writing inverted script with the right hand, and writing normal with the left hand. It appears in this table that the correlations of right-hand mirror writing with the other five types writing/reading are high (at least .413), except with writing normal with left-hand (.062). Despite a possible habituation effect, Downey notes that "it does not appear, then, that the left hand is, in general, more proficient than the right in mirror-writing in both right- and left-handed individuals" (p. 437). And analysis of handwriting quality leads Downey to observe a "better quality of the right hand mirror-writing" and to conclude that "there is no natural tendency for the left hand to excel in such reversal except in so far as there is a latent tendency to left-handedness" (p. 439). At the end of the article, Downey even suggests a correlation between the degree of right lateralization and mirror reading efficiency that would run counter to the traditional view (in 1914) and notes that this is what one would expect if specialization of function is accompanied by increasing adequacy of orientation. Subsequently, more sophisticated and general research has attempted to compare the relative effectiveness of abductive versus adductive movements but with no really decisive conclusion (see the introduction in Fischer & Koch, 2016a).

1.4. The left hand resists

Despite Downey's empirical criticism of the effectiveness of the left hand, the problem of left-handedness persisted in the early 20th century. Manfred Fraenkel's (1908) endorsement of bi-handedness is evidenced by the following statement: "... a system of education which neglects one of the most important members of the human body is to be condemned from the ground up. Every teacher has the obligation to develop in a child not only every mental faculty, but also all the members to their highest capacity" (p. 1307). Fraenkel then points out that in London a

² I have taken the authors' indication, but the writing of 16 could also be a complete mirror writing of 61.

³ Dehaene (2010, p. 273) refers to such an explanation of mirror writing as a "naïve idea". Moreover, it would poorly explain that children make far fewer reversals when copying characters than when writing them from memory (see Section 4.2).

society "for double handed training" has been formed. He ends, with great emphasis: "Gentlemen! We doctors will do well to pay the greatest attention to this important question. Only the school is able to transform our one-sided system into a two-sided one" (p. 1309). This zeitgeist certainly contributed to the proliferation of observations on left-handed writing, in continuation of those of Fraenkel, on children (Fuller, 1916; Gordon, 1921; Hanse, 1931) as well as on adults (Bertha, 1942).

Gordon's research is exemplary in this regard. Convinced that only left-handed writing leads to mirror writing, he began by testing 829 ordinary elementary school students. Despite the use of the left hand, which is generally not usual for these students, only 4 of them wrote in mirror (0.48%). Gordon then focused on special schools for the mentally retarded. There he tested 729 students aged 8 to 16, asking them to use the left hand (generally not usual). Among these students, Gordon was particularly interested in left-handed students with, importantly, laterality established with means other than writing. Regardless of their writing hand, he found 30% of students (41/137) writing in mirror, with a greater frequency among girls (40%) than boys (18%). Gordon's analysis and concerns about left-handedness are such that he further refines his statistics. Among both boys and girls, 40% of left-handed students write with their right hand. Of the latter 32% of left-handed boys and 62% of left-handed girls (but usually writing with the right hand), mirror wrote with the left hand. This statistic leads Gordon to suggest that children who usually write with the right hand may mirror write because they have at one time or another written with the left hand. This suggestion could be contradicted by another that follows. Indeed, Gordon also suggests that left-handed children who write with the right hand may have, during left-hand writing practice, corrected an inclination to mirror write with the same hand at a later period; these children would therefore be less prone to this kind of writing than the right-handed children who write with the left hand for the first time.

Gordon, however, also asked some very good questions. For example, when he asked "why some children write mirror fashion when they first begin to write, as no muscular sensations can have been established in such cases" (p. 358). But, at the time, it was not possible for him either to know or to foresee the answer. Gordon also reports an observation of children tested on the copying of English and Russian words who only made mistakes with the letters common to both alphabets—that is, those whose shapes had a slight relationship—but copied correctly the complicated letters peculiar to Russian, whose shape they had never seen before. About this observation, Gordon suggests a vague but not false explanation: "something had affected the nerve fibres connecting the hypothetical visual memory of words centre with other parts of the brain" (p. 361). Finally, with regard to the few frequently mirrored letters, especially s, d, b, 4, 6, and 9, Gordon has also observed that this writing is probably different from the mirror writing he discusses. He thus seems to foresee, a century ahead of time, the empirical demonstration of the difference between mirror reversal (when writing) and confusion in declarative memory (Fischer & Luxembourger, 2022).

This research on left-hand writing then overshadowed, if not precluded, research on typical young children writing with their right hand, possibly in mirror. This lack of interest in the mirror writing of typically developing right-handed children writing with their right hand is such that Scheidemann (1936) mistakenly (cf., Section 1.3) believes that she published the first case of a right-handed child writing in mirror. This was Thomas, an otherwise unproblematic right-handed 6-year-old who, among other things, produced the mirror writings of numbers 2 and 3 in Figure 3. Scheidemann states that Thomas is right-eye dominant and shows no

tendency to be left-handed, and comments: "This is 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).



Figure 3. The reversed writings of 2 and 3 by Thomas, age 6. [Figure reproduced from Fig. 1 of Scheidemmann (1936), p. 490].

This attribution of mirror writing to children's (only) left-handedness has been so profound that it still persists, in the 21st century, in many books (and minds!), even if it is often more nuanced. For example, for Millichap (2000), mirror writing is characterized by the fact that it is almost always performed with the left hand. For Henderson and Pehoski (2006), left-handed children's tendencies to write/draw and scan information from right to left could lead to reversals, but this does not necessarily presuppose problems; they add that left-handed children could thus undergo a more extensive period of reversal and mirror writing.

1.5. The etiology of mirror writing according to Macdonald Critchley

Critchley (1927), in a short article written at the beginning of his long career (born in 1900, he died in 1997 and even published a posthumous book in 1998), proposed a table on the etiology of mirror writing. In it, he mentions that "certain normal children who are learning to write (left and right hand)" produce spontaneously such handwriting. He also distinguishes complete mirror writing from more fragmentary reversals. But his formulation regarding typical children, by limiting mirror writing to "some" of them, still falls short of Hale and Kuh's assertion that "all" children, at some stage of development, produce reversals. Nevertheless, it could have saved Scheidemmann from her error.

This article, or Critchley's table, has largely contributed to the diffusion of an entertaining practice. This practice consists in writing on one's forehead or under the table, obviously with a sheet of paper between the pen and the support. I have practiced it a lot during science festivals and other brain-related animations in France. However, this is not mirror writing. When we write normally, i.e. from left to right in our culture, on our forehead or under the table, we see, afterwards, a mirror writing on the sheet. But we have not written in mirror, from right to left, reversing each letter. Only an observer looking at us from the front, or lying under the table, could have seen us writing in mirror! In France, Morlaas (1939), without referring to Critchley,

suggested exactly the three means to provoke experimentally mirror writing in normal subjects listed by the latter, namely:

- (1) Make the two hands write simultaneously;
- (2) To have one or the other hand write, with the paper applied to the forehead;
- (3) Have them write with the paper applied to the back of a table.

The writing with the left hand in a right-handed person is indeed a mirror writing in case (1). Unfortunately, Morlaas did not see, or understand, that the two others—(2) and (3)—are cases of normal writing in a right-handed person writing with the right hand. The result of this normal writing being simply seen as a mirror writing by an outside observer or by the writer who turns the paper upside down.

1.6. The theory of Samuel Orton

Samuel Torrey Orton, born in 1876, had completed his medical studies at the University of Pennsylvania in 1905. He was not, until 1925, a prolific publisher. He tried to publish one scientific paper each year according to June Lyday Orton, his second wife, who prefaced Orton (1937/1999). But in 1925, when he was in Iowa, he began his studies of children with specific language difficulties. More importantly, he published an article that would be widely read (Orton, 1925). It is true that Orton was able to promote the diffusion of his work by opening his own clinic in New York in 1928, by becoming the elected president of the American Association for Research in Nervous and Mental Disease in 1932, by publishing a book "Reading, writing, and speech problems in children" in 1937 (reproduced in Orton, 1937/1999), and by getting his third research program financed by the Rockefeller Foundation from 1939 to 1944. After his death in 1948, the memory of Orton's work is maintained in particular by the Samuel Torrey Orton Prize, an award given since 1966 by the International Dyslexia Association for contributions to the understanding of dyslexia. The most recent prize (from 2022) was given to Fumiko Hoeft (e.g., Hoeft et al., 2011), and the previous two to John Gabrieli in 2021 (e.g., Gabrieli, 2009), and Malatesha Joshi in 2020, current editor-in-chief of the journal *Reading and Writing*.

Before discussing his 1925 article, however, it is necessary to render to Caesar what belongs to Caesar. This biblical proverb, here abbreviated, should suggest that the idea of a differentiated role of the two cerebral hemispheres in the production of mirror writing was far from being entirely new when Orton published his well-known figure (see Fig. 4). In general, it can be noted that the idea of a role for hemispheric specialization in explaining mirror writing was already present at the time. Thus, Blom (1928) cites 5 or 6 authors who based their explanation of mirror writing on a bilateral representation in the cerebral cortices well before Orton's paper. Even Erlenmeyer (1879) had already associated manual left-handedness and right hemispheric brain to support his motor hypothesis. But, more directly related to Orton's theory, it is worth mentioning Ireland (1881, not cited by Orton, 1925) who had suggested, more than 40 years before Orton, that the image of C would be, for example, C in the right hemisphere and \complement in the left hemisphere. This is indeed what can be read explicitly on Orton's diagram reproduced in Figure 4, if we disregard the (minor) fact that Orton has represented C in mirror image in the right hemisphere.

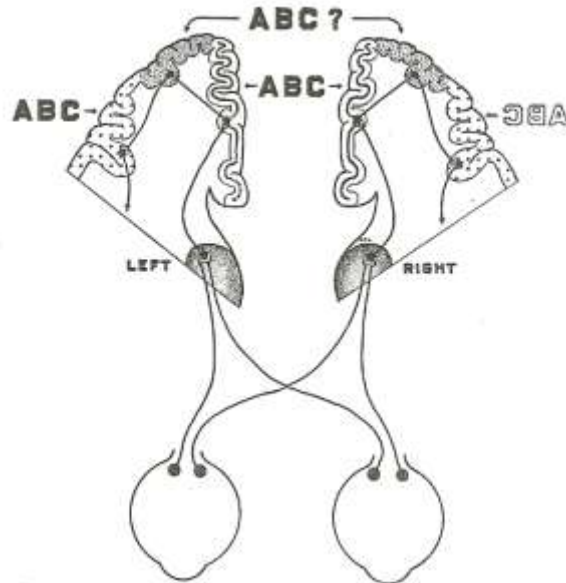


Figure 4. Orton's "historical" diagram. [Figure reproduced from Fig. 11 of Orton (1925), p. 609].

Orton (1925) specifically wrote that "the storage of memory images of letters and words occurs in both hemispheres, and that with the first efforts at learning to read the external visual stimuli irradiate equally into the associative cortices of both hemispheres, and are there recorded in both dextrad and sinistrad orientation" (p. 608). Blom (1928), who analyzed 81 articles on mirror writing, included this hypothesis, of a differentiated representation in the two cerebral hemispheres, in the 6 theoretical hypotheses supposed to explain mirror writing. But, curiously, he does not include Orton among the authors who have defended such a hypothesis. However, one of Blom's conclusions, namely that a child who mirror writes will probably have difficulties in reading and spelling, seems to have been inspired by Orton. This conclusion is indeed a major point of Orton's theory, a point that has largely contributed to its popularization given the importance of reading in our society. Let's look more precisely at Orton's arguments which allowed him to link dyslexia, or "strephosymbolia" as he called it, to mirror writing.

The name itself leaves little doubt that Orton wanted to link the reversal of symbols (letters, digits, etc.) to the problem of reading/writing, since he chose the prefix "strépho" (from the Greek word στρέφω for twist) precisely to indicate a reversal, without distinguishing between reading and writing. This distinction is made clear by the specific terms dyslexia and dysgraphia. When Orton postulates "the existence in the brain of a mnemonic record in mirrored form which serves as the pattern for these motor expressions" (Orton, 1925, p. 608), it is easy to see that children will not only produce confusions in reading (e.g., b and d, p and q), but also in writing. He had already insisted on this point in his article: "This again, however, does not take into account the sensory images which serve as the pattern for writing from memory. Writing in either the direct or mirrored form is possible to some people with either hand, and this potentiality is probably latent in us all though difficult to develop because of the exclusive training of one hand for writing" (p. 599). Such an explanation of the association between reading difficulties and mirror writing, through the same double representation of letters (correct and mirror), remains however theoretical. Thus, in his article with Gillingham, Orton also presents an empirical argument for such an association: "When, however, mirror writing is spontaneously produced by the right hand, it suggests a twist in reproduction of considerable

interest and probably of some prognostic value as most children whom we have seen who have exhibited this initial tendency have experienced considerable difficulty with reading later" (Orton & Gillingham, 1933, p. 268). If one agrees with Hale and Kuh's assertion that all children produce reversals at some stage of development, however, one sees that this argument is either untenable or loses all value. Indeed, if Orton and Gillingham's empirical observation is predictive, all children should end up dyslexic! And if it is only retrospective, one does not see how the dyslexic children they saw could not have produced reversals initially!

In defending this link between dyslexia and mirror writing, Orton also referred to articles by Fildes (1923) or Fildes and Myers (1922). In particular, Fildes (1923) established that mirror reversal occurs both in copying shapes and in reproducing them from memory. If this were true for letters, it would indeed reinforce the association between reading and writing since by copying letters (or words) one reads them, somewhat earlier or quasi simultaneously. But the article by Fildes (1923), although difficult to understand, seems to show precisely that this is not true for letters, nor for digits. Her Experiment 6, on the alphabet and the digits 1 to 9, shows the virtual nonexistence of reversals during copying (see our fuller discussion in Section 4.2). Subsequently, the relationship between mirror writing and dyslexia has not been confirmed. Hécaen (1984), referring to Ajuriaguerra et al. (1956), notes that "there is no particular frequency of mirror writing in dyslexics" (p. 207). And Treiman et al. (2014) caution educators and clinicians against taking reversal errors in writing as a sign of dyslexia.

Orton's theory, neurological to the point of disempowering pedagogues, may have been strongly criticized by the latter. For example, St-Pierre et al. (2010) write: "Although long refuted, Orton's conceptualization has had a definite impact on popular belief based on the existence of an association between dyslexia and letter inversion or mirror writing" (p. 98). In a kind of "counter-revolution" (Corballis & Beale, 1993, p. 58), linked to the cognitive revolution and the expansion of neuropsychology, it has however become respectable to look for brain abnormalities in children labelled as dyslexic. Today, despite the essentially phonological origin of dyslexia, researchers do not exclude, however, that some dyslexias are of visual origin, referring to Orton (e.g., Fernandes & Leite, 2017; Ramus, 2010) or not (Vidyasagar & Pammer, 2010).

1.7. The ambiguous contribution of Gertrude Hildreth

Gertrude Hildreth was an American educational psychologist, President of the American Psychological Association (APA), Educational Psychology Division, in 1949 (see Fig. 5). As early as the 1930s, Hildreth had been conducting tests in classrooms. In her 1934 paper, she tested students in grades 2, 3, and 4. The test used 25 flash cards containing an item such as D, a square with a diagonal, S, Z, 24, bed, JCE, ..., four and six. Each card is displayed for 3 s and, as soon as it is removed, students are asked to copy what they have seen onto a lined sheet of paper. Left- and right-handed children made virtually the same number of reversal errors, and the difference between the two is described as "insignificant statistically" (Hildreth, 1934, p. 19). Because the average error for left-handed students was slightly higher than for right-handed students, I verified that the difference was not statistically significant.



Figure 5. Gertrude Howell Hildreth, 1898-1984.

[Photo retrieved from <https://fr.findagrave.com/memorial/114818156/gertrude-howell-hildreth>].

In a later article, Hildreth (1936) takes a more general interest in the development of writing, particularly of the first name. She also highlights and illustrates the reversal of some capital letters by 5 year olds (see Fig. 6). We will remember, for the following, especially the reversal of the letter J by JOHN (5;0), secondarily that of N by both HELEN (5;0) and ELINOR (5;8).

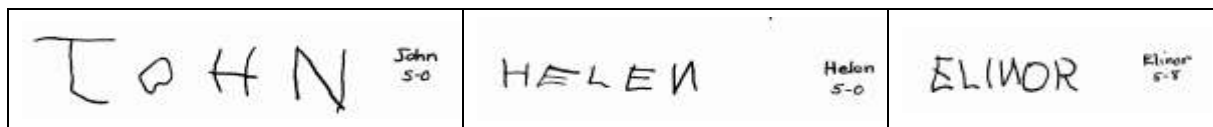


Figure 6. The writing of the first names by three children. [Writings reproduced from Hildreth, (1936), Fig. 7, p. 297].

Bi-manual writing, which Critchley (1927) had mentioned in his table of the etiology of mirror writing in non-pathological individuals, was studied by Hildreth (1940) on 103 children aged 4 to 9 ½ years from an advantaged socio-economic background. The children were asked to reproduce simultaneously with both hands about 15 figures on both sides of a vertical line. Among the figures, there were letters or words (DC, ON) and digits (7) or numbers (63). The last ones (DC, ON, 63) are much less reversed than, for example, the square which is observed during the tracing since, afterwards, it is no longer possible to see if it is mirrored. On the other hand, the digit 7 was mirrored 23 times, compared to 74 times correctly. Hildreth concludes that "Mirroring was quite universal among the five-year-old children. The mirroring seemed to be a very natural performance" (p. 313) and that "Girls tended to make slightly fewer mirror responses" (p. 314).

In 1949, when Hildreth became chair of the educational psychology division of the influential APA, she published a series of five articles, numbered I through V, under the general title, "The development and training of hand dominance" (Hildreth, 1949a, 1949b, 1949c, 1950a, 1950b). This general title, and even more clearly the five subtitles, each of which includes the concept of handedness, draw attention to the problem of laterality. Moreover, the subtitle of the fourth article (Hildreth, 1950a) explicitly associates handedness with developmental problems, which may be surprising since Hildreth (1934) had not observed any difference between left- and right-handed students. It is therefore worth looking closely at this article, especially the section on mirror writing.

Hildreth begins by noting that, of all the writing problems associated with left laterality, ambidexterity, and delayed laterality development, mirror writing is the most curious. She quotes Buchwald (1878), but in the references collected in the fifth article (Hildreth, 1950b), refers to him with the first name DR (abbreviation for DoctoR). It is on page 69 of this article that we find a curious observation, to say the least. After a table reporting observations of left-handed writing by German pupils, aged 7 to 13, at the end of the 19th century by Cahen-Brach (see Table 2), Hildreth writes in a sentence forming a paragraph in itself: "Most observers find mirror writing more common among boys than girls in proportion greater than three to one" (p. 69). This finding is surprisingly false: Cahen-Brach's observation shows that 50/327 (= 15.3%) boys, as opposed to 57/322 (= 17.7%) girls, mirror wrote, and thus contradicts Hildreth's assertion, which is in no way supported by her own research. But Hildreth's nonsensical assertion, which might be due to an editorial problem, seems less troublesome than the general message conveyed by the section immediately following entitled "Left-handedness and mirror tendencies". In this section, ignoring his 1934 observation of no difference between left- and right-handed students, Hildreth again cites observations showing that mirror writing is almost exclusively done by left-handed children. Among these observations, Carmichael and Cashman (1932) described 7 children producing mirror writing, 6 of whom were left-handed. But Hildreth does not specify that these left-handed children were between 9 and 14 years old, while the right-handed child was 7 years and 6 months old. Hildreth also mentions a particular observation that is said to be due to Gordon (1921): in a school where 10 students mirror wrote, almost all of them were left-handed and wrote with their right hand. However, in a note, Gordon simply reports that in a special school (for mentally retarded students, ages 8-16), where 31 students were tested, 10 mirror wrote. He does not indicate that they were left-handed or that they wrote with their right hand.

In the following sections (numbered 13 and 14), Hildreth analyzes particular cases, including that of 7-year-old Corinne (see Fig. 7). Regarding the writing of her first name, Hildreth notes that it is a complete mirror writing, that is, from right to left, with reversal of all reversable letters, especially of the capital letter N. Corinne wrote her first name with her right hand, but before writing with her right hand she had gripped the pencil with her left hand. In addition, Corinne also mirror wrote her first name with her left hand. The additional comments on Corinne's writing illustrate the confusion that results from Hildreth's writings.

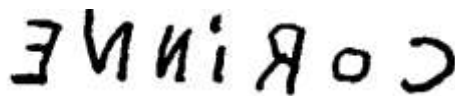
The image shows the name 'CORINNE' written in a mirror image. The letters are reversed and appear to be written from right to left. The capital 'C' is on the far right, followed by 'O', 'R', 'I', 'N', 'N', 'E' in that order from right to left. The letters are somewhat irregular and show signs of being written by a child.

Figure 7. The writing of the first name by C., age 7, a case analyzed by Hildreth. [Writing reproduced from Fig. 6 of Hildreth (1950a), p. 72].

Then Hildreth seems to focus on problems that are attributed to left-handedness: "Left-handedness and spelling difficulties" and "Left-handedness and reading problems", respectively sections 18 and 19 of her article. Although at certain points Hildreth seems to suggest that a distinction should be made between typical and atypical development, she does not really do it. The overall picture of Hildreth's work then leads to an impression of confusion and a backward step toward equating mirror reversal with a left-handedness problem. Incidentally, Hale and Kuh (1901), who strongly asserted the presence of mirror writing in all children at some stage of their development, are not cited, despite more than two hundred articles referenced in Hildreth (1950b).

1.8. What are psychologists doing?

When a faculty is poorly defined, or even impossible to define, such as intelligence, psychologists construct measurement scales, the intelligence quotient (IQ) for my example. This allows them to remedy, humorously, the lack of definition: the faculty concerned can indeed be defined as what is measured by their scale! Mirror writing has not escaped this desire to have a scale for its measurement. The first of these scales, often improperly called "tests", could have been the Jordan left-right reversal test. It was constructed to standardize a measure of symbol (letter and digit) reversal in the typical child, aged 6 to 10 years (Jordan & Jordan, 1974). But, as the 2500 participants in the standardization had to recognize, by crossing out, 11 mirrored letters (ϣ, 2, 1, Я, 3, 8, 3, 5, 9, 7, 8) mixed with 16 true ones, and 5 mirrored digits (8, 7, 9, 1, 2) mixed with 9 true ones, we can see that it is not a matter of writing, but of recognizing, reading, or distinguishing the mirrored characters. Completing the measurement scale with the addition of lowercase letters and words containing a reversed letter, and its new standardization with 3000 children, by Jordan and Jordan (1990), do not remedy this problem at all, since the children's task has remained the same.

Historically, the Reversal Test (Edfeldt, 1955/1970) precedes the Jordan Test. It was first presented in 1955 by the Swedish psychologist Ake W. Edfeldt in the *Research Bulletin* of the Institute of Education at Stockholm University. But, on the one hand, it is also about recognizing inverted figures (and not only left-right inversions), on the other hand, it is less a measurement scale than a real test. This test was mainly used by school psychologists to assess the maturity of children for learning to read, at a time when the French Education Nationale allowed admission to first grade from the age of 5, and had set up a large number of special classes, adaptation classes, waiting classes, between the kindergarten and first grade.

The second scale, the Reversals Frequency Test (RFT), was developed by Richard Gardner in 1978, when he was Associate Professor of Clinical Psychiatry at Columbia University. As it really involved the writing of characters, I will retain it as the first—and main, as it will later appear—scale for measuring the phenomenon of mirror writing. Gardner presented the writing test only as a subtest of production of inversions (Reversals Execution). He included two other subtests in his test, probably because for a century the inversion of characters in writing had been associated with their incorrect recognition in reading. In the Reversals Recognition subtest, the child is presented with a collection of numbers and letters, some of which are mirrored: the child must cross out all incorrectly oriented items. In the Reversals Matching subtest, each item consists of a number or letter model and is followed by four samples of the same number or letter; one of the four samples is correctly oriented as the model, the other three having been reversed or rotated: the child must circle the sample matched to the model. As each subtest is, fortunately, assessed separately, I can now limit my presentation of the test to the subtest of producing inversions in writing.

The participants had to write the characters, under dictation, in isolation and in columns. The characters are the 7 asymmetric Arabic digits and the 17 lowercase letters (printed script). About these characters, let's observe that for Americans participants (USA) 1 is generally not reversible and lowercase y is reversible (in contrast to uppercase Y). Mirror inversions are very broadly defined. They can indeed consist of horizontal mirror (e.g., b for d), vertical mirror (e.g., p for q), double mirror (e.g., p for d, 6 for 9), and even be obtained by a 90° rotation (e.g., b lying down, i.e. 3, for b). Typically developing children selected must have an IQ between

90 and 110 and have produced at least 8 correct scripts. These inclusion criteria limit the generality of the measurement scale. In particular, participants who inverse all, or almost all, of the characters would not be measured as patent inverters (which they certainly are). This subtest also has a small weakness in relation to the material. Indeed, once the lying digits are included in the measure, all the digits should have been included, especially 8 which is, in my experience, the lying digit that children produce most often (∞).

Despite these reservations, the near-uniqueness of this writing test in the literature leads me to present its standardization with 500 typically developing children (of both sexes combined) in Table 3. Gardner presented the data separately for boys and girls. But, a statistical check allowed me to verify that there was little difference between the two sexes, except for the 28 five-year-old girls (5;0 to 5;11) who made marginally more errors than the corresponding 25 boys [$t(51) = 1.697, p = .096$, two-tailed test]. Besides, Table 3 shows a floor effect as early as age 7, making it impossible for a significant gender difference to emerge in the eight older age groups.

Table 3. Inversion errors (out of 16 possible)⁴ produced by typically developing participants in the standardization of Gardner's Reversals frequency test. [Table constructed by combining Tables 1 and 2 of Gardner (1978)].

Age (years)	N	Minimum	Maximum	Mean	Standard Deviation
5	53	0	13	3.85	2.73
6	59	0	11	2.41	2.24
7	50	0	4	0.42	0.93
8	53	0	1	0.04	0.19
9	52	0	1	0.04	0.20
10	57	0	2	0.05	0.29
11	51	0	2	0.12	0.43
12	50	0	0	0.00	0.00
13	52	0	1	0.02	0.14
14	23	0	0	0.00	0.00

Table 3 shows the limited value of this test, since by age 7 typically developing children appear to produce few inversions in writing. However, as a clinician, Gardner certainly needed a scale that would allow him to compare atypically developing children with norms developed with a sample of typically developing children. In the same RFT standardization manual, in fact, Gardner presents data from children with minimal brain dysfunction (MBD).

Gardner has also pointed out that children inverse numbers less than letters, and that this is probably because some letters (print script) are mirror images of others (e.g., b and d), or are close to being so (e.g., p and g). This can be seen at odd with our Section 4.7. However, should these inversions not be interpreted as confusions rather than mirror reversals (see Fischer &


⁴ Because 8 writings had to be correct, the selected participants could not make more than $24 - 8 = 16$ mirror writings.

Luxembourger, 2022)? In addition, the higher average age of this standardization sample than that of the typically developing children primarily studied in this essay may interact with this interpretation problem.

The floor effect, which occurs very quickly in development, has perhaps not encouraged psychologists to pursue or refine the construction of a scale for measuring character inversion in writing. Only, to our knowledge, Janet Richmond in her thesis submitted in 2010, at the Australian "Edith Cowan" University in Perth (Richmond, 2010), or in a poster with Brown (Richmond & Brown, 2008) has yet proposed a test, later called Richmond Reversal Rating (RRR: cf. Venter et al., 2018). But, as the name of the test does not suggest—Rating means evaluation, scoring, and could therefore also refer to writing—it is, as for the test of Jordan and Jordan (1974) above, a judgment (or recognition, reading, discrimination) of reversed characters. We will not comment further on this test, but note that it is also affected by a ceiling effect, since, from the second year of school, the score, both average and median, exceeds 90% of the maximum possible. It should be noted that the reason why the previous floor effect has become a ceiling effect here is that Venter et al. judged correct answers whereas Table 3 reports errors.

1.9. What are educators doing?

Educators, or educational researchers, want to know what students are struggling with and whether the instruction they are being offered is remedial. Edward Lewis and Hilda Lewis of San Jose and San Francisco State Colleges first noted that there was little detailed analysis of the specific difficulties inherent in handwriting upper and lower case letters (Lewis & Lewis, 1965). They then determined the relative difficulty of the $26 \times 2 = 52$ letters of the alphabet, and whether there was a differential effect of instruction. In September 1960, before any school instruction, they asked 354 first-grade students in a California school (15 classes) to copy the 52 letters; then, in April 1961, they repeated the procedure. They distinguish 11 types of errors in letter construction. Tables 4a and 4b report the errors, for upper and lower case letters respectively, only for horizontal mirror reversals (left-right) and vertical mirror inversions (top-bottom). A third transformation, rotation, was not included, although it is interpretable as a double mirror if it is 180° , because Lewis and Lewis categorize as rotation any letter shape whose angle of rotation exceeds 15° (from an imaginary vertical line through its axis). They report the errors from both sessions combined, which is a little embarrassing because the students must have made considerable progress from one session to the other.

In school, teachers teach writing. Lewis and Lewis reported on how the scripts were taught (in California at this period), specifying the sequence of strokes that make up the letter, as well as the direction of the stroke (e.g., o, lowercase or uppercase, is drawn counterclockwise). In order to understand some of the mirror scripts, it is necessary to use this description. For example, U (or u) can be reversed horizontally because its writing has a vertical line on the right that goes down slightly lower than the vertical line on the left: . On the other hand, Z (or z) in vertical mirroring is not different from Z (or z) in horizontal mirroring: Lewis and Lewis then coded it only as horizontal mirroring. Because the combined presentation of beginning and end-of-school-year data may seem inconsistent with the project of testing the impact of instruction, it should be noted that Lewis and Lewis presented several other tables. In particular, a table comparing the average numbers of pre- and post-teaching errors. For horizontal mirror

A long history

reversals, they were 1.13 before teaching and 0.44 after teaching; for vertical mirror inversions they almost disappeared after teaching: 0.22 versus 0.015.

Table 4. Horizontal and vertical mirrors (in numbers) produced by 354 California 1st graders copying letters in September and April of the 1960/61 school year. [Data taken from Table 1, p. 28, of Lewis & Lewis (1965)].

(a) Upper case letters

Inv.	A	B	C	D	E	F	G	J	K	L	M	N	P	Q	R	S	T	U	V	W	Y	Z
Hor.	–	6	5	6	2	2	2	25	2	3	–	47	5	7	3	24	–	18	–	–	–	23
Ver.	1	–	–	–	–	0	10	0	–	1	8	–	0	2	0	–	0	4	5	13	0	–

Note: The letters H, I, O and X are absent because their inversion (horizontal and vertical) is not observable.

(b) Lower case letters

Inv.	a	b	c	d	e	f	g	h	i	j	k	m	n	p	q	r	s	t	u	v	w	y	z
Hor.	15	24	4	44	7	4	8	6	–	17	1	5	7	13	42	4	25	–	21	–	–	40	31
Ver.	–	4	–	4	4	1	5	0	1	1	0	0	0	1	2	0	–	0	5	2	13	0	–

Note: The letters l, o and x are absent because their inversion (horizontal and vertical) is not observable.

Tables 4a and 4b already draw attention to several points that will be found and interpreted more theoretically later: (1) horizontal mirror reversals were much more frequent; (2) horizontal reversals of uppercase letters can differ markedly from those of the corresponding lowercase letter: for example, d is reversed 44 times, whereas D is reversed only 6 times; (3) the letters d and q, whose horizontal mirrors are the letters b and p, are reversed more than the latter: 44 and 42 times for d and q, compared to 24 and 13 for b and p, respectively; (4) the most vertically inverted letter W (or w) resembles the letter M (or m) when inverted.

Lewis and Lewis's careful statistical observation in a public school in a middle-class suburb of California, however, was only for letters. Somewhat earlier, Gesell and his collaborators had studied child development by a biographical-clinical rather than statistical method. From observations of children in New Haven and at the clinic founded by Gesell, also in a rural school in Connecticut, Gesell and Ilg (1946/1975) noted that, at age 5, children mostly reverse 3, 7, and 9; at age 5 1/2, 3, 4, 7, and 9; at age 6, 3, 7, and 9; at age 7, 4, 7, and 9. Except for the digit 4 which, curiously, is not indicated among the reversed digits at age 5, but appears at age 5 1/2, disappears at age 6 and reappears at age 7, recent research shows that Gesell and Ilg's observations still seem interpretable today. It should be noted, however, that most of the observed children (over 50 per age group) come from families with good or excellent social or economic conditions, and 3/4 attended a nursery directed by the clinic before entering a good elementary school; thus, they represent a prosperous American community (cf., the introduction by Gesell & Ilg, 1946/1975).

1.10. Interlude

Corballis and Beale (1976) allude to the theory of Robert Fliess, whose father, who was a friend of Freud, had dogmatically associated bilateralism with bisexuality (an association not accepted by Freud). Robert Fliess became a psychoanalyst and argued that the left-right confusion is symptomatic of a deeper confusion between anal and genital impulses. Corballis and Beale stop their digression on psychoanalysis by noting however still—but did we really need their enlightenment?—that the anal/genital confusion is rather predictive of a front/back confusion

than a left/right one! This indirect reference to Robert Fliess only serves here as an introduction to this interlude.

First, in a psychoanalytical approach, Cady (1988) devotes a chapter to "laterality, writing, drawing", in which a section is devoted to mirror writing. Cady refers mainly to the case of Sophia, a 7 year old child who has difficulties at school due to a laterality not yet established. Her paternal relational situation is blocked since the father has left his wife with full responsibility for the house. For Cady, mirroring refers to the space of imaginary complementarity. She describes a scene in Sophia's psychotherapy in which Sophia mirror writes her name and lifts the paper so that Sylvie Cady can see the transparency. As Sylvie Cady stands in front of Sophia, she sees that the drawing is indeed correct. Cady then observes that Sophia has no other reference than that of the maternal image and that this visibly arranges the child who uses the dual spatial relation, without distance, that of imaginary complementarity.

For Cady, in a general way, "laterality and writing are created in triangular situation, but it is only at the time of the oedipal identification that they are definitely structured" (p. 163). Then, one reads affirmations like "the writing in mirror is placed between the two hands" (p. 169), "the possibility of writing in mirror represents a maternal contact" or still "the graphics in mirror can be a refuge against the writing-nightmare due to an elaboration which fears the child" (p. 170), of which I leave to the reader the task of imagining a sense and, perhaps, an application.

G rard Pommier has written many books. Before Pommier (1993), he had dealt with: "The female exception / essay on the impasses of sensual pleasure" in 1985. Then, many books followed: "Love in reverse" in 1995, "Erotic Anger: A User's Manual" in 2001, "On the proper erotic use of anger: and some of its consequences...." in 2011, "The sexual order" in 2011. By the standards of these titles—here generally translated from French and not all quoted—, the title of his 1993 essay "Birth and rebirth of writing" may seem a bit insipid. But it is nevertheless the one we need to discuss! The book is presented as "A study by a psychoanalyst, former student of Lacan" on the Amazon website⁵. This precision, from a Lacanian background, may prevent the reader from looking for a meaning to the author's mathematizing, to which I refer later, because "Lacan's mathematics are so fanciful that they cannot play any fruitful role in a serious psychological analysis" (Sokal & Bricmont, 1997, p. 38).

In the chapter that mainly concerns us, "The Medusa letter. Topology of Writing and Repression", Pommier ends with a sub-chapter entitled "Repression and Orientation of Writing". In the first sentence of this sub-chapter, he speaks of "dyslexia", and in the second he explains it by inversions of letters when the child writes. Thereafter, Pommier would never distinguish between a particular form of writing—mirror writing—and dyslexia. The very first example given by the author is a "*retournement*" along a vertical axis [*sic*]: An A is thus transformed into ∇ , a U into \cap . Although such a transformation can also be described as a plane symmetry along a horizontal axis or a half-turn around a vertical axis in space, the author prefers name it "*retournement*" (reversal, turn-around in English). Possibly because this last word allows him to interpret it more easily as a "*refoulement*" (repression in English), two words that rhyme richly in French language. But there are not only "*retournements*". Other

⁵ https://www.amazon.fr/gp/product/B07K8S5PDT/ref=dbs_a_def_rwt_bibl_vppi_i0 retrieved on 04/05/2022.

letters experience horizontal spatial inversions: B will be written \mathfrak{B} . Spatial translations are common for the group p and d, p and q [*sic*].

Pommier then takes up the predominant 20th century explanation of left-handedness, supporting it with statistics on dyslexia (quoted second-hand: Granjon after Roudinesco). He also talks about mirror perception in relation to Orton, without citing a specific source. Yet, we have already seen, in Section 1.6, that Orton wrote that a mirror memory recording serves as a pattern for motor expressions. He cites Ajuriaguerra, again without specific reference, and without noting that the statistical observations of Ajuriaguerra et al. (1956) concern deliberate mirror writing and not spontaneous writing such as that seen in schools. Teachers rarely ask beginning students to mirror write and quite routinely put a starting point near the left margin to discourage them. In any case, according to Pommier, "there is a moment when the letter that was written in mirror, or upside down, or for the reader situated opposite, turns right side up", a moment that leads Pommier to wonder: "Does this moment of *retournement* correspond to *refoulement*?" (p. 328).

Finally, Pommier explains that the subject (the boy) "marries his father by writing against him" (p. 332). In this sense, it is understandable that the orientation of his writing during this time of feminization concerns essentially boys, the female sex being concerned only to a lesser degree. If one can infer from this that boys should mirror write more frequently than girls, it must be noted that this result has never been clearly established, neither in the statistics already reported, nor in those to come in this document! Although Pommier could not know the hypothesis of a genetic origin of mirror writing by Mathewson (2004, 2007), we can mention that the latter proposes, totally at the opposite of a prevalence of mirror writing in boys, a sexual ratio of one man for 6 women!

For the rest, the author has found a Klein group, one of Lacan's mathematical insights, in "reversals, inversions in the form of letters and in combinatorics, whether they be of rotation, reflection or translation" (p. 333). While horizontal, vertical, and double mirrors do indeed form, along with the identical transformation, a commutative Klein group (see Fischer & Luxembourger, 2022), it is hard to see what, at the end of the section, this observation can contribute (even if it were presented correctly). On the contrary, one may fear that readers will confuse the elements of an abstract theoretical structure with the processes actually implemented by the children. Let us recall in this respect that, with reference to the great psychologist Jean Piaget (e.g., Piaget, 1955), some teachers, or teacher trainers, in the post-1970s, made children run in a playground, configured as a rectangle, along the Small side, the Great side and the Diagonal, while allowing them to remain Motionless. Since the set of transformations M, S, G and D, with the composition operation of two transformations, effectively form a Klein group, they hoped to implement this group in their students' brains. This group, by virtue of Piaget's theorization, should then allow the students to access all the reasoning of the Piagetian formal stage. Needless to say, these teachers' hopes were dashed.

2. Are the characters oriented?

From my early research on digit writing, under good ecological validity (Fischer, 2010a, 2010b) or experimental control (Fischer, 2011), it was becoming clear that it is the characters rather than the participants that determine reversal. This prompts further investigation of the shape of our characters, especially aspects of the characters that may interfere with their orientation.

2.1. Letters look to the right!

Kolers (1969) was certainly one of the first to notice that, for roman letters, the major vertical stroke is usually on the left edge. For example, B, D, E, F, K, L, M, N, and P, among the capital letters, confirm this observation. But Kolers also noted that their distinguishing marks are on their right. Not all alphabets are spatially polarized in the way that the Roman alphabet is (e.g., the Sinhalese and Thai alphabets). This choice of the right for the distinctive sign, or more generally of the structure of the major (vertical) stroke + distinctive signs on one side, was only made late in our alphabet. If we go back as far as possible in time, we can see that such a structure, for the letters (capitals), was by no means imposed from the start. Figure 8 shows that almost no letter had such a structure in the Proto-Sinaitic script, the oldest known and which we know, almost certainly, was written from right to left (cf. Tallet, 2022). Even 750 years later, in Phoenician writing, this structure is not yet apparent. It thus seems to emerge with archaic Greek, notably for the letters B, C, E, K, L, M, N and the future P.

But the surprise is great when one discovers, in the writings in archaic Greek and especially in ancient Latin, on the same Figure 8, that the distinctive sign expected on the right, is found on the left! Concerning the direction of writing in Ancient Latin, it should be remembered that the latter alphabet originated in a region where only Semitic languages were spoken, and therefore the writing was probably from right to left. However an indecision about the direction was introduced by the boustrophedon script, whose direction alternates from one line to another, like the ox marking the furrows in a field. Figure 8 shows then that archaic Latin, following archaic Greek, accentuated both the number of letters structured "major vertical line + distinctive signs", even if the structure disappears for C. Archaic Latin also slightly accentuated the left orientation of letters, with A, D, F added to the previous left-oriented letters. But a major change, which probably influenced Roman writing, occurred around the 4th century BCE when the writing direction was definitively fixed from left to right. Figure 8 shows that the resulting Roman letters are mostly oriented to the right. What is important to remember is that at the time (a few centuries BCE) when the writing direction was reversed, the orientation of the letters was also reversed: the letters that were previously more oriented to the left (see archaic Latin in Fig. 8) became mostly oriented to the right (see Roman in Fig. 8). In modern Latin, very similar to Roman, we have inherited this right orientation of most capital letters. Note, however, that J and Z seem to be exceptions in modern Latin. We will have occasion to return frequently to these letters J—a medieval creation which appeared very late—and Z which seems to have been borrowed from archaic Greek in the archaic Latin alphabetic system.

Are the characters oriented?

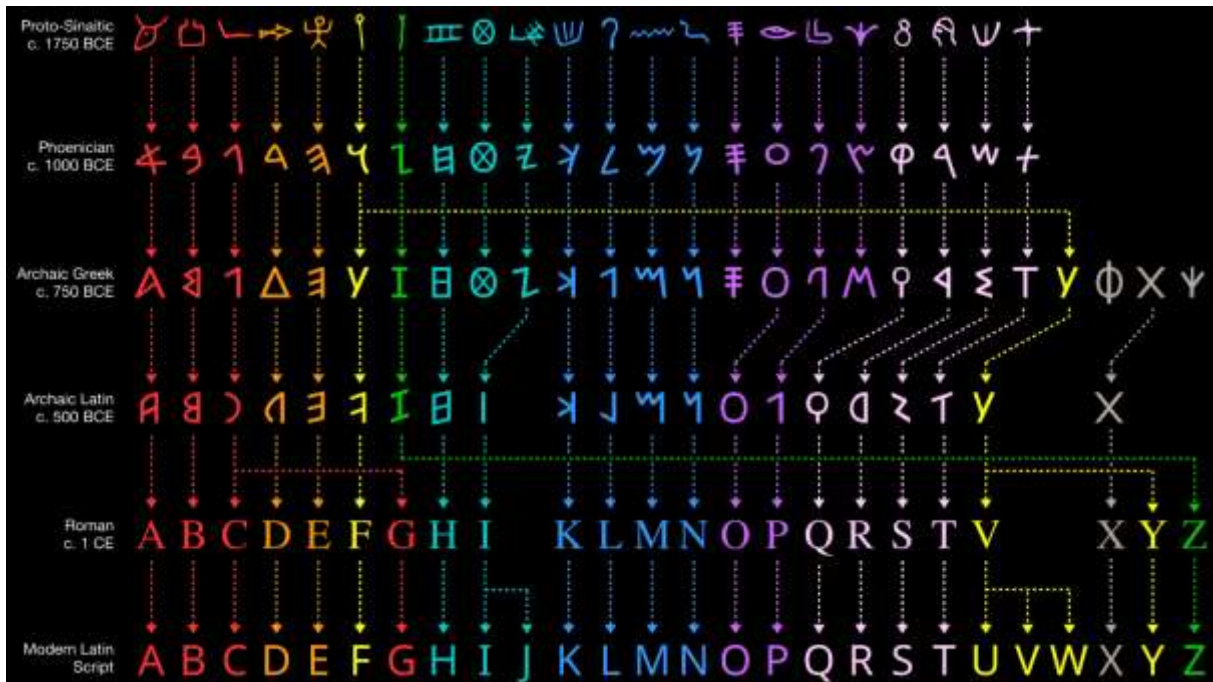


Figure 8. Evolution of the alphabet, by Matt Baker.

[Retrieved from: <https://usefulcharts.com/blogs/charts>].

What looks, therefore, like a compliance of letter orientation with the new and definitive left-right direction of writing is consistent with a recent finding by Miton and Morin (2021). In their computational analysis of a large and diverse dataset (over 47,000 characters, from more than 133 scripts), they indeed observe that the shape of the letters adapted to a culturally induced cognitive bias rooted in the motor and visual habits created by the direction of writing/reading. However, in apparent contradiction with the structuring of vertical stroke (left) + distinguishing sign (right) and the simplicity of a vertical stroke, Miton and Morin also showed that the left half of a character is more likely to be the most complex if it comes first in the writing as it does in the modern Latin alphabet. The contradiction might not be real, however, because for computational constraints these searchers mechanically cut the individual letters along a vertical line equalizing the number of pixels on each side. A letter like D should therefore have for its left half not just the vertical line, but this line completed by small horizontal segments at the top and bottom (I), while the right half would be limited to a portion of a circle (J).

Brekle (1997a) has, by reference to the usage of paleographers, named *hasta* the vertical stroke of a letter (*hasta* means stick in Latin), and *coda* strokes added to the *hasta*. Because of this structuring *hasta* + *coda* our contemporary capital letters seem to look to the right, that is, in the direction of our writing. About the letters C and G, which do not really have this structure, Brekle (1997b) suggests that they are nevertheless "vectorialized" to the right by their Greek origin, where their common ancestor had the structure *coda* + *hasta* (for C, see Fig. 8, third letter of the third line). As a result, a large majority of reversible capital letters look to the right.

Treiman and Kessler (2011) first analyzed contemporary letter scripts using this *hasta* + *coda* structuring principle. Instead of using the *hasta* + *coda* or *coda* + *hasta* description, these authors often prefer the distinction of b-type and d-type letters already present in Simner (1984). They arrive at the following categorizations: with the most frequent font forms, B, D, E, F, K, L, P, R, b, f, h, k, m, n, p, and r are b-type, and J, d, j, q, u, and y are d-type; in addition, with less

frequent font forms, U, a, g can also be seen as d-type. They then proposed that children, upon learning statistically that letters are right-oriented, reverse those that are not, an explanation for reversal that we will reject in Section 3.4.

By this structure *hasta + coda* the visual orientation can be observed only on reversible letters, which excludes A, H, I, M, O, T, U, V, W, and Y. For uppercase letters, we can also see that a significant number of letters do not show it: C, G, N, Q, S, Z. The lowercase letters that do show it are rare and depend on their writing (script, cursive, attached). To, despite these difficulties, support and objectify the relevance of this notion of oriented visual letter form, Treiman et al. (2014), asked 33 students at Washington University in St. Louis (MO), to judge whether the 52 letters (uppercase and lowercase) face left, right, or have no orientation. The students judged, with proportions shown in parentheses, that the lowercase letters b (.91), c (.94), e (.94), f (1.00), h (.88), k (1.00), n (.58), p (.94), r (1.00), s (.73), and upper case B (.94), C (1.00), D (.85), E (.97), F (1.00), G (.91), K (.94), L (.91), P (.97), Q (.52), R (1.00), and S (.78) face right, while lowercase a (.85), d (.94), g (1.00), j (.97), q (.88), y (.91), z (.66), and uppercase J (.97), Z (.55) face left (a neutral judgment was most frequently made for the remaining letters). As can be verified, these judgments are almost perfectly consistent with the hypothesis that the *hasta + coda* structure induces a right-facing visual form.

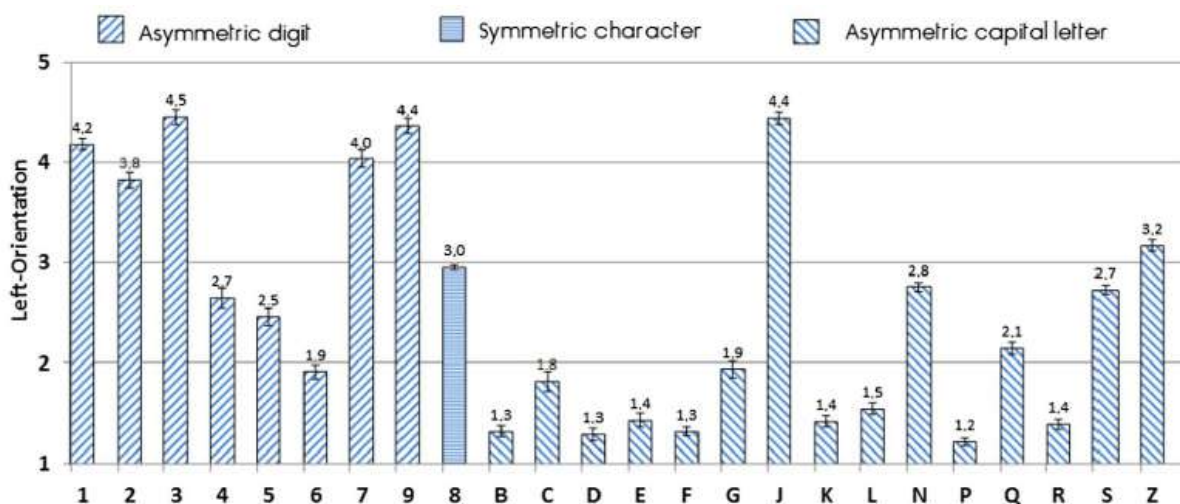


Figure 9. The assessment of the degree of left orientation of reversible characters (except 8) by French students at the University of Lorraine on a scale of 1 (completely to the right) to 5 (completely to the left). [Reproduced from Fischer (2018), Fig. 3, p. 561].

I was also able to verify that 142 French students at the University of Lorraine made almost the same orientation judgments for the reversible capital letters, as the lowercase letters were not offered (see Fig. 9). Notably, as in Treiman and Kessler's observation, J, massively, and Z, slightly, were the only uppercase letters judged to be looking to the left. With these judgments of orientation we already find, for the first time and as previously announced, the singularity of the capital letters J and Z.

If we rule out an explanation for the reversal of letters simply by their systematic orientation to the right by the children, how can this *hasta + coda* structure intervene? As we have seen, the principle of structuring *hasta + coda* (to the right) gives the letter a right visual orientation. One explanation for reversal is that the child who finds the vertical line visually salient and easy to draw, will start with it, then add the coda on the right. A letter like q is then reversed to p. However, three problems may arise with this writing strategy. The first problem may arise from

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the subjectivity of the notion of visual salience: if it is the loop of q that is visually salient, the child will start with it and, as a result, will not reverse q but p. For the other two problems, he or she will start with the vertical line, but (1) the visual appearance to the right may differ from the internal direction of the stroke, or (2) when writing from right to left, the visual appearance to the right will be opposed to the direction of the writing process. A child may then reverse a letter such as D, for example, (1) if he draws the circles counterclockwise, or (2) if he writes from right to left turning the letter to the next. We shall see that it is rather hypothesis (2) that is resistant to empirical observation.

2.2. Digits look to the left!

Numbers and the need to count appeared very early in humanity. They are often dated back to 3000 BCE, in the Sumerian civilization. But the first representations of numbers (notches, number-objects, parts of the body, etc.) do not inform us about the shape of the current digits. The latter, which we call "Arabic", were probably born in northern India much more recently (Ibrah, 1981). In Sanskrit, an ancient Indo-European language now used only as a liturgical and cultural language, it has been possible, for example, to find a versified piece whose verse numbering used the digits shown in Figure 10.



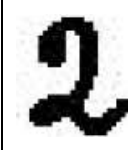

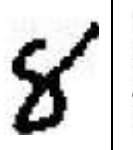
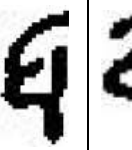
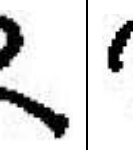
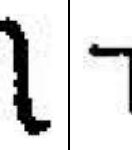
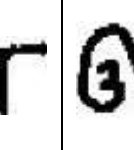

									
0	1	2	3	4	5	6	7	8	9

Figure 10. The 10 digits of our numeration system written in Sanskrit in the year 875 CE. [Figure based on Ibrah (1981), p. 463].

These digits do not have a hasta + coda or coda + hasta structure. At most, one can think that they generally look to the left, notably 2, 3, 6 and, to a lesser extent, 1, 7, 9. However, one should not attach too much importance to the analysis of the orientation of these writings because writing can vary according to the authors who report it. For example, only the Sanskrit digits 0, 2, 3 and 4 of Seife (2000/2002) are identical to those in Figure 10. Besides, Seife also reports Indian (non-Sanskrit) digits that resemble (6, 7 and 9 in particular) more to ours, actual ones. Let's go directly to the latter.

Treiman and Kessler (2011) also analyzed their structuring according to the hasta + coda principle. In the same table as for the letters, they indicate that 5 is of type b, while 4 and 7 would be of type d with the forms found in most fonts; if we consider less common forms, the numbers 1 and 9 can also be categorized in type d. But we can see the limits of such analyses. For example, for 4 and 5, hasta is not very obvious. Primus (2004) then tried to develop heuristic rules to distinguish the hasta (which she prefers to call "head") from the coda. For example, among two vertical lines of different lengths, the longer line constitutes the hasta, and in case of a tie (approximately) the leftmost line. With such a rule, the 4, as it is often written in the French school, with the left line more or less vertical, would be oriented to the right, thus of type b. This argument, together with the ductus (i.e., the direction in which the letter is written) as it is taught in France, led me to consider that 4 is oriented toward the right. This is also the case for 5, according Treiman and Kessler's analysis, and for 6, in Primus according Primus' analysis. For the digits 1, 7 and 9, with a broad conception of verticality for the last two, the

structure *hasta + coda* does suggest a leftward orientation. It remains that, for the digits as for the letters, all the digits cannot be categorized on the basis of the principle of structuring *hasta + coda*: the digits 2 and 3 escape such a categorization.

This last point led me to make 142 students from the University of Lorraine judge the orientation of the digits, with the capital letters, as well (see Fig. 9). Their evaluations corroborate almost perfectly the distinction between the digits looking to the right (4, 5 and 6) and those looking to the left (1, 2, 3, 7 and 9). Notably, digits 2 and 3, for which the distinction *hasta + coda* did not allow to specify the orientation, were clearly judged as left-facing.

2.3. The four writings of 5

The writing of the digit 5 allows three different left-right reversals. The first is the total reversal, i.e. a horizontal mirror writing (see Fig. 11a). The second is to reverse only the upper horizontal line, while the loop is correctly oriented (see Fig. 11b). The third is to reverse only the loop, while the upper horizontal line is correctly oriented (see Fig. 11c). As shown in Fig. 11, we were able to observe all three types of reversal in our observations in GS of kindergarten.

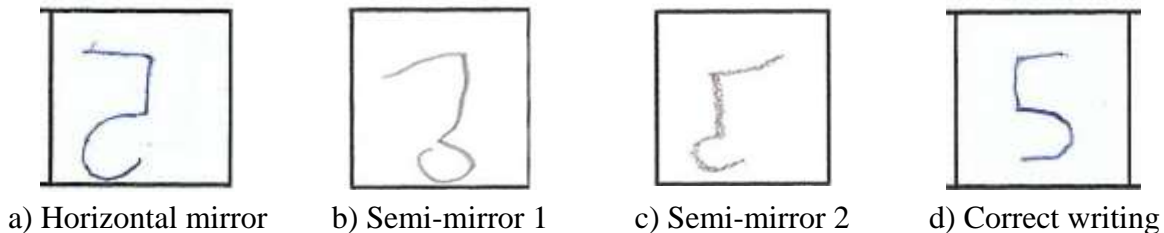


Figure 11. Different writings of 5 by children in the observations of Fischer and collaborators.

This issue may seem like a mere detail, hardly worth noting. And, in fact, I am not aware of any research that has addressed this issue. Nevertheless, if one wants to make statistics on the relative frequency of reversals, one must clearly identify these different scripts and define the type of reversal one is considering. In order to discuss neuropsychological theories, such as the one already described by Orton (Section 1.6) or those to come by Corballis (Section 5.1) or by Dehaene (Section 5.2), it seems almost imperative to consider only the first reversal (Fig. 11a) as a left-right mirroring. Because I did not make this clear to my students, who collected and coded the scripts reported in Fischer (2010a), the script of 5 observed in this initial research, had to be eliminated in the synoptic table presented later (in Fischer & Luxembourger, 2018a; also in the present Fig. 34). Instructed by this experience, I became concerned about this problem and checked all the coding performed by the Masters students in subsequent research.

The question of partially mirrored writing can also arise for other characters. But partial reversals for other characters seem anecdotal and less prone to coding errors. For example, the

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partially reversed 3 in Figure 12 (right part), looks more like an S, possibly a mirrored 2, and can therefore hardly be taken for a mirrored 3.

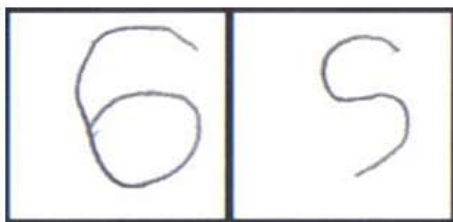


Figure 12. A partially reversed writing of 3, preceded by a correct writing of 6, produced by a 6 year 5 month old, right-handed girl. [Data from Fischer & Tazouti, (2012), Expt 2].

2.4. A concluding summary and discussion

Students' evaluations of character orientation are fundamentally about the visual appearance of static characters. The motor processes of writing, which are implicitly evoked when an adult passively observes letters (Longcamp et al., 2003), are certainly less automated in children. As a result, it is the visual appearance that may primarily influence writing by children. In order to study this influence, it is useful to summarize the previous analyses of the orientation of asymmetric characters.

For lowercase letters, a small majority seems to be oriented to the right (type b). For upper case letters this right orientation is much clearer. On the other hand, for digits, a majority seems to be left-oriented. One could therefore conclude, to a first approximation, that letters look rather to the right, while digits look rather to the left (cf., Primus, 2004).

But Brekle's (1997a) analyses also, or even more importantly, lead us to consider the kinetic dimension of the writing of individual characters and the direction of their joining. Indeed, Brekle listed the following five notions that are useful to remember:

- the internal direction when writing a letter (dextral or sinistral), which is the morpho-kinetic component;
- the dynamic movements of the hand while writing, which is the topo-kinetic component;
- the economic principle in the writing process;
- the visual orientation of a letter, to the left or to the right;
- the problem of a homographic collision of letters that can become too similar.

We can thus see that two fundamental components of writing are kinetic dimensions. Learning to write can then be viewed as learning to reconcile morpho-kinetics and topo-kinetics.

These two components have been nicely illustrated by Marine Portex, in her thesis, with, respectively, the comparative writing and ductus of two words or letters in French and in Arabic (see Fig. 13). The ductus of the Arabic letter kaf, which is close to that of the French letter S, shows one of the major difficulties encountered when trying to categorize characters according to their left or right orientation. Indeed, while the first loop of S is open to the right, the first stroke is drawn to the left. In addition, the ductus taught may not be the same for all teachers/parents, and not all students/children strictly follow what they are taught.

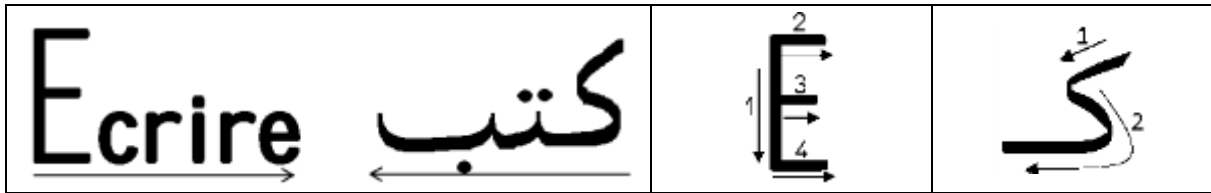


Figure 13. Comparison of the French and Arabic scripts, with the topo-kinetics (left) of the words "Write" and "kataba", and the morpho-kinetics (right) of the ductus of their initial letter E and kaf. [Partially reproduced from Portex (2017)].

2.5. A sort of reciprocal

While our culture will exert a major influence—decisive for explaining character reversals in children—on handwriting, a model recently developed by Anne Maass and Caterina Suitner questions a kind of reciprocal: will handwriting, from left to right, not in turn influence our cultural behavior? Let us first observe that, in their book (Maass et al., 2014a), these authors deplored that "mirror writing in non-clinical populations is understudied," and thus this essay should help to remedy this shortcoming. Let us now report some empirical observations.

In Study 1 by Maass et al. (2009), a content analysis of 200 images of male-female pairs (including artwork, photographs, and cartoons) shows that men are proportionally overrepresented to the left of women, but only for couples in which the man is perceived as more active. In Study 2, the authors show that people tend to draw men to the left of women, but only if they have stereotypical beliefs that associate men with more activity. In Study 3, they investigate whether scanning habits due to writing direction are responsible for this spatial action bias. They observed a tendency for Italian speakers to position active groups (men and youth) to the left of less active groups (women and older people), but the opposite for Arabic speakers who tended to position the most active groups to the right. Taken together, these results suggest a subtle spatial bias in the representation of social groups that appears to be related to culturally determined writing/reading habits.

In several studies by Maass, Suitner, and collaborators, participants are in a situation analogous to that of children who must choose an orientation (which they do not yet know) when writing characters. The participants' situation forces them to choose an orientation, left-right versus right-left, when, a priori, there is nothing to force them to choose one of the two. For example, in Maass et al. (2014b), participants aged 12-19 who were proficient in right-to-left writing (Iraqi participants) or not (Italian and Malagasy participants), were asked to draw a gift exchange (drawing on the left in Fig. 14) or an act of aggression (drawing on the right in Fig. 14) between two people. The Iraqi participants whose drawings are reproduced in Figure 14 tended to orient the direction of the action to the left through their drawing—person A on the right gives the gift to person B on the left and person A on the right insults person B on the left—, while the Italian and Malagasy participants tended to orient it to the right.

Are the characters oriented?

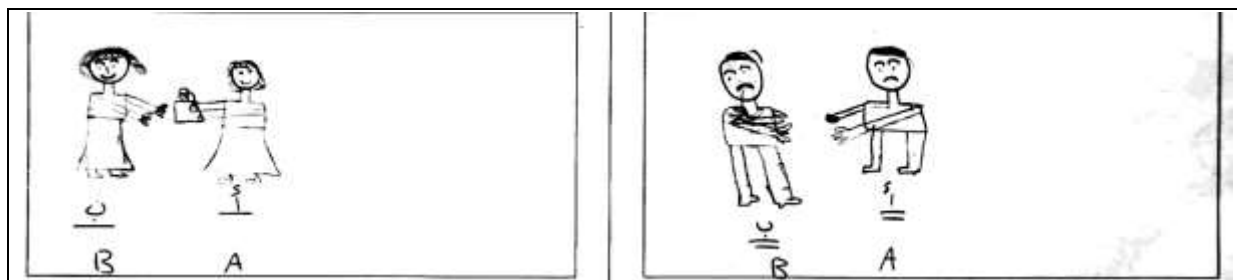


Figure 14. Drawings of Iraqi participants proficient in right-to-left writing/reading. [Figure reproduced from Appendix A of Maass et al. (2014b), p. 996].

The theorization by Suitner and Maass (2016) was called Spatial Agency Bias (SAB). Under SAB, human activity is viewed according to the script direction that prevails in a given cultural context, for example, from left to right in English and from right to left in Arabic or Hebrew. In Western cultures, nearby objects are drawn to the left of distant objects (Vaid et al., 2011) and small numbers are envisioned to the left of large numbers (Dehaene et al., 1993); but the latter placement of numbers may be limited to their ordinal property: see Chan and Wong (2016). The spatial positioning of an object or entity in a horizontal display can provide information relevant to the appreciation of that entity relative to others in the same display (Von Hecker et al., 2022), and the timeline is imagined from left to right in our culture (Bonato et al., 2012; see Fig. 15). Often these asymmetries are partially or completely reversed in cultures where language is written from right to left (Maass et al., 2014a). Interestingly for our practice of writing first names (see Section 6.4), Suitner et al. (2017) point out that a contextually encouraged direction can easily negate the effects of writing habits. Therefore, a "momentarily induced direction" can lead to the reversal of the implicit rightward orientation rule. As the observation in Figure 14 suggests, bias is a joint function of two interrelated asymmetries, one arising from script direction, the other from subject-object order.

This generalization of the role of the direction of writing also allows us to observe that the digits oriented to the left are oriented in the direction of the greatest values. Indeed, in our numeration system the digit a_n at rank n , starting from the right with rank 0, represents the number $a_n * 10^n$. In the writing $a_n a_{n-1} \dots a_i \dots a_1 a_0$, the digits 1, 2, 3, 7 and 9 will thus be turned to the side of the largest numbers. For example, in the writing of 21, the 1 is turned towards the 2, which represents twenty times more than it, or in the writing 12, the 2 is turned towards the 1, which represents five times more than it. Curiously, I now realize that I have never done, nor seen done this kind of comparison of the values represented by the digits of a number.

It must be said, however, that this influence of writing/reading on various behaviors is often of low intensity and thus not always statistically confirmed. For example, Treiman and Allaith (2013) observed that Arabic users (in Bahrain) in grades 2-12 preferred right-facing pictures over those that faced the direction of their writing system, as did US 4th graders. Admittedly, the comparison was not pure, in the sense that Bahraini 4th graders have Arabic as their primary language, but also had five 50-minute English lessons per week. But it nevertheless suggests that this influence of writing/reading on culture can be labile. In Chahboun et al.'s (2017) Experiment 2, Spanish participants are in no way obliged to prefer the right-hand versions, the direction of their writing, and thus to oppose Moroccan participants, who should prefer the left-hand versions in a choice between an image and its mirror. In the same way, the culture does not oblige a French child, at the beginning of learning to write, to prefer to orientate 3 towards

the right (and thus to write ε), the direction of the writing/reading in his/her culture. This reciprocal analogy thus allows me to emphasize that lability is a fundamental property of children's choice of orientation when learning to write.

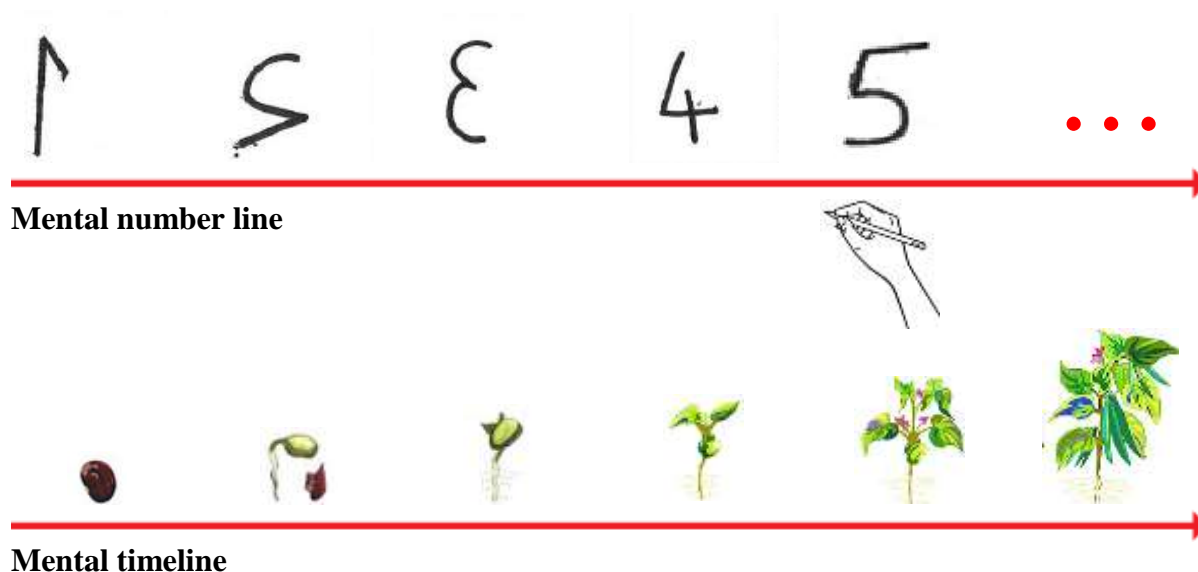


Figure 15. An illustration of the community of representations of the number line and the time axis. [The numbers were written (under dictation) by a 5 year 9 month old right-handed girl in Fischer's (2011) research; the drawings of plant development are adapted from <http://poster.4teachers.org/worksheet/view.php?id=113333>; the basic idea is due to Bonato et al. (2012)].

2.6. Fine confirmations of the difference between two types of characters

Taking up the categorization, resulting from the students' evaluation of the characters looking to the left (see Fig. 9), we can distinguish the sets of digits $Dl = \{1, 2, 3, 7, 9\}$, which they judged rather left-facing, and $Dr = \{4, 5, 6\}$, which they judged rather right-facing. Similarly, we can distinguish the sets of capital letters $Ll = \{J, Z\}$, which they judged rather left-facing, and $Lr = \{B, C, D, E, F, G, K, L, N, P, Q, R, S\}$, which they judged rather right-facing. If, relative to their mirroring by children, the digits of Dl or Ll differ from those of Dr or Lr , children reversing the digits of Dl or Ll will not necessarily be the same as those reversing the digits of Dr or Lr , respectively. A confirmation of the latter hypothesis should result in a negative correlation between reversals of Dl (or Ll) and Dr (or Lr) digit types. This hypothesis may seem audacious because, for more than a century, and some still today, attempts have been made to explain reversal by children's characteristics (e.g., handedness, sexe). Yet, the latter type of explanation should lead to a positive correlation, with "reverser" children reversing all characters, Dl (or Ll) as well as Dr (or Lr), while "non-reversers" would not reverse any. Despite the latter contrary prediction, several of our studies confirm our challenging hypothesis of a negative correlation between Dl (or Ll) and Dr (or Lr) character reversal.

In the research on digits, I determined for each student the reversal rates of Dl and Dr digits (Fischer, 2013a). Although the correlation is quite moderate ($r = -.34$), it is indeed negative and statistically significant with a population of several hundred participants collected with the help of my students. In other words, it can be said that children who reverse Dl digits are more likely to be those who write Dr digits correctly and vice versa. Such an empirical observation throws

Are the characters oriented?

a stone—what shall I say, a rock!—in the garden of those who believed, or continue to believe, that some children have a (general) propensity to mirror reversal (I exclude older or non-typically developing children). The interest of this observation had not escaped one of the experts of the *Journal of Experimental Child Psychology*: he had made the comment that it alone justified the publication of the article.

In the longitudinal study with Anne-Marie Koch, we have available the writing of both letters and digits, and were therefore able to do a similar calculation with the digits and letters combined in the two sets $DLl = DIUl$ and $DLr = DrULr$ (Fischer & Koch, 2016b). Moreover, we have the possibility to duplicate the analysis: once when the children were in GS kindergarten and the other time when they were in first grade. Both analyses supported the previous result since, both times the correlation was negative, low to medium in size, and statistically significant ($r_s = -.40$ and $r_s = -.33$, respectively)⁶.

Finally, in the research with Xavier Thierry in MS kindergarten, the children wrote the digits only from 1 to 5 (Fischer & Thierry, 2021; see also Fig. 23). We thus have subsets $D'l = \{1, 2, 3\}$ and $D'r = \{4, 5\}$ of the sets Dl and Dr . With these reduced subsets, an analysis like the previous ones, would have led to percentages of reversals calculated with only 3 and 2 data per participant, respectively. To approach the question of whether the digits in $D'g$ differ from those in $D'd$ with respect to their mirroring by the children, we therefore preferred to follow a different rationale. We calculated the point-biserial correlation coefficient of the reversal of this digit (coding: 1 = reversed; 0 = not reversed), with the percentage of reversal of the other digits (4 data per participant). Since there are more $D'l$ digits than $D'r$ digits, if the $D'l$ digits have something in common that differentiates them from the $D'r$ digits with respect to their mirroring, there should be a better correlation of a $D'l$ digit, than a $D'r$ digit, with all other digits. The correlations obtained for 1, 2, 3, 4 and 5, namely, .41, .39, .43, .21 and .16 respectively, do indeed verify this prediction.

The consequence of these analyses is that the characters of DLl and DLr do have, intra-set, something in common in their influence on their reversal by the children. We can then recall that the students have evaluated them, respectively, turned to the left and to the right. The analysis of their orientation, taking into account their structure and the dynamics or morpho-kinetics of their writing, agrees with this evaluation. The common characteristic could be their opposition (those in DLl) or not (those in DLr) to the direction or topo-kinetics of the writing in our culture. We will see at length in Section 6.1, that the characters of DLl , i.e. oriented towards the left, thus contrary to the normal direction of our writing/reading, which are most reversed.

⁶ We note r_s the Spearman rank correlation coefficient.

3. Aborted theoretical hypotheses

3.1. Crossing the midline

Crossing the midline is still presented today as a key element in the development of prewriting and pre-reading skills and is an important aspect of child development (e.g., <https://empoweredparents.co/crossing-the-midline/>). In the second half of the 20th century, it generated some empirical research on children who persistently made reversal errors. In theory, the problem does arise since, in writing, the midline of the body can be crossed, at least in children who are well (i.e., conventionally) seated in front of their table or desk. The relevance of the problem seems, however, to be attenuated or modified by the fact that many contemporary parents and teachers (especially in kindergarten) do not insist too much on the position of the child's body in relation to the writing surface. Also, by crossing the midline, abduction turns into adduction, and vice versa: what happens to the abductive writing of the left hand in which some see the origin of mirror writing (see Section 1.1)?

In Chapman and Wedell's (1972) research, the midline crossing task required the child to draw, on a chalk board, horizontal and diagonal lines from the left and from the right, starting from both the top and from the bottom for the diagonals. For these lines, the children had to join two crosses that were two feet and six inches apart on the board. The children stood one foot from the board, midway between the crosses to be joined. Their performance was scored using a two-foot-six-inch by three-inch stencil divided into sections, with the score consisting of the number of sections for which their line came within the stencil. With this task, Chapman and Wedell compared a group of 7- to 8-year-old children with persistent reversal errors with a matched group of "non-reversers." In addition to the midline crossing task, these children were asked to write, under dictation, 10 reversable lowercase letters, 7 reversable digits (not 1), three two-digit numbers and 10 reversible words (e.g., god). The "reversers" made significantly more errors in the diagonal lines, these errors occurring mainly in the 3rd and 4th segments from starting point (i.e., in the middle of the line). Therefore, the result is consistent with the hypothesis of a difficulty in crossing the midline for reversers. Moreover, the reversers showed a marked confusion in the orientation of the letters in the writing task. The authors state that the reversers' difficulties are primarily related to the left-right orientation of the letters.

One developmental study investigated whether children find movements that cross the midline of the body truly challenging (Schofield, 1976). It involved 120 children, aged 3 to 8 years, who faced and copied the hand movements of a model. The children were divided into six age groups, with 10 girls and 10 boys in each group. The study confirmed the existence of a cross-lateral inhibition effect. This effect is reflected in the fact that young children are likely to respond with a movement limited to the same side of the body as the hand being used when asked to make hand movements that cross the body. But the relationship of this effect to age is inconsistent with Schofield's results: 4-year-olds made almost as many cross-body movements as 7- and 8-year-olds, and 6-year-olds made fewer cross-body movements than any other group. So the developmental study's answer to the original question is rather negative. Indeed, the article concludes with a cautionary note: "It seems reasonable to propose that unless the midline inhibition effect can be more positively demonstrated in controlled and fully analysed settings then assessment measures and remedial procedures based on its supposed existence should be regarded with caution" (p. 580). Unfortunately, the author of the study does not refer to Zaslow

(1966), a study that, ten years earlier, had specifically tested a method of remediating reversal errors based on medial body orientation.

The midline method used by Zaslow for correcting reversals stems from theoretical considerations of hand motor patterns with respect to writing movements to and away from the vertical midline body axis. The author suggested that certain primitive motor patterns become fixed with respect to the body midline and may persist independently of the child's intention to produce a correctly orientated figure. The experimental group consisted of 178 children (167 healthy and 11 cerebral-palsy children) selected by their teachers as having reversal problems with respect to numbers and letters (in Section 6.2, we analyze the reversed digits and letters individually). A crossover procedure, in which participants' normal writing position was altered by forcing them to write on the opposite side of the body midline, was used. This procedure corrected reversals in 63% of the healthy children and in 79% of the brain-damaged children on the first trial. In addition, in a control group of 30 healthy participants without specific reversal problems who were instructed to correct reversals in the normal writing position, only 13% corrected their reversals. The author concluded that his technique is effective in correcting a critical factor in the production of reversals, namely movements to or from the midline. Unfortunately, in the individual face-to-face testing situation, only 45% of the children in the experimental group reversed symbols, even though they had been selected from their class for their reversal problems. Therefore, the statistics for the experimental group were calculated only on the basis of these 45% (= 80 children), whereas in the control group no children were eliminated. Thus, the main result of the experiment—a highly significant number ($p < .001$ with a chi-square test) of children correcting their reversals in the midline procedure group compared to the control group—is based on a statistical methodology bias. By recalculating the chi-square test without this selection bias, i.e., by relating the number of children who corrected their reversals to the original 178 experimental participants, the significant difference disappears at the conventional .05 level.

In conclusion, we note that: (1) the limitations of Chapman and Wedell's observation are emphasized by the authors themselves: "The reverser group's inferior performance must therefore be regarded as indicating some disabilities associated with the spatial organization of movement, the exact nature of which requires further investigation" (p. 324); (2) the support of Schofield's developmental study for a cross-lateral inhibition effect is more than mixed; (3) Zaslow's experimental demonstration of the efficacy of a midline-based remediation procedure is weakened by a statistical methodology bias. All of this, together with the questionable contemporary relevance of a study of the child's handwriting position, means that midline crossing should not be a primary variable that can explain spontaneous mirror writing in the typical child today.

3.2. A final attempt of a unified theory

Sergio Della Sala, for a long time editor-in-chief of the journal *Cortex*, and his colleague, Roberto Cubelli, are at the origin of this attempt to bring together, in the same explanatory theory, the mirror productions of children and those of adults affected by certain pathologies. We remember that Critchley (1927) had already brought together, in the same table of etiology, these two groups of people. But he had not brought them together any further.

When Della Sala and Cubelli (2007) proposed their theory of directional apraxia, which was supposed to explain both the mirror writing of typically developing children and adult patients,

they had already reviewed the issue of mirror writing in pathological adults in an article with others (Balfour et al., 2007). In this article, by illustrating it with the writing of the letter "F", they had adhered to Erlenmeyer's motor hypothesis, admittedly old but maintained for over a century (e.g., Chan & Ross, 1988). Indeed, Balfour et al. speculate that if, with the right hand, we have to produce a vertical line and two horizontal segments moving away from the body, producing a correct "F" with the left hand requires a "transformation mechanism". This mechanism would depend on attention translating the program into a vertical line and two horizontal segments toward the body. A misstep in this transformation mechanism will produce a reversed "F" with the left hand.

In their article, the first in the newly founded *Journal of Neuropsychology*, Della Sala and Cubelli (2007) propose a unitary account of mirror writing. According to them, it can be seen as an unavailability of the representation of the direction of the appropriate movement, either because the correct configuration remains to be specified completely (children learning to write), or because of its damage (acquired brain injury). For this reason they propose to call "directional apraxia" the absence of the relevant directional information for writing. This conception of mirror writing as the most open symptom of a widespread higher order deficit allows for the inclusion of all tasks requiring specific, learned motor direction. This predicts that mirror writers should also have problems in dealing cards or turning on a water tap, or, Della Sala and Cubelli add jokingly, rolling up spaghetti on a fork! Consequently, mirror writing should be thought of as a specific form of apraxia affecting the direction of over-learned actions. But their article is not only theoretical. Della Sala and Cubelli take up and analyze all the observations on pathological adults, and add to them observations on ordinary children.

The observations on pathological adults lead to some interesting conclusions, notably that mirror reading rarely accompanies mirror writing. But it is mainly those on children, almost identical to those of Cubelli and Della Sala (2009) that concern us in this essay. These observations show a small but significant decrease in the frequency of mirroring between kindergarten and elementary school and a greater frequency of children copying mirrored digits than letters. To support their unified theory, Della Sala and Cubelli then list the shared characteristics of children and adults. Both groups of people:

- show reversal writing instances in different tasks, including spontaneous writing and copying of letters, words, and digits;
- have been observed writing in reversed fashion while using alphabetic tiles;
- alike reverse the whole word, individual letters within a word correctly written from left to right or the letter sequence with individual letters correctly oriented;
- demonstrate independence between the difficulty with in performing orientation judgment tasks and mirror writing;
- discredit the often-asserted association between mirror writing and left-handedness: only 3 of the 18 patients with mirror writing in the synoptic table of Della Sala and Cubelli were left-handed; for the children, however, this assertion should be moderated as there were few left-handed children in the sample (20 vs. 89 right-handed);
- present a transient phenomenon, fading away with time or practice.

But Della Sala and Cubelli are not totally blinded by their theory. They see that there is also a major difference between children and adults: children reverse letters and words by writing with their dominant hand, whereas most patients mirror write with their left (non-dominant)

hand following a left brain lesion. However, this difference does not seem to be prohibitive because Wang (1992) observed that mentally retarded right-handed Chinese children frequently reverse letters when writing, but only with their left hand. Della Sala and Cubelli conclude that hand dissociation in adult patients and children with disabilities demonstrates that they retain knowledge of the correct writing direction, but fail to implement it when using their left hand. This explanation, which allows Della Sala and Cubelli to consider "apraxic" children as adult patients, could however be different: children, when they do not know the orientation of characters, may consider that any orientation can be suitable and will choose a wrong orientation because it is the most economical (cf., Brekle's economic principle: see Section 2.4) and not because they would be unable to produce a correct orientation. I also have some scruples about treating a child who has not yet learned/retained character orientation as a patient (with apraxia): is this not the same as treating a child of a few months old as aphasic with the justification that he does not express himself audibly or comprehensibly! But it seems useless to criticize at length this theory of directional apraxia because it was not really supported afterwards. It has even been rejected quite directly in the research of Angelillo et al. (2010) and Kushnir et al. (2013), and indirectly in King's (2012) dissertation showing that children (5-12 years old) do not discriminate letters (lowercase script) from their mirrors in the same way as adults (18-26 years old).

3.3. Implicit learning of the right orientation

While I had already directed several psychology student master's dissertation on mirroring digits, I proposed to two students to observe the reversal of capital letters in kindergarten, mainly with the aim of ordering the letters according to their frequency of reversal (Fischer, 2010b). They returned, disappointed by their observations in two classes, because the children had basically only reversed two letters! These letters are precisely those that have a special status in the evolution of our alphabet: they are the letters J—the medieval addition— and Z—an intrusion from archaic Greek (or even Phoenician)—which we have already encountered. Could these additions to our alphabetic system be at the origin of the difficulties of its appropriation by children, just like the difficulty caused by the intrusion of the base 20 in the French decimal system (e.g., eighty, literally translated “four-twenty”, that French children readily write 420)? Since these letters, J and Z, unlike the many letters with a hasta + coda (right) structure, look to the left, a simple but appealing hypothesis was that children implicitly learn that the letters look to the right and, when they write them, make them all look to the right, leading to the reversal of only the letters J and Z. This may explain why the reversal frequencies, reported graphically in Fischer (2011), show a percentage of reversal around 50% for J and Z, while the percentage of reversal of no other letter reaches 20%, most of the latter percentages being even below 10% (see also Fig. 35).

During the last decades of the 20th century, implicit learning was an active research topic. I was involved in some of this with research on implicit learning of an artificial grammar and time prediction (Fischer, 1997, 2000). In particular, learning an artificial grammar, evaluated by a grammaticality judgment, was seen as a near-optimal technique for achieving implicit learning (Reber et al., 1991). This form of learning is characterized by the detection and preservation of invariants. It consists in extracting invariance from environmental stimuli over many occurrences. Children have powerful implicit learning mechanisms, from a very early age (Meltzoff et al., 2009), including in the motor domain (Perruchet & Vinter, 2002). They could therefore extract, from their encounter with capital letters, the idea that they are right-facing.

The overwhelming reversal of only the non-right-facing capital letters thus supported a hypothesis of implicit learning of their right orientation and of systematic application of that orientation.

The hypothesis that an implicit bias might be behind children's reversals of characters, also fits the phylogeny of the notion of implicit bias as described by McNutt (2016). According to this author, implicit bias is embedded in human DNA and we all have it. Implicit bias was indeed the shorthand that allowed our distant ancestors to make split-second decisions (friend or foe?) based on incomplete information. It provided a reaction time advantage that could mean life or death. Implicit bias is, by definition, subconscious, making it an easy issue for the child to overcome or not realize. Researchers who have actually observed children have pointed this out in various terms. In particular, Lévy (1935) observed that the reversed image of an already known graphic sign does not shock most children very much since, in the presence of its reversed form, they always call it by its primitive name. He continues, "Simply ask a whole class, even in the second grade: 'What is this?'—showing them one of these last three signs (**A**, **Э**, and **Е**)— and they will answer without flinching: 4, E, 3." (p. 448). I myself have sometimes referred to "bootstrapping" in connection with the mirror writing of a character. Bootstrapping, used as a verb, means to help oneself, often by improvised means, and, used as an adjective, can describe a process that is self-initiated or self-sustaining, and undertaken or accomplished with minimal outside help. And the result of this bootstrapping, even if it is mirrored, does not shock the children at all. I remain marked by one of my observations in a GS kindergarten class where I tested the pupils in groups of 4. In the room adjacent to the classroom, I had arranged 4 well-spaced small tables/chairs in a square. To avoid copying as much as possible, I placed myself in the center of the square. When I gave the instruction "Write a three!", I saw, almost in the next second, four **Es** appear! As a researcher, I was delighted to have had such an experience, but the teacher, whom I admire because she manages a class of more than 30 children, looked a little defeated when I told her that more than 80% of her pupils had reversed the writing of 3. She commented, in the words of the French education system: "I thought that was acquired". Why then abandon this explanation of mirror writing based on the implicit learning that the letters would all face to the right?

A first reservation regarding such an explanation could have come from the empirical observation of the frequency of reversal of J and Z. Indeed, the most reversed letters J and Z are also infrequent letters. Although involving artificial characters (but letter-like), data from the experimental study by McIntosh et al. (2018a) removed such an objection. McIntosh et al. taught 43 Scottish elementary school children (ages 4.8 to 5.8) four artificial letter-like characters, two of which were left-facing and two of which were right-facing. The characters were novel and therefore not subject to prior exposure effects as letters or numbers can be. Groups of children were assigned to sets of identical but mirror-reversed characters. After learning, the authors found that children were three times more likely to mirror a character when they learned it in a left-facing format than to mirror a character when they learned it in a right-facing format. Thus, the lower frequency of the letters J and Z does not appear to be the primary explanation for their reversal.

A second reservation stems from the fact that, until now, the focus has been on upper case letters. But children are also exposed to lowercase letter and number scripts. Lowercase letters do not support this second reservation. Although they are slightly less frequently oriented to the right (d, g, j, q, y are oriented to the left), they could still contribute to the implicit learning of

orientation to the right. In contrast, of the eight reversible digits, a majority—the five in the set $DI = \{1, 2, 3, 7, 9\}$ —are rather left-oriented which should complicate, if not prevent, the implicit learning of a rightward orientation of the characters.

A third reservation, comes from a fine-grained study of the implicit learning mechanism due to Branigan and Messenger (2016). The hypothesis that children see many right-facing letters and generalize, by induction, that all letters are right-facing is certainly plausible and consistent with the child's reasoning. However, Branigan and Messenger's experiment highlights implicit learning that is based on error and leads us to be wary of the convincing simplicity of such a hypothesis. In this experiment, children, on average 4 years 2 months old, described transitive events (e.g., Dog pushing fireman), immediately preceded by a description by the experimenter in either active (e.g., The sheep is lifting the witch) or passive form (The witch is being lifted by the sheep), in two image association games, organized one week apart. The demonstration of immediate facilitation for the passive structure supports an error-based learning mechanism. Since the children were equally exposed to the active and passive forms, the authors see this as confirmation of the hypothesis that learning is based on prediction error: each occurrence of the infrequent (and therefore unexpected) passive form leads to a significant adjustment of the implicit knowledge system, whereas each occurrence of a very frequent active form has little effect. This raises the question of the role the letters J and Z, in addition to all the symmetrical letters, will play in the statistical learning of right orientation of the characters.

These reservations may seem slight, even irrelevant for part of them. But the reservations about statistical learning in the next section, which are more profound and even prohibitive, also apply, for the most part, to the implicit learning of right orientation and its systematic application as an explanation of reversal. The abandonment of this explanation is therefore justified.

3.4. Statistical learning of the right orientation

Statistical learning involves detecting distributed information and discovering underlying patterns. On a first approach, it can be considered a form of implicit learning. For nuances, I can refer to Bertels et al. (2012) and Perruchet and Pacton (2006); for a discussion of its validity, Erickson and Thiessen (2015), and its relationship to explicit learning to Fischer (2000), Pavlidou and Bogaerts (2019), and Spencer et al. (2015).

Among the results of the many studies on statistical learning, it is worth noting that powerful statistical learning abilities, at least for spoken language, were observed by Saffran et al. (1996) at 8 months of age. In addition, it has recently been shown that statistical learning can involve involuntary attention in a paradoxical manner (Schneider et al., 2022). While neural adaptation to local, transient distributional information is automatic, computing global distributional information over a continuous stream of stimuli may involve an involuntary shift in attention, a process likely deployed by the most successful statistical learners.

In the case of writing, whether correct or in mirror, the statistical learning hypothesis states that children statistically observe that letters look to the right and then orient them all to the right. This hypothesis is not very different from the implicit learning hypothesis. It is simply that mathematical modeling requires statistical details about the material. It was perhaps Simner (1984) who was the first to explain the reversal of left-oriented letters by such statistical learning. But, like Mr Jourdain who was making prose without knowing it (in Molière's "Le

bourgeois gentilhomme"), he described the latter without naming it. He noticed that in the English alphanumeric series there are more letters and digits facing to the right. He indicates that the right-facing letters are more numerous in a ratio of two to one. Note—and this is one of the weaknesses of this theory—that Simner is careful not to specify this ratio (in disfavor of right-facing) for digits. Simner then proposes that children pay attention to orientation when scanning alphanumeric characters and that during the scanning process they become aware of the much higher frequency of right-oriented letters. A speculative version of statistical learning, perhaps involving more awareness, has also been discussed by Simner, followed by Lane (1988) and Richmond (2010). The latter states, regarding for example the letters 'd' and 'q' that "if a child capitalises on the odds of being correct, they will naturally choose to put the distinctive feature on the right, resulting in the reversal of letters facing the left" (p. 56).

This statistical learning theory was later defended by Treiman et al. (Treiman & Kessler, 2011; Treiman et al., 2014). The statistical learning hypothesis is very similar to, if not confounded with, the implicit learning hypothesis because it is difficult to understand how children could implicitly observe rightward orientation if there were not more letters looking to the right than those looking to the left. Both of these learnings have their own theorists, but the "baby statistician" (translated title of Stanislas Dehaene's 2013 course at the Collège de France) is probably more appealing than the "baby implicit learner"! I prefer the implicit qualification, however, because it implies that there is another and, more importantly, better (explicit) learning, since implicit learning can have failures. For example, English psychologists or psycholinguists have much studied the development of the past tense of irregular verbs, children who say "goed, breaked" instead of "went, broke". The "implicit" characterization of learning allows for the inclusion of such pseudo-empirical generalizations that are not accepted in mathematics (Fischer, 2013b), and that a statistician should therefore not make.

Why have I definitively abandoned this statistical learning hypothesis? I will not go back to my slight reservations about implicit learning, which also apply to statistical learning when the latter is seen as a form of implicit learning. Whatever its name, statistical or implicit, this form of learning, if one wants to see it as the origin of reversals in children's writing, leads to a major objection: when children write from right to left, they do not in general reverse the left-oriented letters but, on the contrary, the right-oriented ones (see Section 6.4). The decisive nature of this objection was not escaped to Portex (2017) and Meletis (2020). In particular, Meletis has pointed out, in the evolution of my writing, the shift from a rule of writing (or better: orienting) to the right to a rule of orientation in the direction of writing. This evolution seems important to me. Certainly, a rule of orientation to the right seems valid in our culture, and in Western cultures more generally, but it does not draw attention to what is important, namely the direction of the writing (and not the right, or the left in other cultures). It is worth noting, however, that this abandonment is not about statistical learning itself, but about its ability to explain the reversal of characters by children. In the area of literacy development statistical learning can indeed play an important role. Yin and McBride (2015) show, for example, that young Chinese children detected regularities in written Chinese before they were formally taught about it and that it may result from early statistical learning.

3.5. Priming through the previous writing

In priming, the writing of the preceding character facilitates the occurrence of certain behaviors in the writer, by causing a "switching on" of the neural networks associated with movement

(cf., Desmurget, 2006, p. 23). It is thus possible that motor priming, due to the writing of the previous 6, is at the origin of the incorrectly oriented upper loop of the 3 in Figure 12. Several examinations of the writing of series of characters, collected in Figure 16, also support this hypothesis.

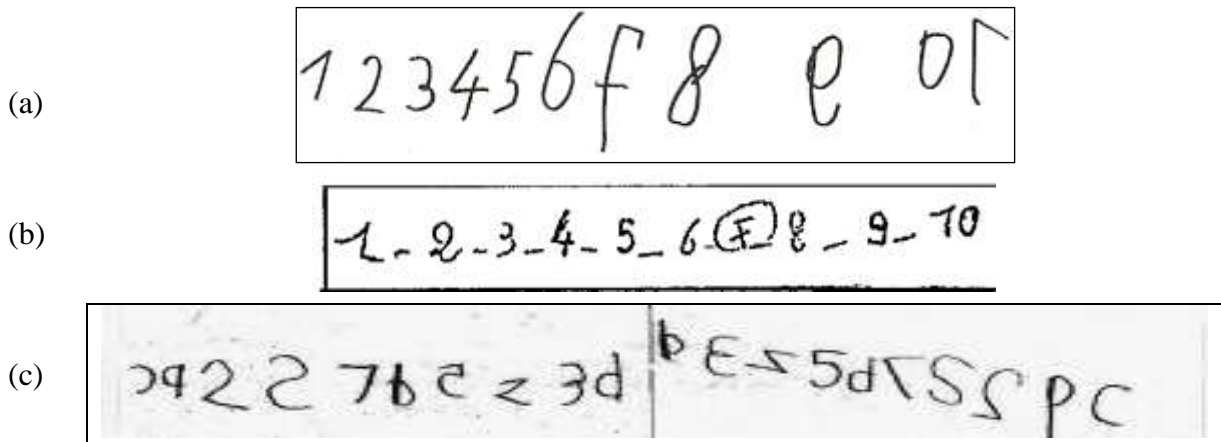
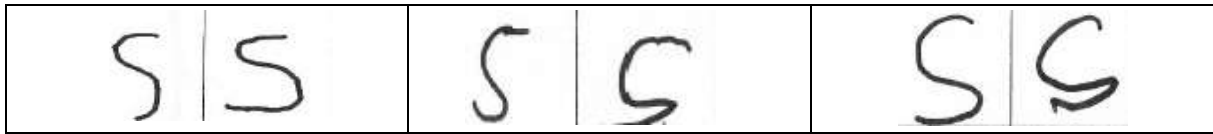


Figure 16. Character series written (a) by a left-handed first-grader (reproduced from Lebrun, 1990, Fig. 2, p. 178), (b) by a left-handed 9-year-old boy who cannot read: the mirrored 7 has been circled (reproduced partially from Meljac, 1994, p. 168), (c) by Tenneson (reproduced partially from Mather, 2012, Fig. 1, p. 175).

The writings of the sequence of first numbers, reproduced in Figures 16a and 16b, show that the two students concerned have written the 7 towards the right, in mirror image. However, the 7 comes immediately after the 6, the most clearly right-oriented digit. The first student then systematically reversed the reversible digits, while the second student returned to the correct orientation after the 8. If one sees in this illustration a confirmation that mirror writing concerns mainly left-handed children, I can repeat that for more than a century mirror writing has been attributed almost exclusively to left-handed pupils; therefore it is not surprising that one finds an over-representation of reproductions of mirror writings by left-handed children. In addition, the handwriting of the second student, older than the typically developing children primarily discussed in this essay, will later be interpreted as a confusion (with the letter F) rather than a reversal. The third writings (in Fig. 16c), are those of Tenneson, a Canadian 1st grade student tested by Mather (2012). This student was encouraged to write the series b, 3, z, 5, d, 7, s, 2, p, c, in upper or lower case, starting once from the right and once from the left of a midline. Its writings, reproduced on the right and left sides of Figure 16c, respectively, illustrate a possibility of priming in several passages, especially the writing of 2 after S. The loops, usually initial, of the 2 and the S are almost identical as long as one of the two characters is reversed. Thus, when following a correct S (right side of Fig. 16c), the 2 could be negatively primed and thereby reversed; but, when following a reversed S (left side of Fig. 16c), it could be positively primed and thereby written correctly.

In one of my series that I dictated to 356 children aged 5 to 6, they had to write normally, i.e. from left to right, a series where 2 followed S. I then observed a quantity of either **SS** or **22**. Figure 17 shows some of them.



a) Reversed writing of 2 after a correct S



b) Correct writing of 2 after a reversed S

Figure 17. The writing of 2 after S in the dictated series: R, E, 3, D, 8, 6, J, S, 2, 9, Z. [Data from Fischer & Tazouti (2012), Expt 2].

Yet, Tenneson's writing can also be explained if we assume that he oriented the letters in the direction of writing. In the right-hand series, i.e., when he wrote towards the right, all characters facing right are written correctly (b, 5, s, p, c), and all those facing left are reversed (3, z, 7, 2), except d. In the left-hand series, i.e., when he wrote towards the left, all characters facing left are written correctly (3, z, 7, 2), except d, and all those facing right are reversed (b, 5, s, p, c). Very speculatively, I propose that the exception of d is due to the presence of b at the beginning of the series: Tenneson would simply have avoided reproducing the same writing. This possibility of explaining almost all reversals by a rule of character orientation in the direction of writing justifies (in part) my abandonment of an explanation by motor priming.

A secondary statistical result also supported the possibility of motor priming of single-digit writing by the previous writing. In GS kindergarten, I had indeed observed that 67.50% of the children who reversed 6 wrote 3 correctly immediately afterwards, against only 52.25% of those who wrote 6 correctly (Fischer, 2010a). This marginally significant observation was surprising because one would expect that a child who tends to mirror 6 is more likely to also mirror 3 than a child who shows no tendency to mirror 6. Yet, from a motor point of view, it was plausible because the specific motor gesture involved in writing 6 (large open loop to the right) could have favored the misorientation of the loops of the following 3, whereas the specific motor gesture involved in mirroring 6 (large open loop to the left), could have favored the correct orientation of the loops of the following 3. But, like Tenneson's explanation of reversals, one can assume that a child who mirrors 6 does not apply the rightward orientation rule and thus will not reverse 3 (because of this rule anyway), whereas a child who writes 6 correctly is likely to use the rightward orientation rule and thus will be found to reverse 3 (because of this rule).

This hypothesis led me to systematically study the relationship between the reversal of a digit and the status—correct or mirrored—of the writing of the preceding digit on 367 GS kindergarten children (Fischer, 2013a). The results seemed, at first glance, to clearly confirm the priming hypothesis. Notably, after a correctly written 6, children reversed the following 3 in 68.4% of the cases, whereas, after a mirrored 6, they reversed the following 3 in only 17.8% of the cases. This result does not mean, however, that direct priming from the previous digit is the only cause of the reversal of the current digit.

First, empirically, I observed that when there is no digit immediately before the digit to be written (at the beginning of the series: children responded to 4 series of 10 digits), the frequency of reversal is as high as in the whole sample of writings. Second, and more importantly, a

methodological problem prevents a direct causal interpretation of the influence of the previous writing. Indeed, the fact that a child is included or not in the group of children who have reversed the writing of the previous digit, is the result of all his previous writings (including past writings, outside of the experiment), and even more generally of his state at the time of writing. Therefore, children who have reversed 6 (for example) may have something else in common that differentiates them from children who have written 6 correctly. This "something in common" may be the strength of representation or activation of an implicit rightward orientation rule. Thus, it is not necessarily the previous writing of 6 that would explain the reversal or not of the following 3: if the child has a strongly activated rightward orientation rule in his implicit long-term memory (I repeat, because it is important: not necessarily, if at all, by the previous writing alone), he will reverse 3 whatever the writing of the previous character.

The latter explanation is appropriate for the set of reversals observed, analyzed in terms of previous writing, in this research (Fischer, 2013a). For example, after 2 written correctly, only 12.7% of children reversed the following 7, whereas, after a reversed 2, 80.5% of children reversed the following 7. This result is not surprising when we know, as we have seen, that 2 and 7 both face left: children, who would not have memorized the correct writing in explicit memory and would apply a rule of orientation to the right, a rule strongly activated in their implicit memory, will write the two digits in mirror. Conversely, if children do not have a strongly activated right orientation rule (or even if they have a strongly activated left orientation rule), they will have a good chance of writing these two digits correctly. This explanation is also appropriate for a particular observation reported in Fischer (2011, Table 1). In this research, 5- and 6-year-olds were asked to write 3 preceded by B. We can now see that B contains a vertical line as hasta and the digit 3 as coda, on the right. As B was correctly oriented by more than 95% of the children, the following digit 3 could have been positively primed. However, this was not the case. More than 65% of the children who had correctly oriented B nevertheless reversed 3, while less than 10% of the few children who had reversed B, and thus could have been victims of negative priming, reversed it!

In conclusion, I no longer adhere to this hypothesis of direct priming by the just preceding writing, even if I do not totally reject the idea of motor priming, such as the misleading priming of 3 by 6, or of 2 by S, that I described earlier. More generally, this discounting of motor priming complements well the thesis, supported and argued subsequently, that the motor component of writing is not fundamental to the causal explanation of the mirror reversal of characters.

Since one should always learn from one's mistakes, I would like to emphasize again this general methodological problem that arises as soon as one creates subgroups from the current observation, as opposed to subgroups created prior to the observation (e.g., by gender or socioeconomic category). This problem is pervasive in the scientific literature. With the Coronavirus pandemic, it was found in the research on chloroquine by Mehra et al (2020). This research has been the subject of much publicity and has been the subject of much political and journalistic excitement, until it was finally withdrawn by *The Lancet* journal which had published it. I am not talking here about the possible fabrication of the data by the Surgisphere company, which would be so grotesque that it is not worth discussing. I am talking about the methodology of the data analysis used by the authors. They presented, in terms of survivors and non-survivors, the results of four types of treatment: (1) chloroquine alone, (2) chloroquine with macrolide, (3) hydroxychloroquine alone, or (4) hydroxychloroquine with macrolide. The methodological bias here is that patients were not randomly assigned to the different treatments.

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Instead, there is reason to believe that patients assigned to one type of treatment already had "something in common" that they do not share with those assigned to other types of treatment. For example, having (on average) a more or less severe form of the disease, before this assignment to a type of treatment. So it is not necessarily because they were given a certain type of treatment that they died more (or less) frequently, but possibly because they were more (or less) ill before the treatment! It is astonishing that the "experts" of a highly reputable medical journal—*The Lancet*—failing to see that the data were wrong or falsified, did not see this methodological error. Once *The Lancet* had expressed concern about the Mehra et al. research, I was curious to see if other experts, interviewed by ScienceMediaCenter, saw this gross error. Of the five (exclusively English) experts interviewed, only one—Martin Landray, Professor of Medicine and Epidemiology at the Nuffield Department of Population Health, University of Oxford— pointed out, without more, the methodological error: "Patients who receive a particular drug (in this case, hydroxychloroquine) are different from those who do not receive it"⁷.

⁷ Retrieved (June 21, 2020) from: <https://www.sciencemediacentre.org/expert-reaction-to-expression-of-concern-on-study-on-hydroxychloroquine-and-chloroquine-in-covid-19-patients/>

4. Some salutary clarifications!

4.1. Attention is not the problem

One explanation for the reversal of characters, especially of a single character, that comes almost immediately to mind is that of inattention. Among the thoughts on the causes of mirror writing, attention was indeed presented, as early as 1893, as the main cause by Treitel (cited after Lochte, 1896). For Heller (1904), when a child repeats with the left hand the writing movements he has learned with the right hand, in the sense of mirror writing, this should be taken only as evidence that he offers no resistance to the initial tendency of symmetrical repetition of the writing movements with the right hand. To resist this tendency requires a higher degree of attention that normal school children do not yet have. Fuller (1916) tried to induce what he called abstraction, but which can be considered a diverting of attention, by mental arithmetic or crystal viewing. This experimental diverting resulted in 30% immediate mirroring (out of 90 usable writings) with the left hand in 15 normal adult persons. Such observations predict an increase in mirror writing when attention is weakened. But it should also be noted that although these findings fit well with the tsunami of left-hand writing (see Section 1.2), they do not specifically inform us about the role of attention in typical children writing with their usual hand.

Much more recently Levy and Young (2016) retrospectively studied letter reversal in more than 1,000 children with potential attention deficit hyperactivity disorder (ADHD), a concept that entered the Diagnostic and Statistical Manual of Mental Disorders in 1994. They noted the maximum age at which reversals still occurred, as well as the laterality of the children, and measured their response time to a task of locating (or not) one letter among 20 others. They obtained, for both boys (much more in the sample) and girls, a significant effect of reversal age, but not of laterality. It is however essential to see that the reversal of characters that they observed is a "static reversal"—one is close to an oxymoron!—which concerns the reversal of the only reversible letters: b and d, p and q (Furness, 1956). The way in which the maximum age of reversal was determined, namely by the report of mothers who were given the example of the reversal of b and d, and the age itself—most of the children were over 6 years old—suggest that static reversal would be better termed confusion (see Fischer & Luxembourger, 2022). In any case, the reversal in question is not a reversal in the course of writing.

We examined the impact of attention in an initial study involving a large number of typically developing children. This number had to be substantial because it is known in statistics that the absence of an effect with a small number of children does not demonstrate much. With my Master's students in psychology, we therefore tested several hundred pupils in two experimental conditions: in one, attention could be concentrated on writing (full attention condition), in the other, it had to be shared with another intellectual activity (divided attention condition). Our hypothesis was that the latter would increase the percentage of mirror writing. In first grade, the children had all nine digits (all digits except 0, the symmetrical digit 8 not being taken into account in the analyses) to write in a 3 by 3 grid. In the full attention condition, the children simply had to write the dictated digits in a non-natural order in the successive boxes. In the divided attention condition, they had to write the one-digit numbers as the result of a calculation. For example, to write 7, they were asked to write the result of $5 + 2$.

In GS kindergarten, the full attention condition was identical to that in first grade. In the divided attention condition, children had to write the digits in a specific box of a double entry table

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indicated by its row and column headers by the experimenter. The experimenter asked, for example, to write 7 in the red flower box (see Fig. 18).

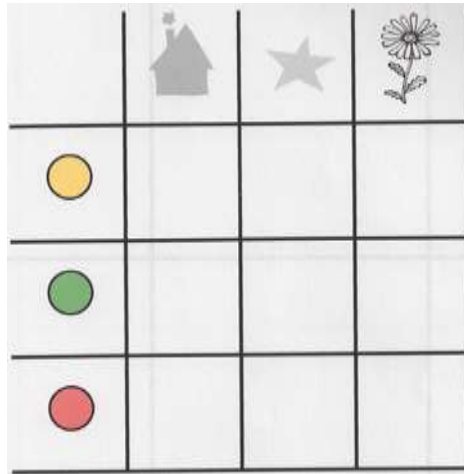


Figure 18. The double entry table used in GS kindergarten for writing digits in a divided attention condition (compared to simple writing in a grid), used in Fischer's research (2010a).

Our initial hypothesis was not confirmed at all: no significant difference between these two conditions in the percentages of mirror writing was observed, neither in kindergarten GS, nor in first grade. In GS kindergarten, children even produced slightly fewer reversals in the divided attention condition! Why did a common sense prediction, that a task in which the child does not allocate all of his attentional resources to writing should increase reversal errors, not hold true? The result of our comparison then helped to maintain the mystery with which mirror writing has often been surrounded, a mystery not entirely usurped since the children produce a writing that no one has ever taught them and that they can hardly have seen.

4.2. Copying and writing from memory are two different tasks

At the beginning of learning to write, children process letters and Arabic digits as pictures. Moreover, by age 5, the Visual Word Form Area (VWFA)⁸ brain area shows identical responses for letters and digits, although faces and letters are already dissociated there (Hannagan et al., 2015). Also, research by Bulthé et al. (2014, 2015) shows there is no overlap in activity between Arabic digits and the dot collections they may represent in the adult intraparietal sulcus (IPS), a brain region that has often been proposed as the central area for abstract representation of numerical quantity. Such results suggest that Arabic digits should be processed as image cognition. In children aged 7 or older Fastame (2020) further showed that simultaneously active visual/spatial working memory processes play a different role in conducting the copying of a geometric pattern than in drawing it from memory. But this does not seem fundamental for our character reversal problem. Not so much because of the age of the participants, but because, in our case, the difference is a truism: in copying, children can reproduce the correct orientation (since it is in front of them), whereas, from memory, they cannot reproduce the correct orientation (since it is not there: see next).

⁸ In this text, I use only the concept of VWFA, although areas of letter shape (Thesen et al., 2012) and number shape have also been distinguished (see the meta-analysis of Yeo et al., 2017, and, subsequently, Grotheer et al., 2018; Vatansever et al., 2020). These latter areas may seem more suitable for thinking about character writing. But their existence and definition, a fortiori their development, seem to me insufficiently well established to refer to them.

Lucy Fildes (1923) was one of the first researchers to test whether children also make reversals by simply copying characters. Yet, first, in Experiment 5 of her research, she studied the question with shapes. Then, in her Experiment 6, she compared writing digits and letters by copying versus writing from memory. Her result was particularly clear: the 32 typically developing children, between 6 and 7 years of age, made only 1 and 0 orientation errors when copying letters and digits, respectively, compared to 22 and 4 in free reproduction (Fildes named her column heading as such, but does speak of writing "from memory" in the text). The 25 deficient children, of the same age, who were compared to them did not do more orientation errors in copying, and even less in writing from memory. Fildes explains this last curious observation by the fact that deficient children did not have the stage of incomplete familiarity associated with orientation errors. But Fildes does not emphasize the difference between copying and writing characters from memory (Expt 6). In fact, Fildes even seems to regret this success of the students in copying. She notes that they copied all of the letters of the alphabet and digits as they were presented and that "it is doubtful whether these children really understood what they had to do" (p. 65), ignoring or forgetting thereby that her own instruction asked nothing more than to copy! As a result, she prefers to emphasize that orientation errors occur both in copying the shapes and in reproducing them from memory (Expt 5). It is therefore less surprising that Orton would have been misled by his reading of Fildes (see section 1.6). Especially since this misreading supported his theory that reading and writing belong to the same process of reversal.

Orton (1925), as we have just seen, referred extensively to Fildes' research. But, subsequently, many researchers "forgot" this research of Fildes which shows a major difference between copying characters and writing them from memory, thus making their mixtures of copying and writing from memory difficult to interpret. We ourselves, without reference to this research of Fildes but rather because the children of MS kindergarten were not yet all able to write the digits from memory, compared GS kindergarten children writing the digits from memory with MS kindergarten children copying them from a model (Fischer & Tazouti, 2012, Expt 1b). The result surprised me at a time when I had not yet integrated Fildes' observation: the children of MS kindergarten produced fewer orientation errors than those of GS kindergarten! But the MS and GS kindergarten studies had not been planned for comparison and did not involve the same children. To remedy this problem, Fischer and Tazouti (2012, Expt 1a) included in a more general level test at the end of kindergarten a test where the same students copied and wrote letters and digits from memory. For reasons of test duration, only 8 uppercase letters were included in the test. About half of the students copied these letters and wrote the 8 reversible digits from memory, while the other half copied the digits and wrote the letters from memory. At the time, I was most interested in the correlation between the two types of writing: did the children preferentially reverse the same characters (e.g., the digit 3, the letter J) when copying than when writing from memory? One day during the summer vacations, when I took the opportunity to analyze the results of the test conducted at the end of the school year, I was extremely disappointed by the results because the calculation of the correlation coefficient made little sense: the students had made practically no mistakes when copying!

Simner (1984) studied the writing of 40 characters (N analyzed separately) by right-handed children of three age groups of 4.9, 5.8, and 6.7 years on average. This was a writing from memory task, but after an exposure of the character for 2.5 s. Thus, the task was much closer to copying than to writing under dictation. We are therefore not surprised by the few proportions of reversals that he obtained, .05, .02, and .00, respectively. Not only do children make few

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reversal errors when copying, but research by Maldarelli et al. (2015), using eye-tracking technology, showed that kindergarteners' visuo-motor coordination process was as efficient as adults' when copying individual letters.

In MS kindergarten many children (general population) have not yet memorized the writing of the characters. Therefore it is difficult to study statistically the reversals during writing from memory. This led us, in the longitudinal study that Anne-Marie Koch was planning for her thesis, to make MS kindergarten children copy the same characters (digits and capital letters) that they were then going to write by memory in GS kindergarten and again in first grade. Although children were recruited from a socioeconomically disadvantaged district, we predicted few reversals in the copying task in MS kindergarten compared to reversals in the writing from memory task in GS kindergarten. The result confirmed the prediction: children produced significantly fewer reversals of the characters in MS (about 3%) than in GS (about 21%) kindergarten; the number of children who produced at least one mirrored character was significantly lower in MS (76 out of 166, or 46%) than in GS (154 out of 166, or 93%) kindergarten.

4.3. A problem of memory, not of perception

The previous observations—the near absence of reversals when copying models and the increase in reversals when children begin to memorize the scripts—constitute a strong and almost sufficient argument to claim that children perceive characters well visually (unless they are visually impaired of course). Nevertheless, these observations need to be placed in a more general framework. The importance of the distinction between perception and memory appears in research on face processing. Thus, a comparison of the rate of development of discrimination versus memory of faces (adult, human), from 5 years of age to adulthood, suggests an early maturity for face perception and a late maturity for face memory (Weigelt et al., 2014).

Half a century ago, the observations of Ray and Joan Over (1967) had already drawn attention to this dissociation in children. Over and Over tested 4- and 6-year-olds in two conditions: one of detection, the other of recognition. In the detection condition, two plaques, with respectively the oblique / and the oblique \, were presented below a third plaque, with either the oblique / or the oblique \, and designated as the correct one. The child had to choose the correct one between the two plates below. In the recognition condition, only the two plates with the oblique / and \ were presented, the child's task being to designate the correct one. In this second condition, it was the feedback from the experimenter that allowed the child to recognize the correct oblique in the following trials. The results show that thirteen 4-year-olds (out of 16) and four 6-year-olds (out of 16) failed in the Recognition condition, while only four 4-year-olds failed in the Detection condition (none 6-year-olds). Ray Over (1967), in an article in *Nature* referring to this research, comments: "The child perceives that mirror image obliques differ in orientation, but seems unable to remember from trial to trial which is the 'correct' oblique" (p. 1272). This is probably what happens with characters as well: the child does distinguish N from **И** but is unable to remember which is the correct writing of N (unless given a mnemonic, as many teachers seem to do: "up, down, and back up").

On the basis of other observations, Bryant (1969, 1973) admittedly interpreted this result of Over and Over differently. In particular, Bryant showed that two non-mirrored obliques are just as confused as two mirrored obliques by 4-7 year olds. However, in his Experiment 1, Bryant (1969) found that children, 5 years 3 months old on average, succeeded in the choice between

an oblique line and its mirror in a simultaneous presentation, but responded randomly when the choice was proposed 5 s later. In regard to these simultaneous comparison successes and delayed comparison failures, Corballis and Zalik (1977) concluded that what is clear from Bryant's results "is that the difficulty of discriminating mirror-images obliques is a problem of memory rather than of perception" (p. 516). Infants confirm the perceptual facility of discriminating mirror images, since at the age of 3 to 4 months they already seem to discriminate such images, although they tend to consider mirror images as equivalent stimuli (Bornstein et al., 1978).

Subsequently, some authors have also emphasized this difference between perception and recognition in memory. We are thinking in particular of Corballis and Dehaene, whose theories we analyse at greater length in sections 5.1 and 5.2, but also of Lachmann and Geyer (2003) who wrote, forcefully, that "mirror-image generalization describes an effect of memory formation and not of perception" (p. 57). Indeed, it is presumably the process of mirror generalization (see Chapter 5) that accounts for the non-recognition of the "correct" oblique in Over and Over's (1967) observation.

Recent indirect support for the hypothesis that confusion occurs in memory, rather than during visual perception, comes from the original data of Gregory et al. (2011). These researchers asked their participants—children aged 4 and 6 and adults—to match objects with different orientations to a target object. The three types of errors made by participants are illustrated with the example of a key in Figure 19.

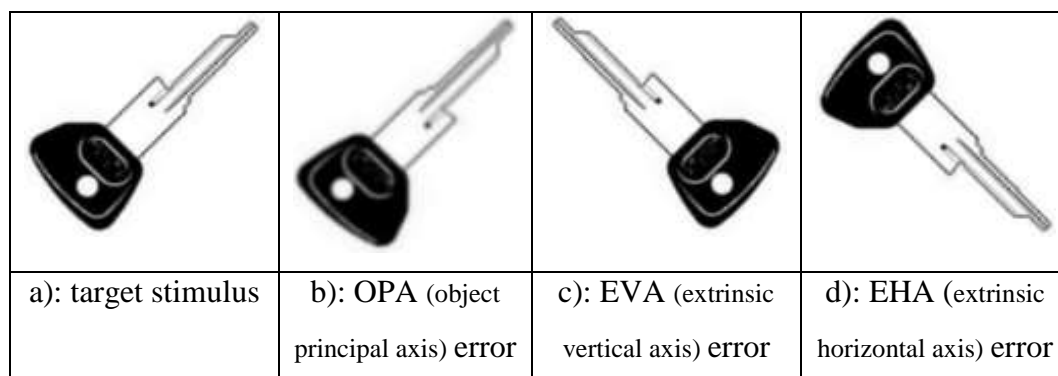


Figure 19. Three types of matching errors produced by participants in the Gregory et al. (2011) research.

The data allow us to test the hypothesis of a memory versus perceptual origin of the confusion between an image and its horizontal mirror image (symmetrical with respect to a vertical axis). To do this, we compare the results of Experiments 1 and 2 of Gregory et al. In Experiment 1, the orientation matching task made minimal demands on memory. On each trial, a target image was presented and remained visible while the child tried to find the image with the same orientation in a forced-choice test array. In Experiment 2, the memory demands of the task were increased by removing the target stimulus on each trial before presenting the forced-choice test array. A hypothetical consequence of this difference between the tasks, and of the hypothesis of the memory origin of mirror-image confusion, is that the less memory-demanding task in Experiment 1 will generate a lower proportion of EVA (horizontal mirror with our usual denomination) errors than the more memory-demanding task in Experiment 2. The analysis restricted to oblique stimuli (like the one in Fig. 19) indeed shows that the ratio between the

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number of EVA errors and the number of OPA errors is significantly lower in Experiment 1 than in Experiment 2.

The fact that mirror reversal is not a perceptual phenomenon has also been demonstrated on adults. Kolinsky et al. (2011) were able to compare illiterate, ex-illiterate, and normally schooled adults, all of whom were native speakers of Portuguese. The illiterate and ex-illiterate participants had never attended school in childhood, for socioeconomic reasons, with the exception of a few participants. No illiterate participant was able to read simple words, most were unable to sign their own name. The ex-illiterate participants learned to read and write in special alphabetization classes for adults that they attended under pressure from their environment (e.g., when enrolled in the army or because their employer insisted on it). Like illiterate people, they were working as farm workers, shoemakers, masons, or maid with the others being retired or unemployed. The finding of Kolinsky et al. is clear: Educated (i.e., reading) individuals diverge from illiterate individuals in enantiomorphy—the ability to discriminate lateral mirror images—at a later, post-perceptual representational level. Therefore the enantiomorphy deficiency is not an input coding problem.

4.4. The form of the characters is memorized early

It is important, because so far the question has not been addressed, to recall that in order to reverse the characters, children must already have memorized the form of the characters (without their orientation). For example, that 3 is formed by two loops, one above the other. Is such memorization of form within the capabilities of a 4 or 5 year old?

The German psychologist William Stern, best known for having the idea of relating mental age to chronological age, which gave the mental quotient and later the intelligence quotient, considered the apprehension of form to be an almost innate behavior. Downey (1914) quotes in English one of his German papers in which he wrote: "There exists in the child a perception of form with an apparent indifference to position that seems to indicate that while form is nativistically determined, perception of position is an outgrowth of experience" (p. 417). Stern (1927), also in German but translated by me here, wrote: "Normal behavior in natural life undoubtedly implies that the little child pays very little attention to color when recognizing objects, whereas he immediately identifies a characteristic form, regardless of the difference in color" (p. 372) and notes that other child development specialists are also convinced of the pre-eminence of shape. In Figure 20, I report one of the experiments summarized by Stern, the material of which is similar to writing characters. The 851 children were first asked to identify the two identical images in the two groups of two above; then they had to find this identical image, which looks like a reversed 3 in this example, among the 10 presented below in Figure 20. Despite the complexity of the task, successes increased considerably between 4 and 5 years, from 7% to 25%.

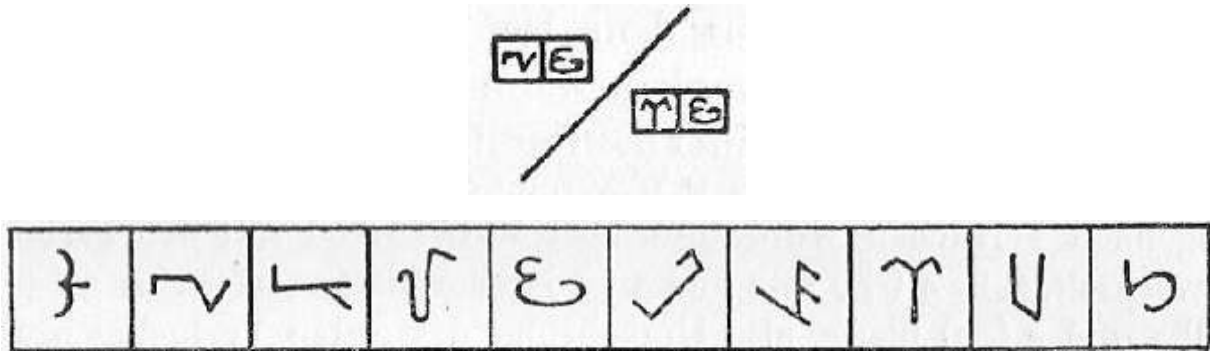


Figure 20. Material from a graphics identification experiment reported by Stern (1927, p. 375).

Form, as the preferred dimension of the very young child, was confirmed in the experiment of Brian and Goodenough (1929). They tested 474 participants, ranging in age from under 2 years to adults, with a matching task of solids or geometric surfaces of different colors. Matching could be done either by form or by color, but never by both simultaneously. Form is preferred over color in children under 3 years of age. Color is preferred over form by every half-year age group between 3 and 6 years. By age 6, form again becomes the predominant factor in this situation, and the proportion choosing form over color increases steadily from age 6 to adulthood. Between the ages of 2 and 2 ½, choices based on form (84%) overwhelmingly dominate those based on color (16%). If we only look at surfaces, this preference is even more impressive: 97.7% of the choices between 2 and 2 ½ years old are based on form against only 2.3% that go to color!

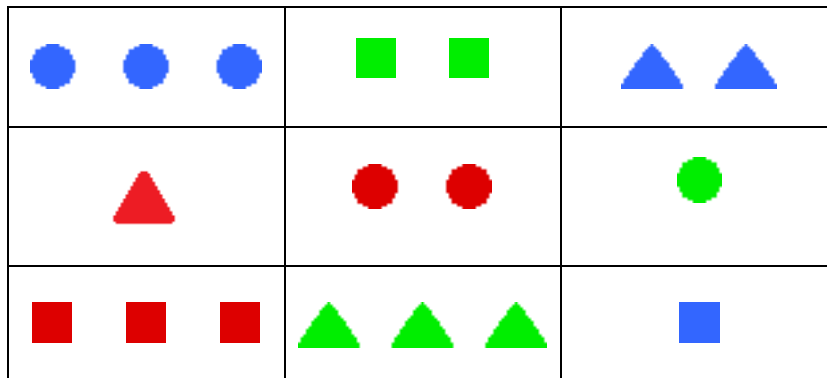


Figure 21. The 9 cards, representing the small collections, to be sorted (free criterion) in Fischer (2004); the large collections were analogous but contained 4 to 6 elements (always aligned and regularly spaced).

I was able to verify, at an age when children seem to be more attracted by color, that form remains a criterion that is not totally neglected (Fischer, 2004). In a free sorting task, the children were asked to put together cards (see Fig. 21) that they thought went well together. At all ages tested, 4 years, 4 ½ years, 5 years, and 5 ½ years, at least a quarter of the children marked a preference for form, despite the appeal of color and the appeal of number (or length) for small collections of less than four items. Regarding the non-distinction of number and length in this observation, it is interesting to note that if these two quantities are put in competition,

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children aged 2 years 2 months to 6 years preferred number in the recent experiment by Sokolowski et al. (2022).

Although this research is concerned with immediate form recognition, Stern's view of its near innateness, the preponderant choice of form by 2-year-olds in Brian and Goodenough's experiment, and some maintenance of attraction to form at 4 or 5 years of age when color seems to exert a major attraction, show that young children's attention to form is very strong. Therefore, it is highly likely that typical 5-year-olds have memorized many forms. Especially the form of many characters, since –Stern had already insisted on this point— the interest in form is stimulated when the material is meaningful for children. And letters, which are used to write the first name, or numbers, which can be used to identify the house or the floor of the apartment, obviously have a great meaning for children. Moreover, the development of their motor skills, supported by school or family teaching, should then allow them to produce the tracing of these forms on paper if one is not too demanding. We have never been so in all of our coding of writing. Among the digits, when they wrote them down in front of me, I remember the digit 8, which seems to be the only digit that the 5-year-olds still had some difficulty to trace: some commented "I am just making two circles", or "I didn't do that one very well"; see also figure 56.

One of the non-trivial consequences of the need to memorize the shapes of the characters (without necessarily memorizing their orientation) should be that it is not the academically least successful students who produce the most reversals. This is especially true since writing requires, in addition to simple memorization, a traced reproduction of the shape, and the association with its name if a character is written under dictation. Of course, since writing results from a learning process, it is not the best performing students who should produce the most reversals either! Thus, the correlation between academic performance and the production of reversals should be at an intermediate level. At least two studies confirm this hypothesis.

Johansson (2005), in his experiment 1, tested 161 Swedish students in the last year of kindergarten (age 6) at the beginning of the school year. The student was given a sheet of paper and a pen and asked to write down the digits he or she knows. Responses were coded into four categories: correctly written digits, horizontally mirrored digits, omitted digits, and illegible digits. These same students were also subjected to addition ($1 + 4$, $3 + 4$, $5 + 7$) and subtraction ($5 - 4$, $8 - 3$, $13 - 6$), always presented as small verbal problems. The correlation between arithmetic performance and the level of digit writing was positive with correct writing ($r = .22$), positive but slightly less so with reversed writing ($r = .17$), and negative with omitted digits ($r = -.21$).

We also obtained such an intermediate correlation for mirrored writing (Fischer & Tazouti, 2012, Expt 1a). In this experiment, 296 GS kindergarten students were asked to write, under dictation, 8 reversible characters (digits or capital letters), and were otherwise subjected to a battery of tests assessing their academic performance. The correlation of the latter with the level of writing the characters follows the predicted order: it is positive with the percentage of correct writing ($r_s = 0.324$), positive but weaker with the percentage of reversed writing ($r_s = 0.145$) and negative with the percentage of other writing ($r_s = -0.448$).

But early knowledge of shape, even without orientation, faces a main obstacle: memorizing a rigid image would be hardly effective because the size and shape of characters are not fixed (for print) and change inter- and intra-writer. Therefore, it is likely that a conceptualization

(Schubert, 2017) or allographic representation (Rothlein & Rapp, 2017) of the characters is memorized. Teresa Schubert provides a systematic description of all digits and uppercase letters. For example, 3 is formed by two superposed identical semicircles or 8 is formed by two superposed identical circles. Such conceptualizations of characters are abstract, i.e., invariant with respect to properties such as size, absolute position, and stroke thickness. They therefore reflect indispensable characteristics of the character's shape. These character representations, whether they are called allographic or not, therefore solve the problem of confronting the brain with countless font variants for a given character by allowing its identification even when its scripts differ. For this identification, Pelli et al. (2006) found that it is not whole letter models that are used, but that the identification of a letter is done by detecting about 7 visual features.

Finally, if children are to orient characters in the direction of writing, they must know the latter in addition to the form. However, we do not think it necessary to devote a long special section to children's implicit learning of the direction of writing/reading in their culture. Indeed, young children are surprisingly knowledgeable about the visual features of writing, including those related to their first names (Treiman et al., 2007). It is true that some parents teach first name writing almost explicitly: for a good example, see Treiman et al. In addition, the reading of picture books by parents, educators, and teachers can easily account for this direction learning (Göbel et al., 2018); TV programs and software, which I am unfamiliar with, probably also. Work by Goldstein et al. (2016), for example, shows that parents read counting and non-digital books to their children, even at preverbal ages (5-10 months)! And McCrink et al. (2017) show that counting by caregivers can promote left-to-right spatial representation even in toddlers (24 to 47 months). In the early 1990s in France, Gombert and Fayol (1992) had already noted the early ability (as early as age 3 for some participants) to produce graphics with some of the characteristics of writing, including left-right direction.

4.5. The primacy of the visual modality in initial learning to write

The purpose of this section is not to discuss directly the relevance of a motor explanation of mirror writing. Subsequent to Erlenmeyer (see Section 1.1), who is credited with the authorship of such an explanation, the motor versus a perceptual explanation has continued to be discussed (e.g., Lebrun et al., 1989; McIntosh & Della Sala, 2012; Schott, 2007). A major argument in favor of the motor explanation is that people who write easily in mirror do not read mirror writing more easily. This pattern can indeed be explained by the fact that the former activity would pertain to a motor representation while the latter would pertain to a visual representation. It is amusing to see that this argument is, even more easily (if the comparison makes sense!), accommodated by our theory since we will argue that reversal in writing has nothing to do with that in reading (see Section 8.2).

Our aim in this section is to affirm that the beginning of learning to write fundamentally involves the visual modality. This has the consequence of making the motor explanation secondary in the sense that it depends on a prior visual representation. Our statement must obviously exclude blind children. But congenitally blind children hardly have to write characters manually, even though they may have a representation of the shape probably in the occipitotemporal cortex. This is possible because the latter not only represents objects visually, which requires visual experience, but also represents them non-visually, reflecting knowledge

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of the shape of objects regardless of the modality through which this knowledge was acquired (Peelen et al., 2014).

The reason for this strong involvement of the visual modality is both general and specific. It is general, because of the visual dominance in humans, especially when vision is compared to touch and proprioception (Gullaud & Vinter, 1998; Posner et al., 1976; Rock & Victor, 1964). Rock's theory even suggests that vision provides spatial information directly but that touch provides such information only through its learned association with vision (Rock cited from Posner et al., 1976). It is specific to the learning process because almost all children, when learning to write their first word—often their first name—first copy it from a model. The same is true for learning to write letters and digits: no teacher or parent teaches how to write a letter or a digit without showing how to do it and without showing the final product. More generally, developmental psychologists and teachers have often noted that the motor program for letter writing takes many years to become operational. In a general review of handwriting acquisition, it is noted that it is certainly not until age 10 that handwriting is automated (Séraphin-Thibon et al., 2018). Before automation the child makes massive use of relevant sensory information, especially visual (Chartrel & Vinter, 2004). Accordingly, it is not surprising that Kim et al.'s (2018) longitudinal examination of U.S. students in grades 3-6 suggests that the relationship between reading and writing may be unidirectional from reading to writing.

In addition, data from Vinter and Chartrel (2008) on children aged 4 to 6 years show that there is a delay of about 1 year between visual and proprioceptive recognition of cursive letters. It is therefore unlikely that proprioception is at the origin of visual letter recognition. Liliane Lurçat, whose husband François Lurçat (1927-2012) was a physicist, has described the development of kinesthetic writing movements in children in terms of physics or geometry. She reported that her daughter, Hélène, at the age of 4, copied everything (e.g., the marks on the pencil sharpener or pen) and, above all, asked her for models (Lurçat, 1979). When copying letters or graphics, Hélène was certainly adjusting her hand movements to her visual perception and therefore should not have had any particular problem with orientation. In the phase where the children move from copying to writing from memory, and where they often use both procedures, depending on the constraints, it is then likely that they will use the same strategy. Consequently, when they do not see the letter to be written, they will try to imagine the letter visually. Unfortunately, the orientation of the letter has disappeared in memory (see Section 5.3). So, to write it, they have to improvise one.

Thus, during the learning process, visual control appears to be used prominently at first, and only gradually decreases giving way to more automatic control and a shift in the balance between visual and proprioceptive control (Danna & Velay, 2015). McIntosh et al.'s (2018a, Study 1) finding of closely similar rates of mirror writing with the dominant and non-dominant hand in 44 Scottish children aged 4 ½ to 10 years suggests that the adult motor patterns are hardly possible until the letter orientations are acquired securely. Ultimately, Scordella et al.'s (2015) finding of “no relation between motor coordination and handwriting skills, while visuo-spatial skills (measured by a visual-constructive task) were related with both” (p. 1) made on 7- to 10-year-olds, which may, at first glance, seem overly radical, seems much less so.

4.6. The primacy of left-right reversals

In general, detecting symmetry about a vertical axis is faster and more efficient compared to detecting symmetry along another orientation (Wagemans, 1995). It is possible that this

observation can be explained by the mirror generalization that concerns only symmetry about a vertical axis. Indeed, it is this mirror generalization that is responsible for children not remembering the left-right orientation of characters (see Section 5.3). If there is no symmetrization about a horizontal axis in the brain, analogous to symmetrization about a vertical axis in memory, which evolution suggests (see the supine tiger in Section 4.11), then we would expect many more left-right reversals than up-down inversions.

Whatever the characters examined, we have indeed noticed that left-right reversals (horizontal mirror) are much more frequent than up-down inversions (vertical mirror) or double inversions. A double inversion correspond to a 180° plane rotation by which 6, for example, is transformed into 9 and vice versa. I give a reference for each type of characters: digits, lower case letters and upper case letters.

For digits, Fischer (2013a) reports 111 up-down inversions, 110 double inversions, compared to 3049 left-right reversals. For lowercase letters, data from Torres et al. (2021), as analyzed by Fischer and Luxembourger (2021, Table 2), show 14 up-down inversions, 10 double inversions, compared to 537 left-right reversals. Finally, for uppercase letters, and although left-right reversals are uncommon (except for J and Z), up-down and double inversions are even much less frequent. In Fischer and Koch's (2016b) original GS kindergarten data, we counted only 5 such up-down and double inversions, compared to 332 left-right reversals. Moreover, are these really inversions? Indeed, 3 of these inversions result from the misplacement and orientation of the Q appendage (upward), resulting in a true up-down Q inversion (such as Q).

In recognition tasks, the same phenomenon can be observed. Uehara (2013) observed reversals of meaningful pictures for children at three age levels. If we consider that letters or digits are meaningful images, it is relevant to report that children made significantly and quite clearly more left-right reversal errors than up-down inversions: 31.0% vs. 13.3% at 4 years, 16.1% vs. 6.8% at 5 years, and 16.0% vs. 3.6% at 6 years. Ahr et al. (2017), using an indirect method, further suggested that horizontal errors are more common than vertical ones in adult readers.

All these data, especially the one directly obtained by the writing of the characters by the children, concur to affirm that the inversions by the children of 4 to 7 years are essentially left-right reversals. Certainly, in our own observations, we did not include M, which is one of the most vertically inversed letters. But, here as elsewhere, one may wonder whether this is really an inversion and not merely a confusion with W.

4.7. Digits are better than letters

Our own observations show that digits are, on average, more reversed than the capital letters. The recent observation by Göbel et al. (2019) further confirmed this, although only 9 letters were tested (notably z was missing). Because the study of mirror reversals requires that children produce them, this is an argument for choosing digits, rather than letters, as study material. In addition, the capital letters are either symmetrical for 11 of them (A, H, I, M, O, T, U, V, W, X, Y), or, for the rest, are almost all oriented to the right (B, C, D, E, F, G, K, L, N, P, Q, R, S). They are therefore not optimal for studying the difference in the frequency of reversal of right-

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vs. left-oriented letters. It is true that there are more lowercase letters oriented to the left. But lowercase letters also have some disadvantages:

- The orientation of some lowercase letters is often difficult to define, especially since they can be written in printed script (e.g., a), school script (e.g., a), or even attached script. For example, the perfectly symmetrical writing of o becomes *o*, i.e., right-oriented, when handwritten in attached script.
- The corresponding capital letters are different and may have different orientations (e.g., d and D, g and G, q and Q) or be symmetrical (A, H, T, Y), and thus coding becomes difficult when a child introduces upper-case scripts in place of lower-case ones, as in the recent research by Torres et al. (2021), in which Brazilian first-grade school children were asked to write lower-case letters.
- There are several reversible letters: b mirrored horizontally, vertically, and double gives, respectively, d, p, and q; similarly d gives b, q and p; p gives q, b and d; q gives p, d and b. Thus, one cannot distinguish a simple confusion from a mirror writing, which is embarrassing if the objective is the study of mirror writing.

Furthermore, in France, the writing of lowercase letters is generally taught later than those of uppercase letters and digits. It is therefore directed at children who are older on average, who learn them more quickly, making reversals more difficult to observe because they are less frequent. Thus, to study them, Portex (2017) had to do prior learning with French pupils. In Scotland, McIntosh et al. (2018b) recruited Irish students, as in Ireland (Eire) lowercase letters are taught from the beginning of learning to write.

On the other hand, the digits seem better suited to the study of reversal. Admittedly, there are only 10 of them, two of which (0 and 8) are symmetrical (left-right). But that still leaves five digits clearly looking to the left (1, 2, 3, 7, 9), in France and many other countries where the 1 is systematically written with a small diagonal stroke at the top left. Writing kinetics (for 4), psycholinguistic analyses (especially for 5: see Fischer, 2013a), or students' judgment (see Fig. 9), allow to categorize as right-oriented the other reversible digits (4, 5, 6).

As we sometimes bring together the data on digits and letters, however, it is important to note that their developments are not completely dissociated. Yamagata's (2007) study showed that the developmental processes of each system went through common phases. Yamagata concluded that it appears that although children before age 4 produce drawing and writing in a specific domain, overall the activity of representation as a symbolic system develops in a general domain.

4.8. Mirror writing is a transient phenomenon

From our early research we saw the rapid decline between kindergarten and first grade of elementary school in the typical child's mirror writing. On average, we obtained more than 30% mirroring of digits in kindergarten, and less than 5% in first grade (Fischer, 2010a). Fischer and Koch's (2016b) longitudinal study also showed this rapid decline: comparable percentages are 21% in GS kindergarten and 9% in first grade. The drop is certainly less clear-cut, but it must be taken into account that, in this second research, it is the writing of characters (digits and capital letters) that was tested, and this in a less favored socio-cultural environment (which may have as a consequence that the mirror writing persists a little longer). The observation of Göbel

et al. (2019; see also Section 6.2) indicates a drop in the percentage of children who reversed at least one of the digits from 84.5% to 48% from the year before the 1st grade to the 1st grade.

The transitory and briefness characteristics of mirror writing probably explain the lack of interest in it on the part of teachers and psychologists, except when the reversals persist, (i.e., are no longer transient!). The only real test developed by the latter (see Section 1.8, Table 3 in particular) confirms the lack of interest of a systematic observation beyond the age of 7. In a number of observations that do not really confirm ours, it is sufficient to look at the age of the children, which then proves to be inappropriate for observing a sufficient number of reversals. Another possible consequence of this transitory characteristic is that the reversals observed on older children are no longer necessarily of the same nature as those observed on children aged 4 to 7. We shall see in Section 8.3 that the reversals in older children can be confusions.

4.9. An epilogue: left-handedness has nothing to do with reversal!

As a precaution, I prefer to begin by reminding that I am discussing primarily, and exclusively in this section, the reversal of characters by typically developing 4-7 year olds. On the other hand, I am obviously aware that, even at the latter age, left-handed children may have difficulty adapting to a world designed for right-handed people. With respect to this difficulty, some material efforts have been made (e.g., left-handed scissors). However, the practical problem of left-handed writing remains. Indeed, when writing from the left to the right with a classical holding of the pencil, the hand immediately covers what one has just written. Yet, in my theoretical approach, this problem of left-handed children is overshadowed by their problem, common with right-handed children, of orienting the characters in a precise direction that they do not know (because it is deleted in memory by the mirror generalization mechanism: see Section 5.3).

The theoretical assumption of no difference in character reversals between left-handed and right-handed children has been largely confirmed empirically. Left-handed children, who are about 10% of the population, are therefore rare in the classroom. This led Anne-Marie Koch, in a district in which she worked as a school psychologist, to take an interest in all the children of GS kindergarten, whose teachers reported to her that they wrote with the left hand. Repeating this recruitment during three consecutive years allowed her to build a sample of 59 left-handed writing children. In Fischer and Koch (2016a), we compared them to 59 right-handed writing children matched for age and school. The result of the comparison, reported in Figure 22 is unambiguous. Children writing with the left hand do not reverse characters much more, and, furthermore, their frequencies of reversal of individual characters are almost identical to those of children writing with the right hand. In particular, children frequently (40% or more) reverse the digits 3 and 7, and the letters J and Z, regardless of their (usual) writing hand. In the same research, the children also wrote their first names. We also did not observe any effect of writing hand on the frequency of reversals of these first name writings.

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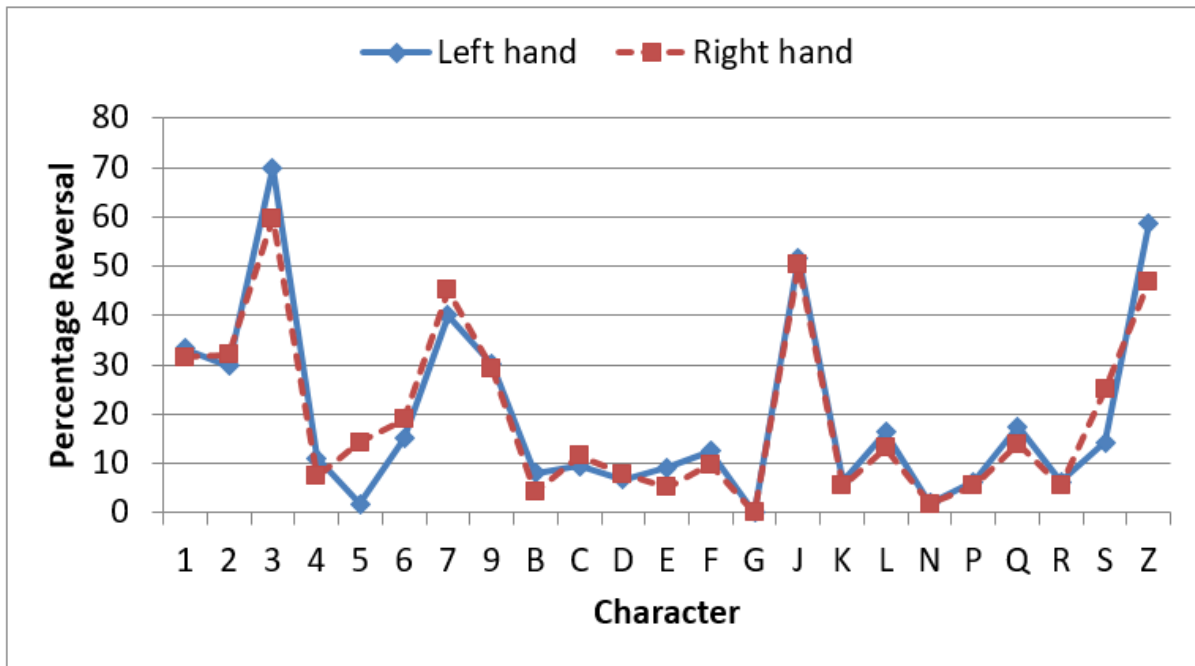


Figure 22. Percentage of character reversal as a function of the character and the child's usual writing hand. [Reproduced from Fischer & Koch (2016a), Figure 2a, on line].

Subsequently, the French Longitudinal Study from Infancy (*Elfe: Etude Longitudinale Française depuis l'Enfance*) offered us another opportunity to test our hypothesis on material restricted to writing the digits from 1 to 5 in MS kindergarten. The Elfe research recruited, at birth in 2011, more than 18 000 children from various maternity hospitals in metropolitan France, with the goal of following their development into adulthood (Charles et al., 2020). At age 3 ½, the child's drawing hand was observed. In MS kindergarten, at an average age of 4 years 10 months, these children were asked to write the number of ducks in the boxes positioned below (see Fig. 23). The teachers, who coded the students' responses, indicated the mirror writing and allowed us to compare 466 children, presumed to have written with the left hand, with 3531 children, presumed to have written with the right hand (presumed because the hand of writing was determined on the basis of an observation of more than one previous year). Despite the statistical power of the test, no significant difference was observed, with the percentages of reversals in the two groups being almost identical.

From a more general point of view, our result fits well with the neurophysiological observation of Gonzalez et al. (2006). These searchers have indeed shown that visuo-motor mechanisms encapsulated in the left hemisphere play a crucial role in visual control of action and that this hemispheric specialization has evolved independently of the hand. Also less surprising are the observations of Goffin et al. (2019) that handwriting plays no role in lateralizing symbolic number processing in the brain. These observations are certainly not directly relevant to our reversal problem, but support the overall idea that the effect of the writing hand may be overshadowed by deeper problems.

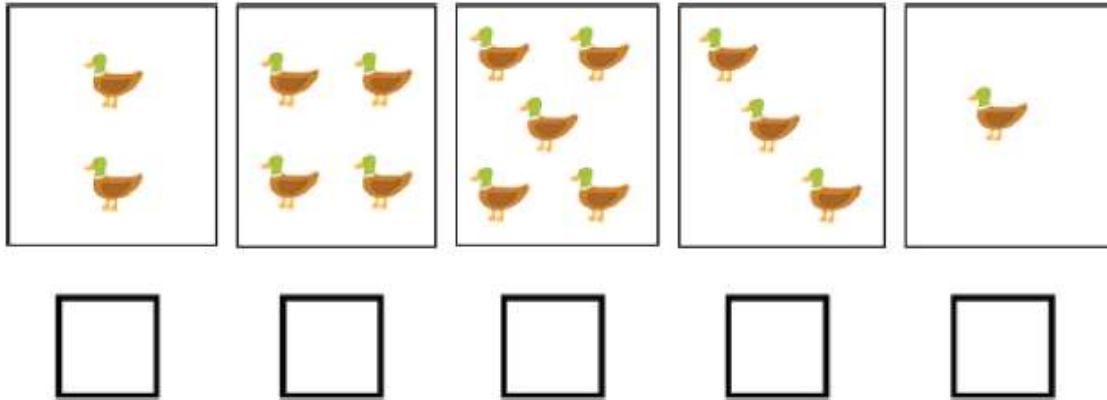


Figure 23. The duck number writing test in Fischer and Thierry's (2021) MS kindergarten assessment.

In conclusion, the lack of difference in character reversals, which had already appeared in several research studies in the 20th century with writing not purely from memory (Hildreth, 1934; Simner, 1984), has been largely confirmed by our research. This lack of difference is all the more remarkable as one might think that the tendency (bias) towards the right should be more marked for left-handed children than for right-handed one. This because left-handed children are obliged to make a greater effort to write from left to right. But Suitner et al. (2017) helpfully explain that this is only true if the rightward bias is related to sensory-motor experiences. Yet, as we saw in Section 4.5, it is mostly related to visual experience, which one can argue is similar for left- and right-handed children.

4.10. Inversion versus confusion

Given the physical similarity (PS) of some characters, the risk of interference or confusion in declarative memory is omnipresent, especially since there are many variants of character writings. Cohen (2009) proposed a physical similarity index (PS) that is computed from a digital dial of 7 segments: $PS = (\text{number of common features}) / (\text{number of different features})$. Figure 24 shows that with such an index, extended to certain letters, the digit 6 is perfectly similar to the lowercase letter b, to the point that the index is not calculable ($PS = 5/0$), or that the digit 9 is perfectly similar not with the lowercase letter e ($PS = 5/2$), but with its reverse not shown on the figure ($PS = 6/0$).

Digital dial	Digit 6	Letter 'b'	Digit 9	Letter 'e'

Figure 24. The "writing" of some characters on a digital dial.

The interest of such an index is to draw the attention on a physical similarity likely to cause confusions in declarative memory. But this interest is considerably reduced by the sometimes too approximate representation of the characters, in particular because of the non-inclusion of

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the curves omnipresent in handwriting, and secondly because of its non-definition for perfectly similar characters. Nevertheless, at an older age than that of typical reverser children (between 4 and 7 years), confusions like those shown in Figure 24, can explain some "reversals".

Terepocki et al. (2002) hypothesized that non-reversible letter orientation errors may reflect different processes than those related to reversible letter orientation errors. This different process—confusion—primarily affects reversible characters, i.e., characters whose wrong orientation gives a real character. If we include up-down inversions and rotations in the orientation errors, the reversible letters are mainly the lowercase letters b, d, g, p, and q, the uppercase letter J approximately mirroring L, and also u inverted into n, or Z transformed into N by a 90° rotation. Table 5 of Terepocki et al. then shows that all orientation errors, observed on 10-year-old children, concern reversible letters.

Traditionally, authors have used two terms or processes to describe the apparent transformation, especially from b to d (and vice versa): inversion (e.g., Frith, 1971) and confusion (e.g., Davidson, 1935), and sometimes both (e.g., Liberman et al., 1971). Yet, in the vernacular, the difference between confusion and inversion is quite clearly delineated. Confusion leads to a state of bewilderment, misunderstanding or chaos. Thus, confusion has a negative connotation even though it can accompany a state of cognitive imbalance that can be beneficial to learning (D'Mello et al., 2014). On the contrary, reversal has a rather positive connotation. In adults, it is an understatement to say that the reversed annotations added to his sketches by Leonardo da Vinci did not devalue them (see Fig. 25). In children, the reversed writings are often precise and neat, as shown by several of them reproduced in this paper. When they are in lower case, attached, they are often beautiful and of the same quality as left-to-right writing: see Figure 26. In addition, they reflect a form of creativity because children write their names in ways that probably no one has shown or taught them.

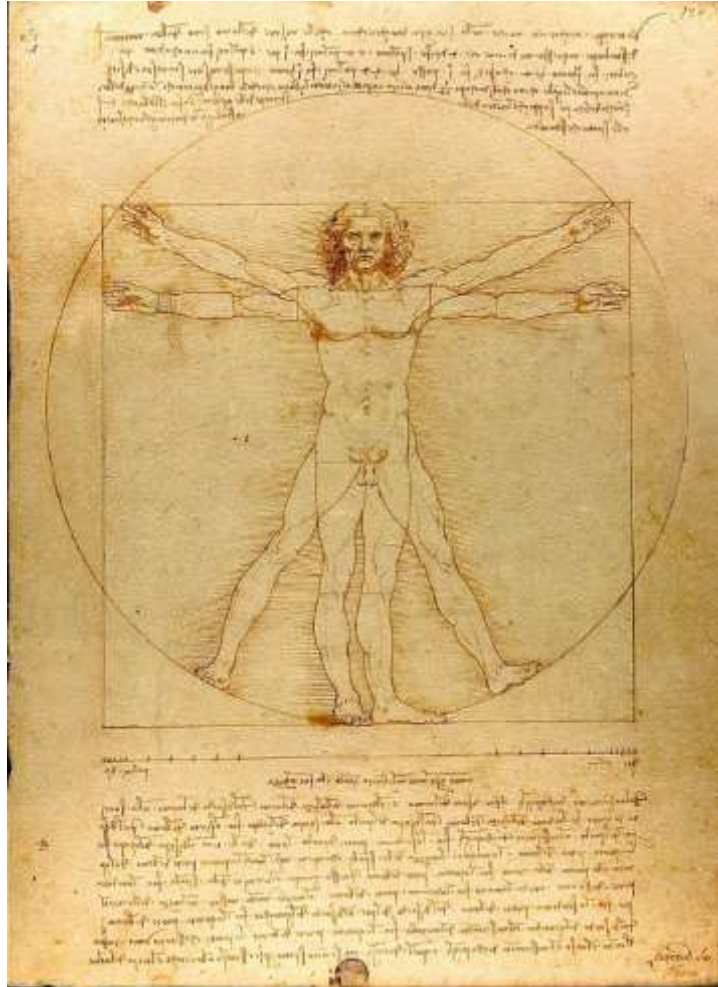


Figure 25. Famous Vitruvian man realized by the hand of Leonardo da Vinci around 1492: the copious annotations are written in mirror (but not the signature).

The possible confusions, if we consider all letters (lower and upper case) and their mirrors, are potentially numerous. In section 8.3, we specify some that seem real, especially in atypical development. Some authors sometimes add to this. For example, I discovered in one of my readings that if the initial loop of 2 is started a little too far down, 2 can be confused with Q!

Why do reversible but non-reversible letters not lead, or less, to such confusions? The obvious reason is that reversed nonreversible letters, which do not exist in the alphabet, are not reinforced by reading. In Section 8.2, we will see that this distinction is crucial because children who reverse digits are not primarily those who confuse b and d.

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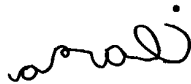
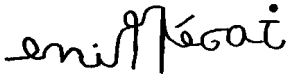


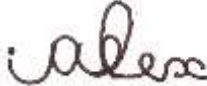


Dot on the left (of the vertical line)	Dot on the right (of the vertical line)
	
	
	
	
	
	
	

Figure 26. Some of children's writings in lowercase letters attached. These writings, in the two conditions—dot left and dot right (see Section 6.4)—were produced at different times (thus without the child seeing the other writing) and assembled a posteriori.

4.11. Adults too!

Humans have adapted to the world as it existed over 30,000 years ago. It is now fully accepted that we are born with perceptual and behavioral programs that were adaptive for our early ancestors and still affect our behavior, information processing, and emotional functioning (Stern, 2015). This adaptation may have led to ignorance of left-right orientation information. The example of a tiger (or other dangerous animal) seen from the left profile but which we should be equally wary about even if seen from the right profile (although lying on its back it seems less dangerous) has often been used (e.g., Rollenhagen & Olson, 2000). This may explain our ability to generalize in a horizontal (left-right) mirror primarily, rather than a vertical (up-down) mirror. The performance of 7- to -8-year-olds on the famous Piagetian Three Mountain Test (Bideaud et al., 1993; Piaget & Inhelder, 1947/1969), in which children are asked to draw the three mountains (or choose from prepared drawings) as the experimenter in front of them sees them, may still be a trace of this. Indeed, the children become aware that what they see in front is seen behind by the experimenter, often before realizing that what they see on the left is seen on the right by the experimenter. This also appears, and even more directly, in an experiment by Dillon and Spelke (2015). In the latter, 4-year-olds were shown a picture of a room (or object) and asked to place a toy in a location in the room (or object) indicated by a dot on the picture. The children ignored the directional information, just as they ignore it when they mistake objects and shapes with their mirror image. Such separate consideration of shape and

orientation is made possible by functional and spatial dissociation in the brain systems encoding object shape and orientation (Dillon et al., 2014).

But this ignorance of orientation information does not only affect children. While the bulk of this paper and our work is devoted to the problem of mirror reversal by typically developing 4-7 year olds, we have also designed a quiz, offered to adult participants at various science festivals, brain week, or other research night. Dehaene (2010) reversed the image of Da Vinci's famous masterpiece "Mona Lisa", of the Statue of liberty, and of a coin print⁹, in the aim to suggest that they are still familiar to us. Our quiz more systematically presented 12 pairs of images (one correct, one reversed), in which one had to distinguish the correct image, and 12 images for which one had to recognize whether it is correct or not (an image is either correct or reversed). The purpose of this quiz was to show that even adults do not always retain the left-right orientation of common images. Such retention would allow them to know that on the rest area sign the tree is to the right of the table ("A" correct on the left part of Fig. 27) and that the image of the crosswalk sign has been reversed ("No" correct on the right part of Fig. 27).

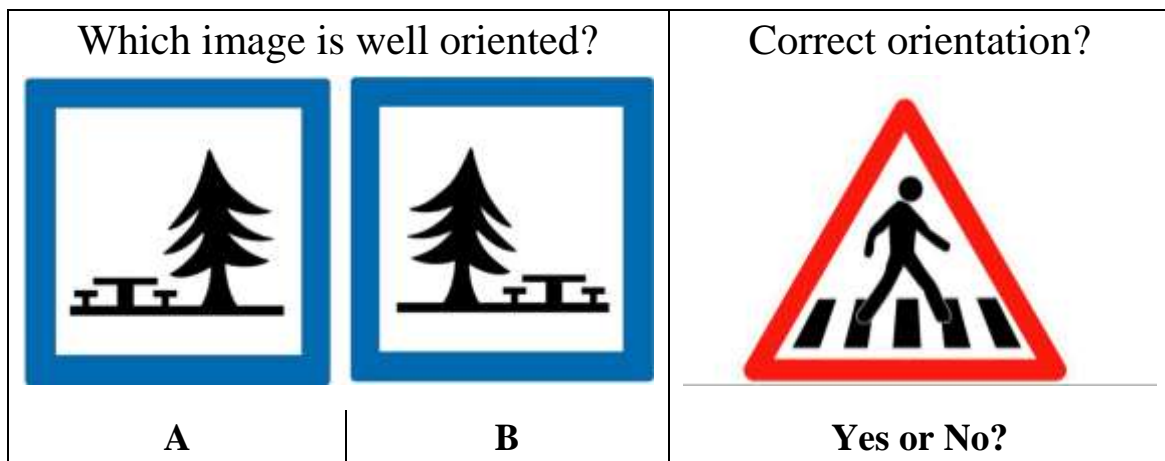


Figure 27. Distinguish a current image from its mirror (left part of the figure) and recognize whether an image is correctly oriented or not (right part of the figure).

However, participants were far from answering correctly to many of our images that concerned paintings, commercial logos, or road signs. Regarding the latter, we even obtained a percentage of correct responses, out of several hundred participants, that is below chance responses (= 50%) for the two road signs in Figure 27. This last result is particularly impressive since most of these participants were adults and presumably had a driver's license! These observations were certainly not well controlled experimentally, but they are all the more convincing because the participants were not obliged to give back the result of their quiz, which must have favored a restitution by the participants who thought they had done well. They thus confirm that even adults do not always retain the left-right orientation of common images even though they have certainly seen them many times.

⁹ Because of the written inscriptions, one can remark that the true coin has been reversed. One can also successfully speculate that the Statue of Liberty has been reversed since the vast majority of humanity is right-handed, whereas in the picture (p. 268 of Dehaene's book) the statue holds the flame with its left hand!

5. Advances in neuropsychology

5.1. The pioneering work of Michael Corballis

Michael Corballis was born (he died in November 2021 at the age of 85) in New Zealand, where he also spent a large part of his academic career as a professor of psychology at the University of Auckland. However, he defended his thesis in Canada, at McGill University (Montreal). This allowed him to teach statistics, notably to Steve Pinker—the neuroscientist mainly known for his book "The Language Instinct"—and to collaborate with Justine Sergent who was affiliated to McGill University in the 1980s/1990s. These details are not only anecdotal. His initial theory of a dual representation in the cerebral hemispheres, like that of Orton, may indeed seem audacious, or simply adapted to the zeitgeist. Let us not forget that hemispheric specialization was a preeminent subject of study in the 20th century, culminating in Roger Sperry's Nobel Prize in Medicine (Sperry, 1982, is a reproduction of the lecture he gave at the reception of the prize in December 1981 in Stockholm). One may then wonder about the adventurous or opportunistic nature of Corballis' theory. Dehaene (2010), who presents/discusses Corballis' theory at length, does not reject it as clearly as he rejects Orton's hypothesis. My cursory investigation of the persona then led me to note that Pinker, describes him as "urbane, charming, witty, irreverent"¹⁰. My familiarity with the field—the apprehension of numbers—of Corballis and Sergent's (1992) research allowed me to see that he was not always a model of rigor, even before the—and regardless of the—accusations that marked the tragic end of life of his co-author Justine Sergent. That said, Catani's (2022) posthumous tribute to Michael Corballis reports several anecdotes that show a man full of humanity. This is also my experience as he even offered to seek funding for the article that eventually appeared under Fischer and Luxembourger (2018b). But humanity does not preclude some audacity. And, in my opinion, it requires some when we see words, and their mirrors, as Corballis has represented them in the cerebral hemispheres (see Fig. 28).

¹⁰ Cf. his blog: <https://twitter.com/sapinker/status/1461526854247104515>, accessed on 20/05/2022.

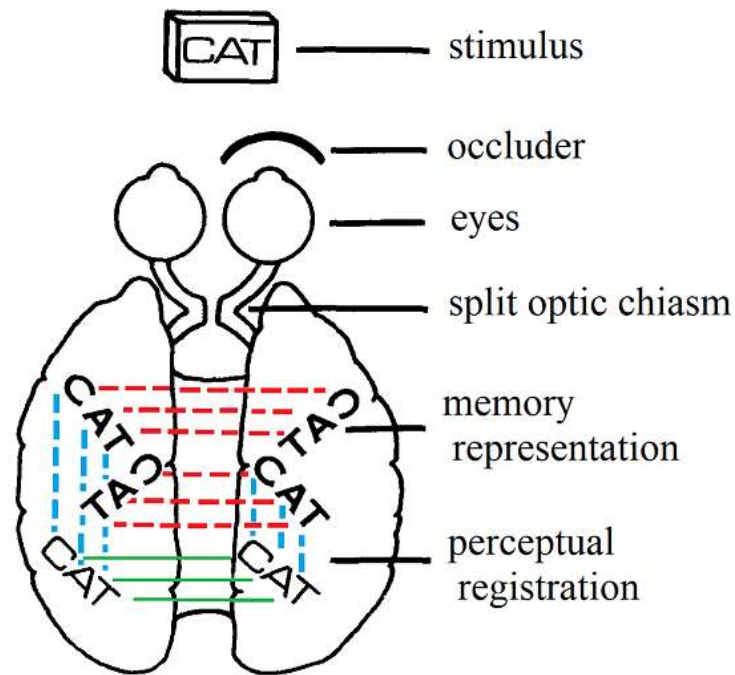


Figure 28. The schematic representation of words in the cerebral hemispheres, which I have colorized (see explanations in the text), using the original Fig. 3 by Corballis (1974, p. 30).

Corballis has been interested for more than 50 years in this question of mirror reversal. I will not revisit his early work, with Ivan Beale, on pigeons, following that of Nancy Mello and John Noble (on monkeys), as this work is difficult and summarized/discussed by Dehaene (2010, pp. 280ff). In his book, co-authored with Beale (Corballis & Beale, 1976), Corballis repeats the schematization he had previously proposed in Corballis (1974). In this schematic representation, Corballis occluded the right eye and divided the optic chiasm for comparison with Noble's monkey experiment. In this way, the word "CAT" should almost exclusively reach the left visual cortex, but I am not sure that a human treated in this way would still be able to read much! Then, it is correctly transferred to the right visual cortex (green continuous lines) and, intra-hemisphere, to memory from the two representations in the perceptual visual cortex (blue dashed lines, discontinuous to show that there can be a transformation, other than reversal). Finally, the two resulting representations, which are still correctly oriented, are reversed by the interhemispheric transfer (red dashed lines). Note that the transfer visualized by the blue dashed line could produce a more abstract representation, an idea that Corballis takes from N.S. Sutherland's theory that he discusses with Beale (pp. 47-50; see also the following). Let us also note that we already find—and in this the 1974 article and then the 1976 book were avant-gardist—the notion and the word of generalization (in mirror), of which the inter-hemispheric transfer would be the mechanism.

Corballis went on to support, for the rest of his life, this double representation of letters originally proposed by Orton (or Ireland: see Section 1.6). But Corballis disagreed with the idea that the stimulus orientation would simply be veridical in one hemisphere and reversed in the other. In the exchanges we were able to have, he insisted that reversal occurs during interhemispheric transfer, so that each hemisphere could carry both veridical and reversed representations. Given the predominance of the left hemisphere, the veridical version could be stronger in the left hemisphere, resulting in a strengthening of the reversed version in the other hemisphere. But, he pointed out, the idea that representations are simply reversed between

hemispheres is too simple, and Orton's version of how this might have happened does not make sense.

Faced with children's massive reversal of the writing of certain characters (J, Z, 3) and the virtual absence of reversal of other characters (C, D, 4), Corballis simply put forward a cultural factor. But our brains have probably adapted to reading/writing (Dehaene, 2010), a recent cultural invention. On this point, section 2.1 should not be misleading: ordinary people were hardly likely to write in the proto-Sinai era! This invasion, partial or total, of the brain by a new cultural object cannot be seen as a simple addition to a biological brain, invariable in the course of time and whose performance would simply be modified by culture. The observations on pigeons, which are Corballis' first research, may have led him to underestimate the importance of culture, which Jerome Bruner underlined, at the time, with his famous statement "culture-free means intelligence-free" (cf., Greenfield & Bruner, 1966, p. 90). More recently, Erich Kandel, winner of the Nobel Prize in Physiology in 2000, has given a severe denial to those who still believe that genes alone determine behavior: "they also respond to environmental stimulation such as learning", notes Kandel (2006/2007, p. 284).

As a preliminary to their theoretical proposal, Corballis and Beale (1976) had, as is appropriate in a scientific approach, described the approach of other theorists. Sutherland N.S.'s approach, already noted, is important for what follows because he proposed that it is abstract descriptions that form the basis of recognition and generalization. In particular, he suggested a description that does not distinguish a shape from its horizontal mirror image, but distinguishes it from its vertical mirror image. Thus, we can think that b is confused with d because these two lowercase letters are formed by a loop and a vertical line that goes beyond the loop, but not with p because for this last letter the vertical line does not go above the loop (it is even below it as for q, a letter with which p risks being confused).

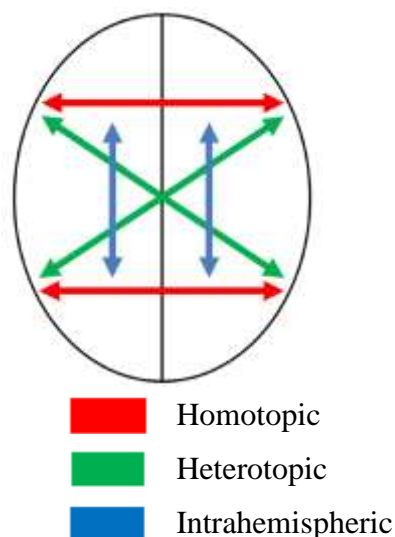


Figure 29. Schematic diagram of the three types of neural connections differentiated by Corballis. [Reproduced from Fig. 3, p. 5, in Corballis (2018)].

In his most recent paper on the subject, which we have commented on uncritically (Fischer & Luxembourger, 2018b), Corballis (2018) re-explains that if commissures connect mirror-image points in both hemispheres (homotopic connections), activation in the sending hemisphere would be mirrored in the receiving hemisphere, which would therefore register the information

as if it were left-right reversed. This was already the reversal process described, called interhemispheric mirror image reversal, by Corballis and Beale (1970). Corballis insists, as we do (see Section 4.3), on the difference between perception and memory and on the presence of orientation information at an early stage of visual information processing. But then, these homotopic connections become troublesome: they would also prevent us from perceiving images correctly! This not being the case, Corballis points to the existence of heterotopic connections between visual cortices (see Fig. 29), highlighted in mice by Chovsepian et al. (2017) and designed to maintain perceptual continuity when crossing the midline (see Section 3.1). But these are complications that make it difficult to both understand and use the theory. Especially since Corballis (1974), with reference to Sperry (future Nobel Prize winner in medicine), had himself pointed out that visual areas are not homotopic.

Whereas Corballis (and others) had focused primarily on the anterior commissure as a medium for interhemispheric transfer, in 2018 he also points out that the hippocampal commissure may play a role in the symmetrization of memory circuits. This suggestion is interesting because the hippocampus is fundamentally involved in declarative memory, the memory of facts (see Fischer, 1992). And it is a fact that three is written 3, and not ε , as I had already pointed out in Fischer (1999).

5.2. The contribution of Stanislas Dehaene (2010)

Stanislas Dehaene's book on reading was originally published in France, in 2007. But it has been distributed worldwide, thanks to—among other things: the content and its treatment have obviously also contributed to this!—to the prestige of the author, a professor at the Collège de France, and to its translation into English (Dehaene, 2010). In it, he calls Orton's idea that a letter such as "p" would be correctly represented in one cerebral hemisphere and mirrored in the other "a fundamental error" (p. 273). He is much less severe with the model of Corballis and Beale (1976), which also postulated this duplicated representation (see Fig. 28). This is partly because the model ruled out the idea that reversal during interhemispheric transfer was a perceptual process, which is not as clear in Orton's model (see, however, my citations of Orton in Section 1.6). This treatment of reversal as a process in memory makes it biologically more plausible. In Fischer and Luxembourger (2021), we point out some neurobiological references showing that in the first milliseconds of information processing in the visual cortex, the orientation of objects is perceived correctly. We can add the impressive observation of Yamazaki and Lioumis (2022). The latter studied the phenomenon of stochastic resonance (SR) in the early visual cortex during figure orientation discrimination using transcranial magnetic stimulation. It is not so much the method of observation—which I do not deeply understand!—that I want to call impressive, but its result. Yamazaki and Lioumis indeed found that an SR-like phenomenon can be produced by stimulating the early visual cortex (V1/V2) at about 60 ms after the presentation of visual stimuli.

Not only does Dehaene not reject Corballis' model, but he uses it to illustrate, by example, the problem created by inter-hemispheric symmetrization in reading. He calls this example "concrete", but its concreteness is likely to be undermined by children who move their heads frequently and rapidly! I am adapting the example here to writing since that is my topic. The child who sees b in his right visual field will have a true representation in his left hemisphere (because of the crossing of the fibers coming from the nasal retina in the optic chiasm), but a mirror representation in his right hemisphere (by the intra-hemispheric transfer). The teacher

will have taught him that this letter is called [bi:]. When, the next day, the child is asked to write a [bi:] from memory, he may find the mirror representation and produce a reversed writing of b, which is d. We will see, most clearly in the concluding chapter, why this explanation of reversed writing is not the most relevant. But let's go back to Dehaene's book. How will the brain handle, according to him, this problem of symmetrization, an embarrassing problem because in the end it will be necessary for students to correctly identify b and d (in particular).

The distinction, widely confirmed in the early 1980s, of two visual information processing pathways (Goodale & Milner, 1992; Mishkin & Appenzeller, 1987; Ungerleider & Mishkin, 1982), allowed Dehaene to suggest that it would be a contribution of the dorsal pathway that could be used to distinguish an image from its mirror. It should be remembered that in the dorsal pathway, which projects from the striate cortex to the posterior parietal region, neurons analyze the spatial relations between the various components of the visual field. On the other hand, in the ventral pathway, which projects from the striate cortex to the inferotemporal cortex, neurons respond to simple and limited features (identity, shape, color). But Dehaene specifies—and this is fundamental here—that these neurons of the ventral pathway ignore size and spatial orientation, including left versus right.

The dorsal pathway, because it recognizes and differentiates between a loop to the right of a vertical line (as in b) and a loop to the left of a vertical line (as in d), is well adapted to reading. It is also suitable for writing since it serves visually guided actions towards objects (Goodale & Milner, 1992)¹¹. It therefore complements the work of the ventral, occipitotemporal pathway, to which Dehaene attributes mirror generalization. This could be done by assigning to b and d (in the example) “distinct neural populations that cease to generalize across mirror reversals” (p. 288). But later, Dehaene also makes motor learning play a role in this orientation memorization. However, the idea of the involvement of new neuronal populations and of possible motor learning do not fit well with the notion of “unlearning” of symmetrization put forward by Dehaene. These processes of assigning detectors are also difficult to envisage if we take into account the four representations of a letter that the inter-hemispheric transfer, postulated by Corballis, is likely to have created (see Fig. 28: in the simplified version given by Dehaene, there are only two). Let us observe that this notion of “unlearning” is more compatible with that of inhibition (Ahr et al., 2016; Borst et al., 2015; Brault-Foisy et al., 2017; Torres et al., 2021) but is chilling to any constructivist pedagogue.

In Dehaene's theorization, however, this unlearning allows the neurons of the occipitotemporal pathway to be perfectly autonomous for letter recognition. Expertise can then be built up for groups of letters only in the left hemisphere. From that point on, “the mirror images of letters are no longer exploited by the reading system” (p. 294). But it is possible that the mirror representations of the letters are simply dormant, not conscious. In this case, we are more likely to think of them as circumvented than unlearned.

Finally, in his theory of neural recycling, Dehaene notes that “evolution did not anticipate that our brain circuitry would one day be recycled for word recognition” (p. 302). Therefore, the neural systems that allow us to learn are imperfect. Taking inspiration from Dehaene, we can

¹¹ One might object that when children write from memory, their writing is not visually guided. But young children, whose motor skills are not automated, can produce their actions from a mental (visual) image.

see in the mirror writing of children—the focus of this paper—a stigma of the evolution that could not foresee that some neural systems would one day be retrained for reading/writing.

5.3. Cerebral modelling

5.3.1. *Orientation disappears from patch to patch*

Do technological advances in the study of the brain, mainly functional magnetic resonance imaging (fMRI), make it possible to "see" the processing of images in the brain, in particular their symmetrization? Several research projects have embarked on an enterprise that is far from simple, especially when it concerns humans, and children a fortiori. This is why I first selected a research on animals, macaque monkeys in this case, by Freiwald and Tsao (2010).

Freiwald and Tsao studied the face processing network of the macaque monkey. It consists of six face-selective interconnected regions. These regions were recorded from the two intermediate patches (ML and MF) and two anterior patches (AL and AM). A didactic diagram allows to follow their sophisticated modeling (see Fig. 30).

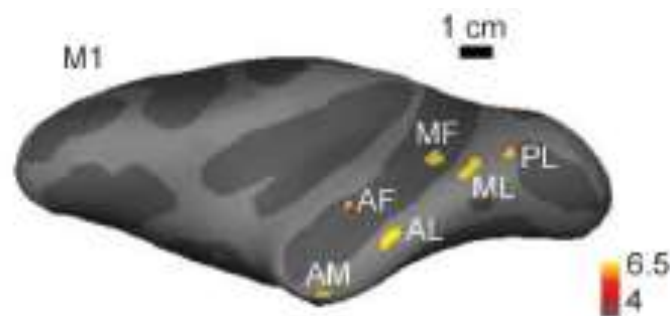


Figure 30. Inflated macaque left hemisphere (dark gray areas mark sulci, light gray–dark gray boundaries mark the middle of the bank within a sulcus) showing six regions in the temporal lobe of monkey M1 that responded significantly more to faces than to objects in fMRI experiments (PL: posterior lateral; ML: middle lateral; MF: middle fundus; AF: anterior fundus; AL: anterior lateral; AM: anterior medial; color scale corresponds to level of statistical significance). [Reproduced from Freiwald and Tsao (2010), Fig. 1A, p. 846].

The transformation of the face representation from ML/MF to AL produces *de novo* a surprising new property in AL, not found in ML/MF: the mirror-symmetric orientation of the head produces an activation similar to the original orientation. The emergence of this property shows that a partial invariance with respect to head orientation has developed. Neurons in AM, the most anterior face part, achieve an almost total invariance that certainly allows the monkey to recognize a face regardless of its orientation. Although inferotemporal cells, tuned for mirror symmetry, have been reported previously (Rollenhagen & Olson, 2000), this is the first time such cells have been shown to be clustered in an intermediate node of a shape processing network.

Research such as that of Freiwald and Tsao has two major drawbacks for the understanding of human reading/writing processes. On the one hand, it can only deal with material that is significant for monkeys—faces in this case—and on the other hand it raises the question of the degree of similarity between the brains of monkeys and humans. Freiwald and Tsao provided some assurances on the latter point (Tsao et al., 2008); these assurances were reinforced by a

research by Rajalingham et al. (2015) showing that rhesus monkeys and humans have a common neural representation of shape that directly supports object perception. In addition, the research of Kietzmann et al. (2015) did involve humans. But their results, which support “models emphasizing the role of interhemispheric crosstalk in the formation of viewpoint-invariant face perception” (p. 16398), have little application to character (letter and number) processing.

5.3.2. *Orientation is lost in the posterior fusiform sulcus*

Dilks et al. (2011) studied adult humans in an adaptive fMRI experiment. They begin by noting that while object-selective cortex can confuse an image with its mirror, it should not be the same for scene-selective cortex, as the processing of a scene changes if it is mirror-reversed. With images like those in Figure 31, they observe, as predicted, tolerance to mirror reversals in an object-selective region—the posterior fusiform sulcus.


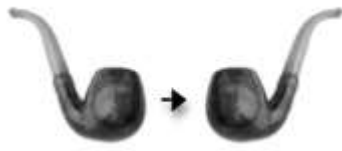

Condition	Objects
Same	
Mirror	
Different	

Figure 31. Example of object image pairs used in Dilks et al. research. (Figure based on Dilks et al. (2011), Fig. 1, p. 11306].

However, a more posterior object-selective region (which is therefore assumed to be anterior in processing)—the lateral occipital sulcus—showed sensitivity to mirror reversals, suggesting that the orientation information that distinguishes an image from its mirror is present there. Although difficult to understand as a whole, this research still suggests that information about the left-right orientation of an object does not exist in the posterior fusiform sulcus, but is present in an earlier stage of the hierarchy of visual object information processing. It would therefore have disappeared!

5.3.3. *The dorsal pathway to the rescue of the ventral pathway*

There is a growing consensus that attention/dorsal and recognition/ventral-based processes should not be viewed as separate, but rather as complementary functions (e.g., Boros et al., 2016; Reilhac et al., 2013; Vidyasagar & Pammer, 2010; Zhou et al., 2016). Fernandes et al. (2016) subjected first graders and preschoolers to two matching tasks, one based on orientation, the other on shape. They found that performance on both tasks was associated with visuo-spatial

abilities known to be related to dorsal stream functioning only for first graders. Thus, it appears that literacy acquisition enhances the exchange between the two visual pathways.

Subsequent to Thiebaut de Schotten et al.'s (2014) observation that literacy acquisition is associated with a strengthening of left temporoparietal connections, Moulton et al. (2019) directly explored, longitudinally, in ten children at ages 6 and 7, the structural connectivity of the VWFA (see Note 8) emerging in early reading learning. In particular, they concluded that the most specific connections of the ventral VWFA were with the dorsal posterior parietal cortex. Furthermore, microstructural changes suggest that the localization of the VWFA depends on its connectivity with distant regions, in particular the left inferior parietal region. The latter may play a crucial role in visual field representations and eye movement dynamics, in addition to controlling attention in letter-by-letter reading and resolving mirror-letter ambiguity during the early stages of learning to read.

If the ventral pathway, which incorporates the VWFA, can recognize strings of letters it cannot precisely code the location of these letters. This last deficiency cannot be held responsible for the reversal of individual characters. It can only lead to one of two expressions of mirroring, namely the inverting of letters in a word (e.g., saw instead of was) or of digits in a number (e.g., $5 + 7 = 21$). Hypothetically, the rapid dorsal pathway would provide feedback to V1 and VWFA about where attention should be focused in order to specify their order in a word. But, in an attempt to move forward in understanding isolated character reversal, it is the notion of form- or object-centered intermediate representation (Vannuscorps et al., 2021) that we will primarily elaborate on. The detailed observation of a young girl—Davida—has largely contributed to this notion.

Davida is a right-handed, athletic, and highly cooperative young woman. She was 15 years old when this study began in October 2016 and 17 years old when it ended in March 2019. No other medical, neuropsychological, neurological, psychiatric, or ophthalmological history was noted in Davida. Although her vision and hearing screening also led to results within the norms, she had difficulty with reading beginning in the second grade. She perceived sharp-edged, medium to high-contrast 2-dimensional (2D) stimuli (e.g., numbers and road signs), as reflected on their own axes. This highly selective disorder contrasted with otherwise normal perception of 3D shapes, strongly blurred or with very low contrast. Such a perceptual peculiarity should have made her perceive b as d and p as q (and vice versa). Among the many tests Davida was subjected to was a memory writing test. She had to write, under dictation, a series of 15 letters and 15 words (see Fig. 32).

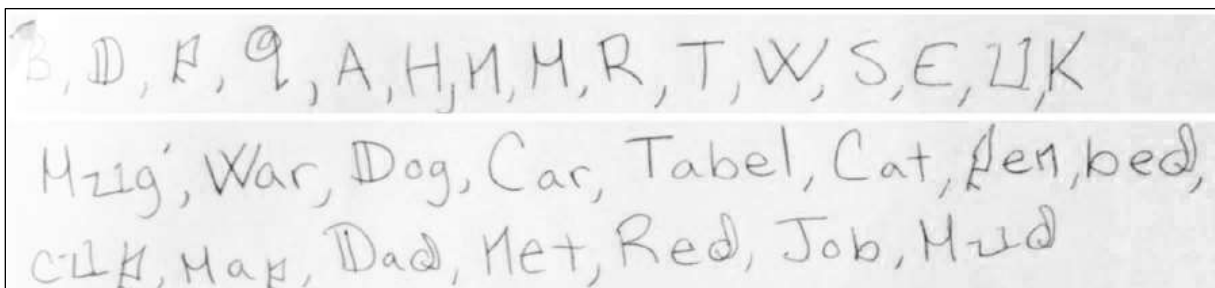


Figure 32. Idiosyncratic writings of the letters d and p (invented by Davida) allowing one to differentiate between d and b or p and q if one has not overcome mirror generalization. [Reproduced from Fig. S8 in Vannuscorps et al., (2021)].

She made only one mistake, reversing the last two letters of the word "table" (Tabel). But what is most interesting is that she used a personal font in which reversible letters are given different shapes. This personal font consists of doubling the hasta (vertical line) of the d (lower or upper case) and replacing the coda (semicircle) of the p (lower or upper case) by a kind of unclosed triangle. One can see the effectiveness of such a strategy. For someone who retains that b or p is constituted by a loop and an appended line that goes beyond it (above or below) without retaining that the loop is on the left or on the right, confusion with d and q, respectively, is inevitable (including when rereading one's own writings). In contrast, Davida's personal font makes b or p clearly distinguishable from d or q. In fact, she told the experimenters that she developed the font to be able to read her own writing.

Freud and Ahsan (2022) immediately elaborated on this observation of Davida to suggest that her specific deficit could be the result of a deficient dorsal to ventral flow of information. Indeed, this redefinition of the traditional role of the dorsal pathway is the subject of a growing body of literature (Gurariy et al., 2022). In section 5.2, we have already presented these two pathways—ventral and dorsal—of visual information processing. Their distinction is sometimes doubled by that of the parvo-cellular (ventral pathway) and magno-cellular (dorsal pathway) systems, which it is interesting to recall was—and still is—an explanatory theory of dyslexia (Livingstone et al., 1991). Freud and Ahsan note that the dorsal pathway receives most of its input from the magnocellular and koniocellular systems (konio in Greek can mean dust: these are neurons with a small cell body). Although they recognize that this separation is relative rather than binary, Freud and Ahsan support the hypothesis that different cortical regions may be involved in the computations of object-centered intermediate representations. In particular, it is plausible that the dorsal pathway computes its representations on the basis of magnocellular inputs, while the ventral pathway computes them on the basis of parvocellular inputs. Freud and Ahsan then announce the modeling by Ayzenberg and Behrmann (2022) that I will now comment on at length because it remarkably completes this part: after having seen how, from patch to patch, the orientation information disappears (Section 5.3.1), then having seen that it has indeed disappeared in the posterior fusiform sulcus (Section 5.3.2), I am obliged, since in fine almost all students manage to write/read without reversing b and d (among other things), to suggest how it could be restored.

It was already known that dorsal regions are sensitive to many spatial properties, among them orientation. Ayzenberg and Behrmann test whether the dorsal visual pathway represents the relationships between the component parts of an object and whether this information can support object recognition processes in the ventral pathway in 18 participants, or 12 to comply with pre-registration. To do this, they analyze functional connectivity, task-dependent, to see if dorsal regions of interest (ROIs) sensitive to relationships between parts are correlated with ventral regions. But establishing a correlation is not enough. It is critical to additionally test the direction of these interactions and, more specifically, whether dorsal cortex predicts the response of ventral cortex, rather than the contrary. From a temporal viewpoint, this leads to testing whether the encoding of relationships between parts in dorsal ROIs precedes the processing of objects in ventral ROIs.

In their Experiment 1, Ayzenberg and Behrmann first localize object-centered partial relations in the dorsal pathway. They identify them in the posterior (pIPS) and anterior (aIPS) intraparietal sulci (IPS: intraparietal sulcus) in the right hemisphere (rpIPS, raIPS) of each participant and in 10 of 12 participants in the left hemisphere (lpIPS, laIPS). But an analysis for

all participants leads to significant clusters of neurons only in the right hemisphere, and additional analyses suggest that partial object-centered relations are more strongly represented in right hemisphere parietal regions than in left hemisphere regions. Ayzenberg and Behrmann also determined ROIs of allocentric relations for each individual. These ROIs are the voxels that respond more to the distance condition than to the brightness condition. This allows them to suggest that the dorsal pathway represents object-centered part relations, and that this representation is independent of the allocentric spatial relations represented by the dorsal pathway (also of other object properties). Investigating the connectivity of IPS ROIs with a ventral region (LOC: Lateral Occipital Complex) then revealed significant connectivity between rpIPS and raIPS with bilateral regions of the ventral pathway. Taken together, these results thus suggest that dorsal regions involved in the computation of partial object-centered relations, particularly in the right hemisphere, are preferentially connected to the ventral stream to support object recognition. Yet Behrmann et al. (2006) previously reported that patients with LOC lesions and object recognition deficits were impaired in the perception of part relations. This suggests a ventral locus for object-centered relations opposite to that predicted. It became then essential to test whether the connection between the IPS and the LOC is dorsal → ventral directed.

For this last test, Ayzenberg and Behrmann use a method whose logic is, in its broad lines, relatively simple to understand. First, they calculate a statistic F_{dv} associated with the dorsal ventral effect and a statistic F_{vd} associated with the ventral dorsal effect (Fisher's F-statistic). If the direction is indeed, as predicted, dorsal → ventral, F_{dv} should be greater than F_{vd} , i.e. $F_{dv} - F_{vd} > 0$, for each participant. Then, they show with another classical statistic (Wilcoxon) that these differences are significantly above 0. Furthermore, from a temporal perspective, Ayzenberg and Behrmann point out, with reference to Figure 2 of Regev et al. (2018), that their result is consistent with research showing that information about visual objects reaches posterior parietal cortex between 100 and 200 ms earlier than ventral regions¹². They also mention research showing that topological properties of objects can only be represented in the ventral pathway by top-down connections, another argument for a dorsal → ventral stream.

In Experiment 2, Ayzenberg and Behrmann show that the regions of the right posterior IPS involved in computing relations between object-centered parts can support categorization of object exemplars. Such a result seems interesting to overcome the problem of the large variety of fonts and, even worse, of individual scripts. The results confirm that object processing in dorsal cortex precedes and predicts object processing in ventral cortex. Since character or word recognition is fundamentally a left hemisphere function, it is also important to note that the pIPS shows significant effective connectivity with the left LOC. This is consistent with the hypothesis that the pIPS propagates information about relationships between parts to the ventral pathway for such recognition.

In the discussion, Ayzenberg and Behrmann recall the temporal plausibility of their results, their agreement with top-down processes, and further point out that studies have also shown that temporary inactivation of posterior parietal regions impairs ventral object processing. They conclude that their results, in combination with these studies, suggest a causal role for dorsal

¹² The reference seems optimistic (in favor of the theory!). For example, Foxe and Simpson (2002) indicate an anteriority of information in the parietal lobe compared to the temporal lobe of about 10 ms, but anteriority nonetheless.

cortex in ventral object processing, in which dorsal cortex transmits information about objects to the ventral pathway to support object recognition. This role of the dorsal cortex could even be more important for writing than for reading. Indeed, comparing the brain areas critical for reading and writing in 111 stroke patients, Baldo et al. (2018) found that writing is primarily associated with the left inferior parietal cortex and reading with the left ventral occipitotemporal cortex. By highlighting the contribution of the dorsal pathway to the ventral pathway, where previously we were confined to the ventral pathway (Fischer & Koch, 2014), we believe better describe and understand the broader network that supports character recognition and writing.

A possible interesting facet in a discussion of Orton's (Section 1.6) and Corballis' (Section 5.1) theories is that Ayzenberg and Behrmann's results differ by hemisphere. Specifically, the coding of object-centered part relations is stronger in the right hemisphere in almost all analyses. This result reflects the classic global precedence effect of the right hemisphere in which global properties of the shape are most often represented, whereas local properties of the shape are represented in the left hemisphere. However, attention should be paid to the particularity of this effect for letters, a particularity that Lachmann et al. (2014) established with adult participants.

5.4. What mechanism for transmission from the dorsal to the ventral pathway?

I have described, with reference to Ayzenberg and Behrmann's (2022) modeling, the nature of the information—the relations of object-centered parts—that could be transmitted from the dorsal to the ventral pathway. In the case of writing, such transmission could be to a putative grapheme-related area partially dissociated in VWFA. Indeed, Bouhali et al. (2019) showed that the latter is functionally connected to dorsal parietal areas involved in letter-by-letter reading.

Once this dorsal → ventral transmission is accepted, the question of its mechanism and, from a developmental perspective, whether it is transitory or not arrives. On the latter point, the data of Chang et al. (2015), suggesting early visual tuning to important visual shapes such as letters, are consistent with a non-transitory nature. In contrast, the results of Hutchison and Gallivan (2018) clarify that the functional coupling of ventro-lateral Occipito-Temporal Cortex (OTC) areas to dorsal and ventromedial parietal structures is flexible and task-dependent. This suggests that regions of lateral occipital cortex, in particular, may play a non-definitely fixed role in mediating interactions between dorsal and ventral pathways.

One theoretically appealing hypothesis is that this mechanism could be an inhibition of mirror generalization (Brault-Foisy et al., 2017; Ahr et al., 2016, 2017; Borst et al., 2015). Indeed, if character orientation is present at the beginning of visual processing, inhibiting generalization would be sufficient to recover the original orientation in later processing. Since learning to read increases mirror discrimination as early as the first 100-150 ms (Pegado et al., 2014), inhibition would certainly have the advantage of allowing rapid suppression of mirror generalization. Perea et al. (2011) observed such inhibition for reversible letters on 4th graders. But in another domain—that of the interference between naive and scientific theories—where the implementation of an analogous inhibition mechanism seems indicated, it could be rejected (Stricker et al., 2021).

Harrison and Strother (2018) replicated Ahr et al.'s negative priming methodology on adults fairly completely, with the same priming letters and with targets that are images of animals.







But, while the presentation of primers is central, the presentation of targets can be lateralized (Expt 1) or not (Expt 2). This allows them to state that their results show that active inhibition of mirror generalization occurs in both hemispheres, and that it is related to—but distinct from—the right hemispheric advantage for recognizing that mirrored or repeated (translated) objects are the same. They note, however, that other studies suggest that inhibition of mirror generalization during letter and word recognition is automatic and occurs with recycled neural mechanisms in the left occipitotemporal cortex (Dehaene et al., 2010; Pegado et al., 2011).

This proposed inhibition of mirror generalization was supported by a research of Song et al. (2017). They found that parietal GABA level correlated with size illusion magnitude but not with orientation or brightness illusion magnitude. In contrast, occipital GABA level correlated with orientation illusion magnitude but not with size or brightness illusion magnitude. Because higher GABA levels are associated with better visual discrimination ability and less sensitivity to distraction, the inhibitory neurotransmitter GABA may be the agent of mirror generalization inhibition.

Finally, Xingliang and Houde (2021), two Chinese authors, have attempted a difficult synthesis. They present generalization inhibition as a quasi-unique process to remedy mirror reversal. Unfortunately, this synthesis is difficult to read (in Chinese, only the abstract is in English), uncritical and not always relevant. In particular, when the authors hypothesize that mirror generalization is a more important explanation than the cultural direction of writing, whereas the two follow and complement each other.

5.5. Some neuroscientific observations on adults

As already pointed out, neuroscientific observations on children, who are mainly concerned by this work, are rare for the double reason that the techniques used must be totally non-invasive, and that lesion studies are almost impossible (fortunately, due to the lack of participants). On the other hand, several researches on adults have studied their reactions to stimuli, notably alphanumeric characters, reversed in mirror.

Alivisatos and Petrides (1997) measured regional cerebral blood flow with positron emission tomography during a task in which participants (10 right-handed adult males) had to distinguish between normal and mirror images of vertically presented alphanumeric stimuli. Specifically, G, F, R were to be distinguished from , ,  and 2, 5, 7 from , , . Compared to the control task, they observed significant increases in flow in the right posterior superior parietal cortex and left inferior parietal cortex.

A lesion analysis allowed Martinaud et al. (2016) to study the discrimination of mirror stimuli (see Fig. 33). Their data suggest that the right visual dorsal pathway is essential for accurate perception of mirrored or rotated stimuli. But the selective cognitive process and an anatomical network underlying our ability to discriminate between mirrored images are different from the process of discriminating between rotated images.

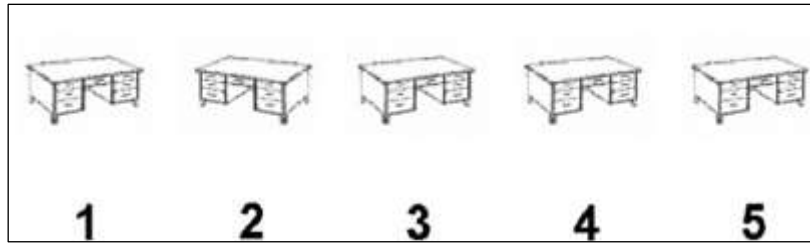


Figure 33. An example of mirror stimuli in the observation by Martinaud et al. (2016). Patients were asked to indicate the number of the image that is not in the same direction as the others.

Studying stimulus- or event-related potentials (ERPs), by using electroencephalographic techniques, Carreiras et al. (2013) confirmed that the initial component (around 150 ms) of the electrical activity corresponds to the visual shape of the letters, and that a later component (around 300 ms) corresponds to a more abstract shape. By further investigating the visual shape-related component, again by ERP, an orientation sensitivity could be observed around 100-140 ms, as well as a larger amplitude response for reversed characters than for normal characters (Milivojevic et al., 2011; King, 2012).

We can conclude that a certain specificity of mirror images remains in adulthood, and that their recognition or discrimination still seems to involve the dorsal pathway. However, this research, apart from the fact that it concerns adults, does not focus on writing, but on the recognition or identification of mirror images, tasks which we shall see may have little in common with writing (Section 8.1). The reason for this lack of observation on writing (or drawing) is certainly methodological: inversions in writing/drawing by adults would be rare (and therefore difficult to analyze statistically) and are more difficult to evaluate objectively than recognition or discrimination responses, which are often binary or, at least, with a limited number of response choices.

6. The mystery unraveled

6.1. Characters differ in their frequency of reversal

As we highlighted in Section 1.9, by the mid-20th century educators had clearly seen that characters are not reversed as frequently as one another. Simner (1984), near the end of the century, had observed the preferential reversal of d-type letters compared to b-type letters. This general result, of a difference in the frequency of reversal according to the characters, had thus clearly appeared before the end of the 20th century. But Simner's research had not supported predictions of left-handed reversal and came at a time when the tsunami of the studies of this prediction had not yet fully calmed (see Section 1.4). As noted by Treiman and Kessler (2011), this may explain why Simner's work did not have much impact.

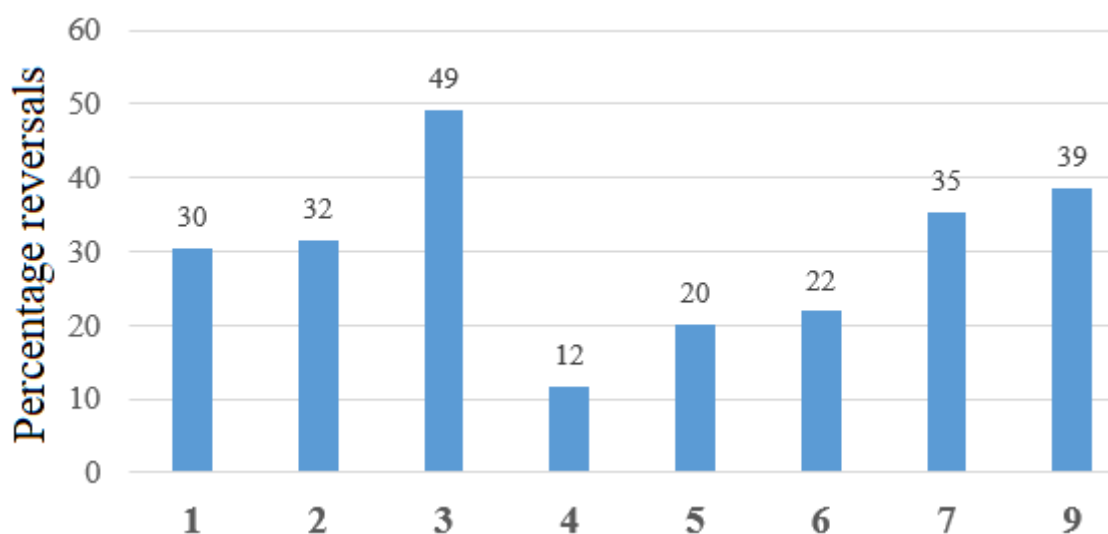


Figure 34. Mean percentage reversals of the eight reversible digits. [Weighted averages of 6 studies; 1563 children of kindergarten, mean age 5 years 8 months; for details see Fischer & Luxembourger (2018a), Table 1].

Although children produce millions of mirrored characters annually in French schools alone (especially kindergartens), no one, to my knowledge, had tried to establish the frequency of these reversals as a function of the characters. For well over 10 years, starting in 2008, we have tried to do so by controlling as much as possible the conditions of writing. For the good reason that children mostly produce reversals when writing from memory (see Section 4.3), we quite systematically dictated the characters (digits and capital letters), except for their first name, which the children wrote alone from memory. Children who did not know how to write a character were instructed to put a cross in the square corresponding to that character. Because we have almost exclusively dictated the characters to children of 5 years or older, the number of these crosses is, in general, negligible. For the coding of the writings, it is important to specify that only the orientation was judged without any requirement of a high quality for the other components of the form. For the calculation of the percentages, shown above the bars in Figures 34 and 35, the number of horizontally mirrored writings was related to the number of theory-relevant writings (horizontally mirrored or correct writings). Not taking into account the other types of mirrors only slightly increases this percentage compared to a percentage calculated on the totality of exploitable writings, because the other mirrors are very few (they mainly concern

a confusion between 6 and its double mirror, 9). We summarize the results obtained in the two figures 34 and 35.

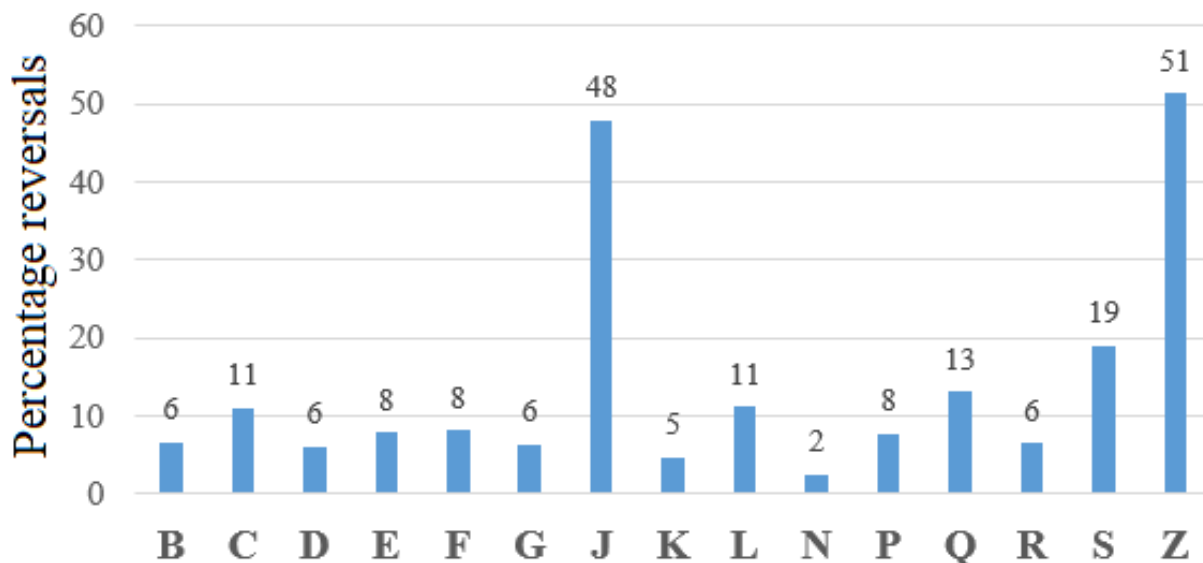


Figure 35. Mean percentage reversals of the 15 reversable capital letters. [Weighted means of 4 studies; 679 children of kindergarten, mean age 5 years 8 months; for details see Fischer & Luxembourger (2018a), Table 2].

For capital letters, Figure 35 highlights the two capital letters Z and J. For Z, there are even more than 50% reversals; this means that there were more horizontal reversed writing than correct writing! Note, however, that for J, we did not distinguish with its lower case j which has the same orientation. These reversals of Z and J fit perfectly with both the theoretical analysis and the students' judgment of their orientation (see Section 2.1). The peculiarity of these letters was also apparent in our analysis of the historical evolution of writing.

For lowercase letters, I explained in Section 4.7 that they are not an ideal material because, at the typical age of reversal, children often do not yet know them well enough. A statistical evaluation will therefore result in the exclusion of many children or an abundance of missing data. This may bias the comparison of reversal frequencies between letters, and has caused some researchers, as Ritchey (2008), to refrain from presenting them. This is also the case for McIntosh et al. (2018b), who had asked their Scottish students to write the lowercase letter after the uppercase letter, but gave up on analyzing their data on these lowercase letters. Because they were published as supplementary data, we nevertheless analyzed them. The missing lowercase letter writings were mostly for lowercase letters with very similar corresponding capital letters (e.g., c and C). I therefore considered that the students who had just written this capital letter did not want to produce an identical writing immediately after. For these lowercase letters (c, f, j, k p, s, and z), I then repeated the writing (correct, reversed, or missing) of the corresponding capital letter. Figure 36 shows the percentages which, thanks to these repetitions, could be calculated for more than 20 children.

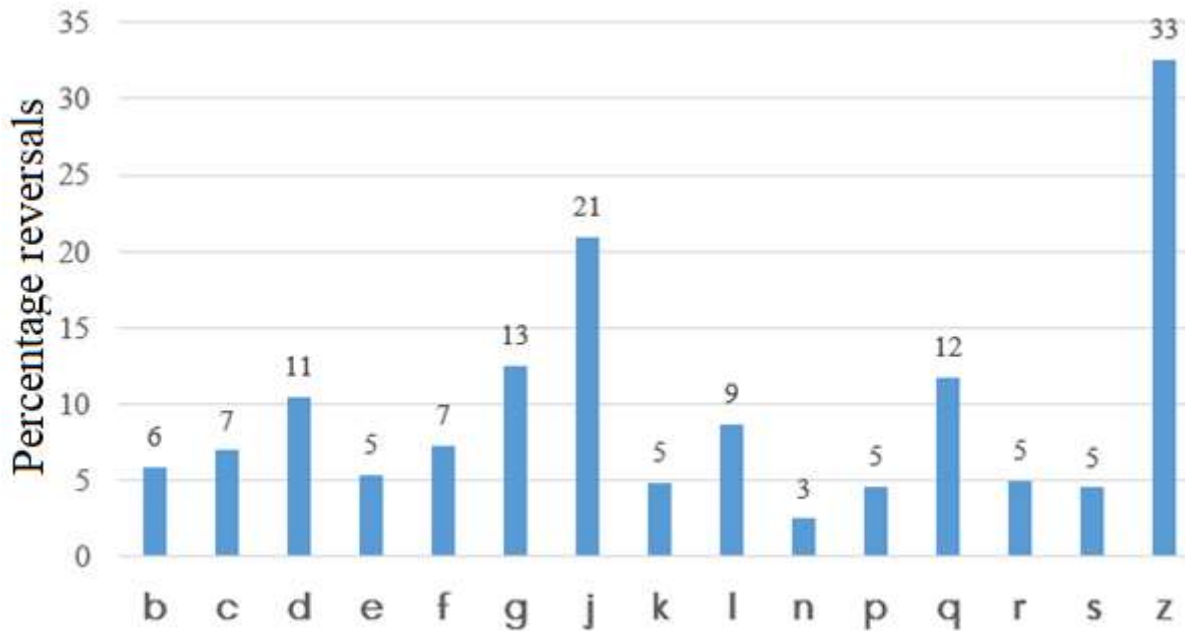


Figure 36. Mean percentage reversals of the 15 lowercase letters corresponding to the 15 reversible uppercase letters, calculated from the augmented data (see text) of McIntosh et al. (2018b, Study 1).

Figure 36 confirms that, for lowercase letters too, z and j are the most frequently reversed letters. Another interest of the figure is to show the influence on their frequency of reversal of the letters whose orientation changes when one switches from writing them in upper case to writing them in lower case. This is the case of the capital letters D, G, Q oriented to the right and which are clearly oriented to the left when written d, g, and q (see Section 2.1). These three letters then appear most frequently reversed, after z and j. As a result, the 5 lowercase letters oriented to the left (z, j, g, q, d) are each more reversed than all the lowercase letters oriented to the right (b, c, e, f, k, l, p, r, s) or with undetermined orientation (n).

To overcome this problem of children's insufficient knowledge of lowercase letters before elementary school, McIntosh et al. (2018b) tested Irish students whose school system teaches lowercase letters early on. Their data include at least 80 respondents for each letter. But, presumably not wanting to mix two problems (see Section 8.2), McIntosh et al. excluded the reversible letters b, d, and p (i.e., all but q).

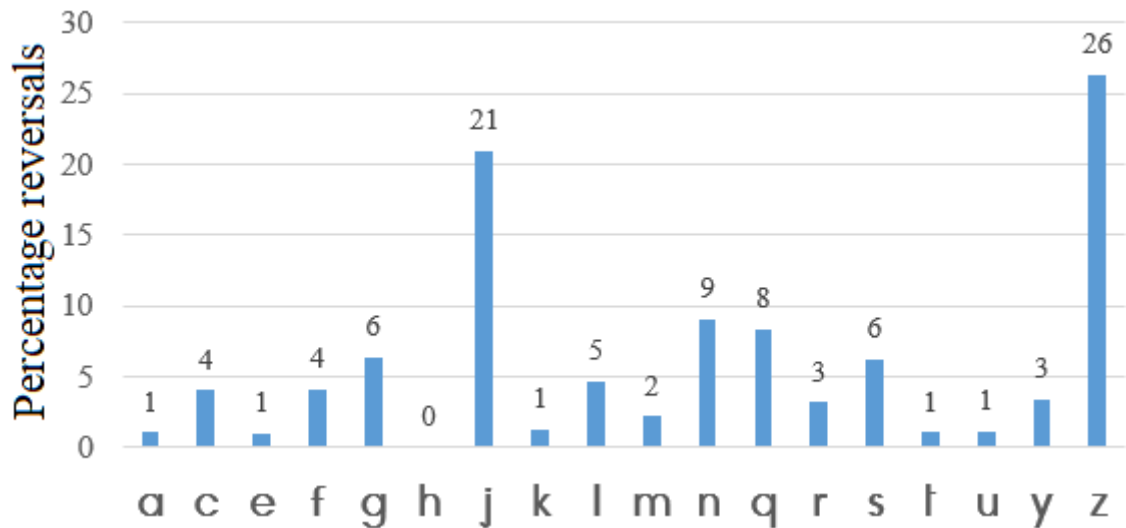


Figure 37. Mean percentage reversals of 18 lowercase letters, corresponding to the 26 letters of the alphabet, minus 5 non-reversible letters and 3 reversible letters, calculated from data in McIntosh et al. (2018b, Study 2).

Figure 37 again clearly confirms that z and j are the least reversed letters. The difference between left-facing letters (z, j, q, g, y, a) and right-facing letters (n, s, l, c, f, r, e, k, h) in Treiman et al.'s student assessment (see Section 2.1), with l, m, t, and u being neutral, is not as perfect as the one obtained in the preceding analysis. This imperfect differentiation may, however, stem, in part, from questionable categorization, or from writing whose orientation is difficult to judge. This is particularly the case for the right-oriented letters n and the left-oriented letters a and y in the evaluation by Treiman et al. These letters greatly reduced the difference in reversal between left- and right-oriented letters.

It thus appears that, for lowercase letters, j and z are the most reversed, as are J and Z for uppercase letters. This observation is not surprising since j and z are not very different from J and Z, at least as far as orientation is concerned. In addition, we also retrieve, although less clearly than for uppercase letters, the contrast between left-oriented letters (frequently reversed) and right-oriented letters (less frequently reversed).

6.2. The universality of the frequency hierarchy

The contrast between the numerous reversals of 3 and the rare reversals of 4, as well as the reversals of J (or j) and Z (or z), which clearly dominate those of the other letters, raise the question of whether such a differential susceptibility to reversal has been frequently observed. Unfortunately, research that has systematically observed the writing of reversible capital letters and digits from memory (with their dominant hand) by children of the age to reverse them—say, 4 to 7 years old—is rare. We can accept some deviations from these conditions. However, the task must be a writing from memory task. Indeed, we have seen that copying is a fundamentally different task from writing from memory (see Section 4.2). When the task proposed to the students allows for some copying—even if it is only partial, as in Simner (1984) where the children looked at the character for 2.5 s before writing it—it is not clear what is being analyzed. As a consequence, the results are difficult to interpret. I find it hard to understand why experienced researchers are not aware of this, when it is obvious that one can copy Chinese characters (for example) while being totally unable to write one from memory.

We now analyze, for comparison with our own, the data of McIntosh et al. (2018b) for the 15 reversible capital letters. These data were obtained in the first study, on 44 Scottish (Edinburgh) children aged 4 ½ to 10 years (nearly 7 years on average), writing with their dominant hand. The data correlate well with ours in Figure 35, $r = 0.76$. In particular, in McIntosh et al.'s data, Z (33% reversals) and J (26%) are the two most frequently reversed letters. The quantitatively lower percentages can, at least in part, be explained by the higher average age of their Scottish participants. In addition, McIntosh et al. ensured that the participants could read the letters before writing them.

Janet Richmond tested 126 students in grades 1-4 in Australia. The children were asked to write the alphabet and digits from memory (Richmond, 2012). In a poster presented at the Australian Occupational Therapy Association Conference in the Northern Territory (Darwin, Australia), she only very briefly presents the results of these writings for letters written in lowercase script. Since the letters j and z (in script) show the same orientations as their uppercase counterparts J and Z, Richmond's reversal percentages can nevertheless be compared to ours for these two letters and some others (c, p and s). Here they are: j (9.5%), z (11.9%), b (0.8%), c (0.8%), i (0.8%), q (0.8%), t (0.8%), d (1.6%), l (1.6%), p (1.6%), s (2.4%). These percentages, at least those which are comparable (j, z, c, p and s), agree almost perfectly with ours, showing in particular that the frequencies of reversal of j and z dominate those of the other letters. The fact that these frequencies, of about 10%, are lower than ours (of about 50%) can be explained by the age of the students, which exceeds 7 years for most of them. Richmond does not indicate reversals for the digits: the age of the children suggests that she has hardly observed any.

Kristen Ritchey, from the University of Delaware, tested letter writing (lower and upper case) on 60 kindergartners, average age 5 years and 9 months, from the northeastern United States (Ritchey, 2008). Although she does not report reversal percentages, her graph (after rectifying the legend!) allows us to calculate them approximately for all reversible uppercase letters: Z (35%), C (22%), J (17%), S (13%), with all the next 11 letters at less than 10%. One is a bit surprised by the presence of C as the second most reversed letter. Ritchey explains this by the change in direction involved in drawing it, an explanation that also applies to S and Z. But the Australian students of Richmond, the Scottish or Irish students of McIntosh et al. and our French students also had to change direction and did not reverse the letter C much! We will put forward another explanatory hypothesis at the end of the section.

Recently in England, Sylke M. Göbel (the name is also spelled Goebel) and colleagues (Göbel et al., 2019) reported observations of English children, at the Mathematical Cognition and Learning Society conference held June 16-18, 2019, at Carleton University (Ottawa ON, Canada). The digits 1-9 (not in their natural order) were dictated three times, along with the letters, to students in two grade levels: 84 children 49-75 months old were in the year before first grade (Year 0), and 75 children 58-80 months old were attending first grade (Year 1). The authors report reversals of individual characters only for digits. Omitting 1, which is not reversible for a portion of English children who write it without the small diagonal line at the top left, the graph in Göbel et al. shows the following hierarchies of reversals:

- In Year 0: 9 (almost 60%), 7 (50%), 3 (almost 50%), 2 (almost 40%), then, much less reversed, 5 (barely 10%), 6 (less than 10%) and 4 (about 5%).
- In Year 1, 3 (almost 20%), 9 (over 15%), 7 (over 10%), 2, 5, 6 and 4 all below 10%, with 4 close to 0%.

The mystery unraveled

It is interesting to observe that the participants in Year 0 are approximately the same age as our participants. At this age, Göbel et al.'s data show impressive percentages of reversal, around 50%, like the one we observed for 3 (see Fig. 34). We also observe that 3 is the most frequently reversed digit in Year 1, while 4 is very rarely reversed, and even the least reversed digit in both years.

In France, but in a region—the South-West—almost diagonally opposite to the one—the Lorraine—where Fischer et al. made almost all of their observations, Marine Portex studied only a few letters and digits. But the experimental conditions perfectly match our requirements (Portex, 2017; Portex et al., 2018). Indeed, because she implemented prior learning, she was able to test writing under dictation with 30 very young children (4 years 3 months to 5 years) of a few characters: B, E, N, R, S, J, Z, 1, 3. Under normal writing conditions, i.e., from left to right, J, Z, 1, and 3 were reversed considerably more frequently than the other characters: J, 1, and 3 were reversed nearly 70% of the occasions, Z more than 50%, N and S 10% or less, and B, E, and R, not at all. Once again, the dominant reversal frequency of the letters J and Z was clearly confirmed, as was the impressive reversal frequency of the digit 3.

Among the research from the second half of the 20th century that more or less satisfies my conditions, I was able to select those of Zaslow (1966) and Suggate et al. (1997). Robert Zaslow, from San Jose State College (California), undertook a learning experiment with 80 students with reversal problems, most of whom were 6 or 7 years old, but some of whom could be older. He reports the frequencies of reversal for the digits fairly consistently, but simply states that the letters Z, b, and C were the most frequently reversed. For digits, the descending order by frequency of reversal is: 2 (25%), 7 (19%), 3 (17%), 9 (% not indicated), 6 (9%), 5 (8%) and 4 (6%). These reversal frequencies are consistent with the distinction between the left-oriented digits of $Dl = \{\text{(possibly 1), 2, 3, 7, 9}\}$ and the digits of $Dr = \{4, 5, 6\}$.

Jennifer Suggate et al. tested sixty-seven 4- and 5-year-olds at the beginning of their first school year in England (in September or January) and at the end of the first school year (in July). They asked the children to indicate on a piece of paper how many bricks there were (from 1 to 10). Between the initial and final tests, the percentage of reversed digits increased slightly, from 19% to 24%, but the order of digit reversals was the same, with 7, followed by 2, 9, and 3, being the most prone to reversals and 4, 5, and 6 being the least prone to reversals. This order of digits, according to their frequency of reversal, is also in agreement with the distinction between the digits of Dl and those of Dr .

As Zaslow's experience, reported above, suggests, universality also holds over time. Although I am not aware of any systematic study of mirror writing under the desired conditions (characters written from memory, with the dominant hand, children under 7 years of age) in the first half of the 20th century, I can refer to a few figures presented in the historical section and to an anecdotal observation by Hildreth (see Fig. 38). The latter observation shows that in 1934, at barely 5 years of age, Robert was already clearly orienting the letters in the direction of writing. Figure 6 shows that in 1936, John had only reversed J in the writing of his first name. Almost in the same year, Figure 3 shows that Thomas had, in perfect agreement with the reversal according to our categorization of the characters (left oriented or not), reversed 2 and 3, but not 4 and 5 (1 is neutral in the USA). And even, already in 1901, Figure 2 reproduced reversals of 2 and 3 by a right-handed child.

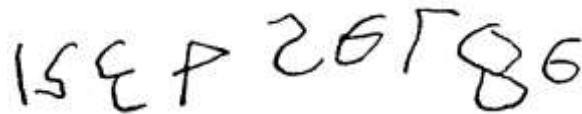

 A handwritten sequence of digits: 1 5 2 7 8 6. The digits are written in a simple, childlike style with some irregular spacing and a slightly slanted orientation.

Figure 38. Robert (5 years old) spontaneously writes the sequence of digits out by interest. [Reproduced from Hildreth (1934), p. 3].

Concerning this universality in time, and the rarity of well-controlled observations of character reversals in the 20th century, it must be recognized that such observations are easier today. Indeed, contemporary children are encouraged to write younger and younger, both by their family circle, who want give them a good start in life, and by some educational systems, worried that the performance of students is not up to the desired level in international comparisons. In this regard, it is worth recalling that only half a century ago, at least in France, there would have been talk of children learning to write prematurely at the age of 4 or 5. In 1982, the well diffused French journal "Le Monde de l'éducation" wrote: "For five-year-olds, learning to count to 10 is of little use (if not to please the parents)". A fortiori, the same journal would certainly have condemned the practice of writing numbers by children who do not see any sense in it! Writing, which is encouraged at an early age today, has certainly favored the observation of the numerous mirror writings in our research. The results of Johansson (2005), who directly compared the reversal of numbers by Swedish children, around the year 2000, to those of old research, around the year 1950, corroborate an increase in the frequency of mirror writings. With a comparable number of correct writings, the 6 year olds (not yet enrolled in school in Sweden) of his observation produced 2.4 reversals, whereas those of the 1950s (1942 to be precise), aged 7, produced only 0.9 on average (scores out of 10).

In conclusion from these observations in different parts of the Western world and secondarily over time, it is clear that Z and J are two very frequently reversed upper (and lower) case letters, often significantly more so than the others; also that the numerals 4, 5, and 6 are less reversed than the numerals 2, 3, 7, and 9 (and 1 when appropriate). This confirms the universality of the greater frequency of reversal of the characters 2, 3, 7, 9, J, Z, and possibly 1, compared to the other characters. At the level of individual characters, in addition to J and Z, 3 is also frequently reversed. Nevertheless, these frequency hierarchies must be qualified: 3 for example does not always seem as frequently reversed in other countries as in France; C seems frequently reversed at least in some regions of the USA (northeast, California). As explained in section 2.4, it is not so much the orientation of the letters per se that matters, but this orientation in interaction with the layout taught to the children. The insistence in France on counterclockwise drawing of circles (see Sections 7.2 and 7.5) helps explain both discrepancies: it induces both the mirroring of 3 and the correct writing of C. Finally, special mention must be made of 4: in all the Western cultures I have been able to examine, it is the digit that is most resistant to the mirroring error. In Fischer (2013a), I had explained why the dynamics of its writing are in perfect harmony with the writing from left to right. With the terms and notions introduced in section 2.1, I can say that the morpho-kinetic and topo-kinetic of writing 4 coincide, regardless of the morpho-kinetic induced by the child's teaching or environment.

6.3. An apparently discordant observation

One of the reasons why the explanation for the reversal of characters has been slow to be understood is that the literature, especially the early literature, contains conflicting observations. Often the age of the children is a relevant and sufficient explanation for the observed

discordances. But this is far from being the only explanation. An observation by Legrün (1931) seems particularly interesting and important to analyze because it leads, in view of our observation of the frequent reversal of 3, to a result at the exact opposite of ours, since 3 turned out to be the least reversed digit. Let's analyze this observation closely.

Alois Legrün had, by 1931, already published several articles on mirror writing: in 1921, an article entitled "Mirror writing" (*Die Spiegelschrift*) in a journal for in-service teacher training (*Lehrerfortbildung*); in 1928, an article on mirror writing generated by the right hand (*Über rechtshändige erzeugte Spiegelschrift*) in a journal of educational psychology (*Zeitschrift für pädagogische Psychologie*), and, in 1929, in the same journal, a clinical article on the left-handed writing of a right-handed hemiplegic student (*Über die Linksschrift einer rechtsgeläimten Schülers*). In his new article from 1931, Legrün reports observations on children entering school who had to write down, from memory, the numbers they knew. Specifically, the arithmetic teacher Konrad Falk (whose books from the 1920s can still be seen on the Internet) had asked two female teachers in Vienna to test their pupils at the beginning of the obligatory school year. In 1930, one of the teachers, Mrs. Fechner, made the observation on September 18 and repeated it on October 24, while the second teacher, Mrs. Kreith, made the first observation in the week from September 29 to October 4, and the second on November 13. Between the two observations, the children did not learn to write digits and were only in contact with numbers in the form of numbers on notebooks, boxes and other items (catalog numbers).

The observations, when compared with our own, are surprising: "3" is indeed among the three less reversed digits. In the last point of the summary, Legrün writes: "The individual digits do not elicit, to the same extent and with the same constancy, a mirrored representation; the digits 6 and 9 are reversed most often, the digits 2, 3 and 5 more rarely" (p. 557). To try to determine the origin of the discrepancy between our observations and those of Legrün, I constructed a table from his data. Except one error in the total (1001 instead of 901, with an impact on the percentage) and some of Legrün's unconventional rounding, I was able to replicate his totals and percentages. By combining the 2 x 2 testing sessions, I obtained a total of 6389 digits written "spontaneously", mostly in the natural order according to the reproduced children's productions. Among those, 687 digits were mirrored, that is to say approximately 11% if one includes the digits 8 and 0 (as Legrün did), or 12.5% if one excludes 0 and 8, which could not be (and were not) written in mirror.

In my table (not reproduced), it is confirmed that 9 is, with 23%, the most mirrored number, before 6 (19%), 1 (15%), 4 (13%), 5 (9%), 3 (6.5%) and 2 (6.2%); these percentages differ slightly from those established by the author because he did not weight the means. With the unweighted means 3 really does rank last! Many explanations, which are not only not mutually exclusive but may even interact to contribute to the observed discrepancy, can be advanced.

(1) Student age. Contrary to our observations in kindergarten, where the children have an average age of less than 6 years, the pupils at the beginning of obligatory school should have an average age of more than 6 years. Let us specify that the children entered school at 6 years old, even if there is a slight ambiguity because the author speaks of the 6th year of life (but it would be unreasonable to think that the children entered school at 5 years old) and that there was a tolerance of 4 months for those born at the end of the year. In the year of observation (1930), school started on September 16.

(2) The nature of the task. Students spontaneously write the numbers they think they can write. Certainly they write them from memory, but the retrieval is not based on the number word heard by the student, as in the case of dictating numbers not in their natural order.

(3) The count of the writings. The numbers were written unevenly: 1 was written 1840 times, about 5 times more than 7 or 9 (351 and 371 times); 3 was written 696 times. This is explained by the fact that the children wrote more two-digit numbers beginning with 1 than two-digit numbers beginning with 7 or 9. On the one hand, they probably knew how to write the latter less well, and on the other hand, they generally had less time and less space to write them, if they wrote the numbers in natural order. In one session, each student wrote, on average and approximately, 52 digits, which corresponds to the writing of numbers from 0 to 30. A theoretical simulation suggests that a student who is not very advanced in writing the numbers and who has only reached 9, has written only one 3, while a more advanced student who has written the numbers up to 39 has written fourteen 3. There is reason to believe that a 6 year old student with a low level of development is more likely to mirror write than a 6 year old student with an advanced level of development. We can therefore see how the correct writing of 3, which is over-represented in the numbers from 30 to 39 written by the most advanced pupils only, could have contributed to the low percentage of mirroring of 3. A simulation convinced me that this is a major explanation since I got 18% of mirror of 3 by limiting the analysis to numbers up to 29.

(4) The quality of the observations. The experiments were carried out by two different teachers in a classroom situation (30 or more students in each), with the instructions of a didactician. It is therefore by no means certain that the latter, nor the teachers, thought of taking down the character displays (letters and numbers) that are usually found in classrooms in the first year of school. Some children were able to copy the numbers on these displays, and also on their classmates. Besides, there is no correlation between the percentages of mirroring of the 8 reversible digits in the two classes: for the two sessions combined, $r = .04$; for the first session, the correlation is even negative, $r = -.33$. This suggests that the two classes were tested in different conditions. The intra-class correlations between the two tests (spaced about 5 weeks apart) are themselves quite weak ($r = .22$ and $r = .46$) and sometimes surprising. In Ms. Fechner's class, for example, 6 was the least mirrored in Session 1 (6%), but the most mirrored (21%) in Session 2!

(5) The uncertainties of the coding. The problem of the 9, which in double mirror becomes 6 (or vice versa), is not mentioned. Moreover, in his figure 6, Legrün reproduces a 4 in a vertical mirror (i.e., with respect to a horizontal axis of symmetry). This suggests an inclusion of non-horizontal mirrors in his coding of mirrored writing. Such an inclusion probably contributed to the high frequency of inversion of 6 and 9, which are the two digits most frequently subject to vertical or double inversion in our observations.

6.4. The decisive contribution of the writing of first names

Anecdotal (e.g., Legrün, 1931; Hildreth, 1950a, see also Fig. 7) or moderately well-controlled (Cornell, 1985) observations have long shown that when children write from right to left, they reverse the letters facing right to left, i.e., in the direction of their (non-usual) writing. In our research, we used Cornell's procedure of dividing a sheet of paper by a vertical line, and indicated to the child, with a dot, the starting point for writing his or her first name. The starting point could be to the left or to the right of the vertical line (the dots are visible in Fig. 39, 40

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and 43). Cornell had indeed noticed that, when the dot is on the left, young children quite easily start writing (completely) in mirror so as not to cross the vertical line. We have thus been able to obtain more than a thousand first names written in mirror. We sometimes call them spontaneous as opposed to procedures where children are explicitly asked to write in mirror, "backwards". Although we sometimes speak of a constrained condition, we have never forced children to write mirrored, backwards, and have accepted writing that crosses the vertical line, such as ELIES (see Fig. 39). But we are obviously aware that these mirror writings were induced by our procedure and that some children were "guessing" our desire to get such backwards writings. A 5-year-old girl said to me: "Ah! You want us to write backwards. In the past I knew!"

Figure 39 first illustrates a range of possibilities. The children were able to write, still with their dominant right hand, in uppercase, from right to left, reversing (1) all the reversible letters, (2) some of the letters, or (3) no letters. They could also write (4) normally from left to right. Finally, we also added (5) right-to-left writing in attached cursive lowercase letters to suggest that, with this sort of writing, children are almost forced to systematically reverse letters.

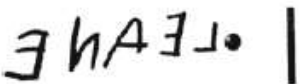


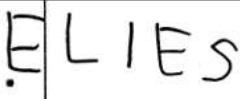
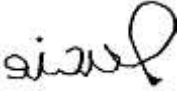
Child	Writing point on the left	Comment
(1) Leane, 6 years 1 month		Written from right to left, with all reversible letters, L, E (twice), and N reversed.
(2) Capucine, 5 years 3 months		Written from right to left, with all reversible letters reversed except E.
(3) Anissa, 5 years 4 months		Writing from right to left, without any reversal of the asymmetric letters, N and S (twice).
(4) Elies, 7 years 0 month		Writing from left to right crossing the vertical line. Note that the student, who is 7 years old, was in first grade.
(5) Lucie, 5 years 9 months		Writing from right to left, with all letters reversed. With the cursive lowercase letters one can see that the 'l' is reversed.

Figure 39. Different types of writing in the condition with the dot to the left of the vertical line always produced by children with their dominant hand.

Because all children who produced writings in the dot-left condition also wrote their first names in the dot-right condition and were tested on writing isolated capital letters under dictation, we were able to calculate three different correlation coefficients (Fischer, 2017). The first one, between reversed letters when name-writing in both conditions—placement of the starting point of writing on the left and on the right—is certainly the most surprising one because the very strong correlation is negative. This is surprising because one might have thought that if children tend to reverse letters they would reverse them independently of the conditions; or that if children orient letters to the right because they have realized that most letters are oriented to the right (statistical learning), they always orient them to the right. This is clearly not the case. On the contrary, the reversal of the characters in their first name seems to be fundamentally determined by the direction of writing (see Fig. 40). When children write toward the left, the many right-facing capital letters are most often turned to the left, therefore reversed, whereas

when they write toward the right, the same capital letters are oriented to the right, therefore correctly written! To illustrate this negative correlation, we can consider the letter E, which is very present in the children's names. When writing names to the right (usually in the dot-right condition), less than 1% of the letters E were reversed; but when writing names to the left (usually in the dot-left condition), 84% of the letters E were reversed.

Dot on the left	Dot on the right	Dot on the left	Dot on the right
EWITTEIEM	•MARIETTE	YVNEJ	•IENNY
TUABIH	•THIBAUT	EMIZAY	•ENISSINE
ENIENINE	•VALENTINE	MEKREJ	•GURKEM
LOJ	•LOIC	•DORIAN	•DORIAN
EMAXENCE	•MAXENCE	•ALDIN	•ALDIN
•ROBIN	•ROBIN	•LISA	•LISA

Figure 40. A sample of writings (always produced with the dominant hand) of their first names by children participating in Fischer and Tazouti's research (2012, Expt 2). First names are written correctly on the right (normal condition) and completely reversed (constrained condition due to the vertical line and the starting point on the left of the vertical line).

The two other correlation coefficients calculated are in perfect agreement with this first observation. On the one hand, the correlation between the reversal of the isolated letters and their reversal when writing normally the name, towards the right, is positive (and strong). On the other hand, the correlation between the reversal of the isolated letters and their reversal in the name writing to the left, induced mainly by the dot to the left of the vertical line, is negative (and quite strong).

These results led us to speak of a rule of orientation of characters in the direction of writing, which encompasses or implies a rule of orientation to the right in our culture. They are qualitatively and quantitatively impressive and were confirmed in Marine Portex's independently developed thesis (although I was later a member of the thesis jury). We describe this thesis in more detail in the next section.

6.5. A confirmation of the orientation in the direction of writing

We have previously referred to the research of Marine Portex (2017; Portex et al., 2018). Through prior learning, she asked very young children to write not only characters but also whole French words from memory: BISE, NEZ, OURS, JOUE, and ROSE (KISS, NOSE, BEAR, CHEEK and ROSE).

The mystery unraveled



Figure 41. The 7 picture cards that served as the visual support for the story, a support for learning to write whole words. [Reproduced from Portex (2017), Fig. 23].

Learning to write was based on an attractive story: "When you give him 3 KISSES on his NOSE, little BEAR has 1 PINK CHEEK" which could be illustrated with cards as in Figure 41. Next, Marine Portex repeated Cornell's (1985) two writing conditions, normal (right of vertical line) and constrained (left of vertical line). Portex et al. (2018), in their paper taken from the thesis, reproduced a child's productions, putting the writing in both conditions face to face (see Fig. 42). In the figure, it can be seen that the word writings to the left of the line are almost completely mirrored: writing (most likely) from right to left, and reversing all individual letters, except J and Z. On the other hand, the writings of words to the right are almost completely correct: only the letters J and Z are reversed. The latter letters are quite remarkable: when the child writes normally, he reverses J and Z, but when he mirror writes he writes them correctly! The digits 1 and 3 are similarly remarkable: mirrored when the child seems to write normally and correct when he seems to write mirrored.

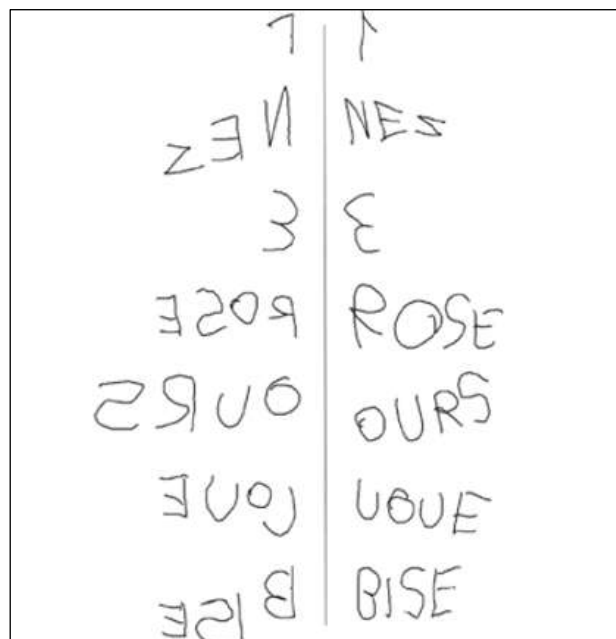


Figure 42. A child's productions in the two conditions, constrained on the left, and normal on the right. [Figure reproduced from Portex et al. (2018), Fig. 3].

This observation, in particular the a priori curious but quite logical correct writing of J and Z when children mirror write, is not anecdotal. We also noted all sorts of tergiversations around the letters J and Z. Figure 43 shows that when children write J correctly in the normal condition, they may reverse it (Jeanne) or write it correctly (Juliette) in the constrained condition. But what is most interesting is to see that those who reverse it in the normal condition (Hadjer and Jarod), write it correctly in the constrained condition even if, like Hadjer, they reverse all the other reversable letters. The letter Z was less present in the children's names, despite the

popularity of the world champion footballer Zinedine Zidane! But one of the few children who had it in his first name (Zacharia) did reverse Z when writing it normally and wrote it correctly when writing his first name in mirror!



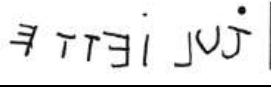
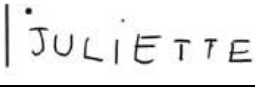


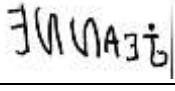
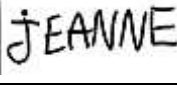

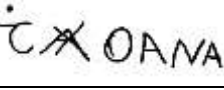
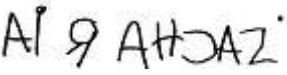
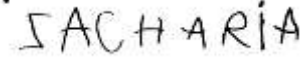
First name & age	Constrained condition	Normal condition
Hadjer, 5 years 10 months		
Juliette, 6 years 2 months		
Doraj, 5 ans 8 months		
Jeanne, 5 years 2 months		
Joana, 5 years 2 months		
Zacharia, 6 years 0 month		

Figure 43. Children's tergiversations about writing J and Z in their first names.

6.6. The mountain gives birth to a mouse!

At this point we have surveyed a literature—over a hundred articles cited, perhaps many omitted!—on the mirror writing of typically developing children. The clear finding is that children reverse characters relatively often, but not at all randomly. They preferentially reverse digits (1, 2, 3, 7, 9) and upper case (J and Z) or lower case (j and z, in particular) letters oriented to the left.

The explanation for this may seem derisory simple: children reverse characters, sometimes groups of characters (words, numbers), simply because they do not know (yet) their orientation and then do it in the direction of the writing of their surrounding culture! This leads them to preferentially reverse, in our culture, the letters oriented to the left. We will propose a slightly deeper explanation in conclusion, by making a link with the historical development of writing in the course of humanity, a link that we have already partially made for the letters J and Z.

This simplicity makes the misunderstanding of some authors—who oppose the neurobiological theory of mirror generalization and the cognitivist theory of orientation in the direction of writing—difficult to understand. Let us therefore repeat that the two theories complement each other, the first being a prerequisite for the second. If the orientation of the characters were not erased in memory because of the mirror generalization, children would not need to make a choice of this orientation. The choice, which they make statistically in the direction of writing, and the reversals to which it leads as a result of the orientation and of the dynamics of the characters' writing, thus support, in return, the hypothesis of the generalization in memory (without which they would not need to make a choice!).

The mystery unraveled

7. Can (or should) schools avoid mirroring?

7.1. Empirical methods of remediation

The phenomenon of reversal, because it makes parents fear dyslexia and because at school children are expected to learn to write correctly, has always been considered embarrassing. Consequently, the psycho-pedagogical literature is full of relatively imprecise and poorly controlled attempts to remedy it. Vogel's research (1979) is an exception. In this research, 36 kindergarten children were first shown a series of 10 pencil drawings of objects. Because they then showed a poor ability to distinguish between these images and their left-right mirror images, the author implemented remediation that could take one of three forms: Children could be prompted to (a) give detailed verbal descriptions of the images, (b) specify a difference between what they see and what the experimenter sees, or (c) both. After each verbal response, the images were masked and the child repeated his or her verbal statement. All 3 induced strategies were equally effective. But, in a posttest conducted about a week later, the children did not maintain the use of any of these effective strategies! This suggests that such verbal strategies are of limited value.

Is attention (as the authors call it) or a positive, supportive attitude from the teacher enough? Long before the concepts of positivity and friendliness became popular in school, Hasazi and Hasazi (1972) report the case of a student (8 years old) in an elementary school of California who almost systematically reversed the order of the digits when adding numbers leading to a two-digit sum. For example, in response to the sum of $5 + 7$ he wrote 21. During an initial baseline period, the teacher would respond to the reversal of digits by pointing out the incorrectness and providing the child with additional assistance until all sums were correctly expressed. Both the student's current teacher, and the previous school year's teacher, had managed this student's reversal problem in this manner for almost a year before the study began. In his experimental period, all sums were marked as correct, whether the digits were reversed or not. Extra help was not provided continuously and correct, i.e., non-reversed, answer forms were praised with a smile, a pat on the back, and a brief comment. During this period the reversal rate decreased sharply. Then, for a consecutive period, the teacher again responded to reversal as she had during the baseline period. An increase in reversals toward the baseline level then occurred within three days. Finally, a final period, replicating the experimental period, followed: it was characterized by a strong decrease in reversal rates. This observation can therefore be seen as a favorable effect of a positive, friendly attitude on the part of the teacher, but without any systematic control or attempt at statistical demonstration of the effect.

Wagner (1981) provides examples—and suggests explanations and remedies—for five types of mathematical errors due to perceptual or cognitive difficulties. One type of error is precisely mirror writing. Among the errors of this type that he has observed, during his work with students with arithmetic deficiencies (dyscalculia), he describes the case of the subtraction $44 - 23$ that led to two types of error. One student answered 12. Wagner assumes that the student did the subtraction correctly in his head but reversed the digits of the number 21 when writing it down. Another wrote **21**, reversing each of the digits 2 and 1 individually. Note that 1, with a small oblique stroke upwards to the left, is distinguishable from its mirror, although the author is an associate professor in Valdosta, Georgia, USA, where 1 is possibly written without this small oblique stroke. In regard to these examples, the author quotes someone who would write (or

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read) was for saw, pointing out that this visual-spatial orientation problem refers specifically to left-right discrimination. As a remedy, he suggests a tactile-kinesthetic approach (e.g., writing in sand or salt), the use of colored cues (which seems to be relevant only for the inverted writing of digits in a number, such as 12 instead of 21) and, more original, writing numbers on the back, with the thumb or the erasing side of a pencil. In the latter case, the student must first say the number written on his or her back and then write it on a piece of paper placed in front of him or her. This is a guessing game-like activity that children should enjoy, but because of possible slippage (in the lower back, for example!), it cannot (or no longer) be practiced without precautions.

About this writing, by another, on the back, I would like to reiterate my point from Section 1.5, that writing, by oneself, on the forehead or under the table, is by no means mirror writing. Instead, when someone else writes an ambiguous letter (such as 'b', 'd', 'p', 'q') on your forehead, you can take an internal perspective, as if you were looking outward from an imaginary point in the middle of the body (the 'egocenter'), or an external perspective, as if you were outside yourself. Spence et al. (2010), referring to an old psychology course, even indicate that 75% of people adopt the first perspective, while only 25% adopt the second. Note that it is only the internal perspective that leads to mirror reversals and that for letters drawn (or presented) on the belly a similar confusion occurs when adopting this perspective. In contrast, the majority of people tend to correctly report letters (or other symbols) that are drawn on the back of their head or on their back.

7.2. Is kindergarten dangerous?

I have long believed that kindergarten, particularly through workshop work where a group of children are seated around a table, some facing each other, could promote the development of mirror writing. Indeed, suppose a child can write the French word **BEC** (beak) and the teacher encourages the other children to look at how their classmate has written this new word: those opposite the successful writer will see **ƆEB** and, perhaps, write it and remember that the [be] heard at the beginning of [bɛk] is written **B** or **BE**. For numbers, the same is true, or even worse. If we assume again that a child with advanced developmental skills can already write 36 and that the classmates sitting opposite look at his writing, they will see **93**! But the reader can easily see that I did not choose my examples at random. The letters of the word **BEC** and the digit 3 all have a horizontal axis of symmetry, and they are the only ones, along with D and K. As for 6, all teachers know that 6 must be underlined to differentiate it from 9 in games with removable and therefore rotatable digits. The theoretical argument against my belief of a biasing effect of grouping children around a table is that the point of view of the reader sitting in front of the writer does not generally reverse (left-right) the characters but rotates them by 180°. And, most importantly, the empirical argument that definitively annihilated this belief is that children almost never reversed the letters B, C, D, E, and K (see Fig. 35).

As I just suggested with the digit 6, this issue of children seeing the characters from an inappropriate point of view or angle also arises with the removable cardboard, wood, or plastic characters of Scrabble, or Mathable, its equivalent in the number domain. Although children between 4 and 7 years of age do not yet typically play these games, they can see their elders playing them and, more importantly, use such removable characters in many other games. Now when one draws a character (hidden by flipping or blind) in such games, one has a non-zero probability of drawing it rotated 180° from a standard position (let's say 1 chance in 4), like the

characters on the computer keyboard in front of me. As visualized in Figure 44, some of these characters appear in mirror image of the real characters. Although amateur Scrabble has been the subject of much debate about the acceptance of certain words, abbreviations, or conjugations, it is remarkable that there has never been any doubt that a draw like the one in Figure 44a2 is a C. Figure 44 illustrates that a C or a 3, even if it is rotated 180°, is a C or a 3. There is thus a clear semantic problem: is a mirrored C or 3 really a C or a 3? Lévy (1935) was probably wrong to be surprised (at least for E and 3, less so for 4: see Section 3.3) that students, even in second grade, identify a character, if it is presented in mirror image, without hesitation. For a Scrabble or Mathable player too, a C or a 3 drawn in mirror is indeed a C or a 3, without hesitation either! For these games, nowadays often computerized (especially on tablets), the problem of the physical drawing does not arise anymore. But the problem of the inappropriate point of view always arises, in an analogous way, for an observer who is in front of the player.

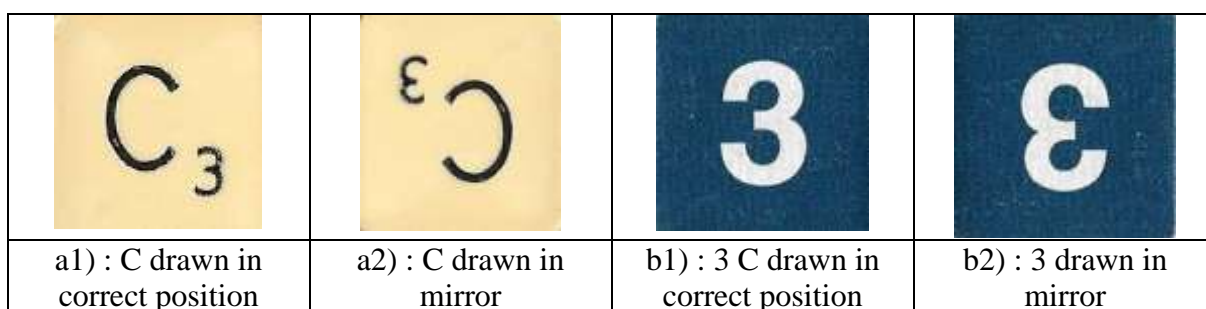


Figure 44. Initial character draw (hidden by flipping or blind) of the letter C from a Scrabble game and the number 3 from a Mathable game, in the correct position or rotated 180°. Note: (a) the value 3 indicated for the letter C also appears in the mirror, but on top! (b) the mirror of 3 is not perfect because the lower loop of the true 3 is slightly wider.

7.3. A comparison of three types of schools

Mather (2012) studied mirror writing, with a technique similar to Cornell's (1985), in 1st, 2nd, and 3rd grade in three types of schools: public, Montessori, and Waldorf, in Canada. Montessori schools are often characterized by multi-modal learning. Waldorf schools, also known as Steiner schools, are based on the educational concepts of Rudolf Steiner (1861-1925), an Austrian philosopher and occultist. According to a publicity presentation, children in Waldorf schools learn with their hearts, heads and hands. In order to understand the results, I must first briefly present not Mather's theory, which is somewhat complicated, but at least the notion of inverse reversal. To do this, we can return to Figure 16c, which shows some examples of student Tenneson's reversals. Tenneson also wrote his first name correctly in the right hemi-space, but mirrored in the left hemi-space (except S). This is the normal pattern of first name reversal in a left-to-right writing culture. In contrast, in the dictated sequence b, 3, z, 5, d, 7, s, 2, p, c, he reversed the characters 3, z, 7, 2 in the right hemi-space and wrote them correctly in the left hemi-space. This is a writing pattern that we have encountered previously with some of the children's tergiversations with the letters J and Z in their first names (see Fig. 43) or with the writings of 1, 3, J, and Z reproduced in Figure 42. We have simply called them for what they are, namely, correct writings. Mather's label of inverse reversal assumes that children have a reversed representation of a character and inverse it again. Our theory is more parsimonious: we simply assume that children do not know the orientation of the characters and then put it in

the direction of the writing. That said, the label "inverse reversal" emphasizes the spectacular nature of these writings, incorrect in normal writing and correct in mirror writing!

With this notion of inversed reversal clarified, I can now present Table 5 comparing the three types of schools and the three grade levels. First, we can note that simple reversals are more frequent in the left hemi-space than in the right hemi-space. Since the characters to be written seem balanced in terms of their orientation—3, z, d, 7, and 2 face left, while b, 5, s, p, and c face right—this result shows that students are far from systematically reversing left-oriented characters in the right hemi-space. The age or school level of the students certainly contributed to this observation: Table 5 suggests this, since the difference between hemi-spaces is lowest in level 1 in the public school (0.80), and highest in level 3 in the Waldorf school (3.80). Next, we can verify that the inverse reversals are systematically less frequent than simple reversals in the right hemi-space. This observation is simply logical, given the definition of an inverse reversal, namely a character that is reversed in the right hemi-space but correct in the left hemi-space. But can we infer from this that when students produce an inverse reversal they are inverting an already reversed character? In addition, the inverse reversals do not differ much between the different schools. Simply, not surprisingly, they decrease with the school level.

Table 5. Mean number M (out of 10) and standard deviation SD of simple and inverse reversals by class, school, and hemi-space. [Table constructed from Tables 2 and 3 in Mather (2012), p. 175].

Level	School	n	<u>Simple reversal</u>				<u>Inverse reversal</u>	
			<u>Left hemi-space</u>		<u>Right hemi-space</u>		M	SD
			M	SD	M	SD		
1	Public	20	3.25	1.52	2.45	1.67	1.65	1.42
	Montessori	17	4.88	1.97	1.82	1.29	1.29	1.45
	Waldorf	15	5.07	2.05	1.87	1.60	1.48	1.42
2	Public	20	3.40	2.26	0.95	1.19	0.40	0.68
	Montessori	15	4.20	2.62	1.60	1.72	0.53	1.06
	Waldorf	20	4.65	2.56	1.05	1.64	0.55	0.95
3	Public	20	2.15	2.41	0.35	0.93	0.00	0.00
	Montessori	12	1.75	1.91	0.75	0.87	0.58	0.79
	Waldorf	20	4.50	2.78	0.70	1.03	0.55	0.76

For simple reversals, a mixed 2 (hemi-space) x 3 (grade level) x 3 (school type) analysis of variance, in addition to confirming the main effect of hemi-space already discussed, also leads to a main effect of school type. Unfortunately, this effect is difficult to interpret. For example, there appears to be a lower frequency of simple reversals in the left hemi-space in public school students than in Montessori (1st and 2nd grade) and, especially, Waldorf schools. Mather merely observes that there is “no obvious reason” for this lower frequency of mirror errors in the public school. However, for the Waldorf school, he suggests that the greater number of mirror errors may be due to that school's policy of delaying writing instruction, as it has been found that the decline in children's mirroring is less related to age than to writing practice. But couldn't the opposite be argued for the Montessori school? Indeed, the material of rough letters, in three formats (lower case and upper case, cursive), which is one of the characteristics of the Montessori method, is precisely intended to impregnate the shape of letters in the child, and

this as early as 4 years old in the commercial advertising. It should also be noted that only one school of each type was included in Mather's research: a generalization is therefore impossible.

7.4. A promising research (according to the authors!)

Recently, experimental research was implemented on Brazilian children in Natal (Torres et al., 2021). The name of this large city, in northeastern Brazil, is derived from the Latin *Natale* because it was founded on December 25, 1599, the day of the nativity of Jesus. Using an ecologically valid school design, Torres et al. showed that multi-modal teaching of mirror invariance suppression for letters represents a major advance for the acquisition of reading fluency in first grade. The authors' summary, which I have already partially quoted in the preceding lines and which I largely repeat in the following lines, is euphoric. The causal approach, in a synergistic combination with post-learning sleep to increase consolidation of learning, revealed an unprecedented improvement in reading fluency, which became twice as fast. This gain was achieved with only 7.5 hours of multi-sensory and motor training to distinguish between mirrored letters, such as "b" versus "d". The magnitude, automaticity, and duration of this mirror discrimination training were greatly enhanced by sleep, and the gains were fully maintained even after 4 months. The results were systematically replicated in three randomized controlled trials. They not only reveal an extreme plasticity in human cognition (i.e., inhibition in only 3 weeks of a 25-million-year-old visual mechanism), which allows adaptation to a new cultural activity (reading), but they also show a simple, low-tech method that can efficiently unleash the reading fluency potential of millions of children worldwide.

Will such promising research lead to applications in schools? Most likely not. One reason is the practical complexity of implementing it in classrooms, particularly because it requires a post-learning siesta. Another consequence of this complexity is that the research is difficult to replicate, especially since the test conditions were very particular: participants had to write the individual lowercase letters immediately after a presentation for 3 s, blindfolded. However, it would be necessary to reproduce it because the analysis of the writings, which the authors have put online, shows a curious observation that I cannot, after 20 years of research on children's mirror writing, explain clearly: the children almost systematically reversed the letters b and d, b into d and vice versa, whereas, even at random, one could have expected at least half of the writings to be well oriented. We tried to accommodate a model that could account for such an observation. But the result is not really convincing (see Fischer & Luxembourger, 2021).

The research of Torres et al. would be even more in need of replication as it has some other imperfections. For example, one half of the icon-images used for mirror discrimination were axially symmetric, although they were described as asymmetric (see Fig. 45). The children had

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to judge whether two horizontal mirror images of one of these figures are the same or different. Many adults would be embarrassed to answer the test item shown at the bottom of Figure 45.

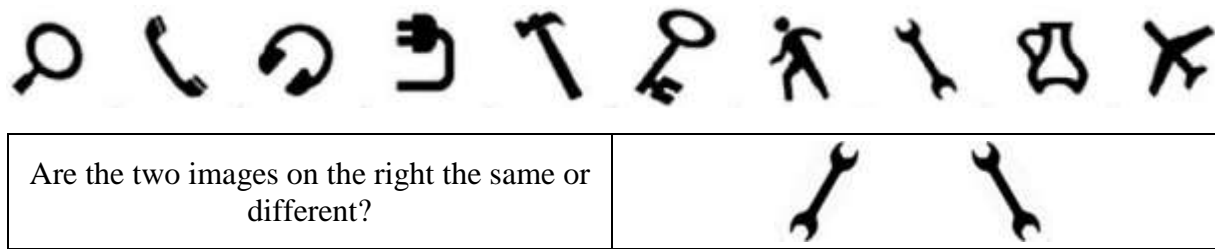


Figure 45. The 10 image icons used for mirror discrimination by Torres et al. (2021, p. e3) and, below them, an example test item.

Finally, if reliable, the results on the relationship between reversal in the writing task and discrimination of mirror images of letters and icons in the visual task are also surprising. Indeed, while the number of icons correctly discriminated from their mirror significantly predicts the percentage of letter reversals (a result in agreement with an observation by Göbel et al., 2019), the number of letters visually discriminated from their mirror does not (Fischer & Luxembourger, 2021). Good visual discrimination of mirrored letters therefore does not significantly reduce mirror reversal in writing. Such a surprising result, however, can be reconciled with the result in Section 8.2, which will show that letter recognition of b and d is not related to digit reversal in writing, in the sense that children who confuse b and d a lot in reading are not the ones who frequently mirror write.

7.5. The French national department of education asks to turn clockwise!

The French National Education Department, presumably having caught wind of the frequency of character reversals, has made some recommendations in a more general publication on kindergarten writing (Eduscol, 2015). Written by an anonymous panel of experts, it includes an example of reversing the R and N in the writing of ROBINET (water tap) by a child whose age is not specified. In contrast, the other example of reversing the letters in the word RENARD (fox) is not correct, or is incorrectly presented, since the letters E, N, and D are not reversed at all (the letter R is written awkwardly).

Then, regarding digits, the document reproduces the writing of a child, in the order 1, ..., 9, who reversed the 2, 3 and 5. Based on this example, the authors write that it is "mainly 3, 5 and sometimes 2" that are reversed, and comment: "Observation shows that these three digits require a rotational movement to the right, i.e., the reverse of round letters, which can undoubtedly explain this reversal. This supports the idea that it is necessary to train students to draw circles both to the left (the direction of rotation of round letters) and to the right, a movement necessary to write 2, 3, 5, but also some capital letters (B, D, P, R)" (p. 15).

This explanation by the direction of rotation of the round letters is quite relevant for the digits 2 and 3. The pedagogical recommendation that follows is all the more relevant since Anne-Marie Koch, in a master's dissertation, was able to verify that almost all of the numerous commercial books proposed to parents/teachers for teaching children to write from MS kindergarten onwards, teach them to draw circles in a counter-clockwise direction (see Fig. 46). This counter-clockwise drawing of circles may also explain the relatively low reversal frequency of 6, and the very high reversal frequency of J and, less clearly, Z. But it does not

explain well the few reversals of 5 (totally mirrored: see Fig. 11), B, D, P, R, and 9. Moreover, it is also much less relevant to explain the frequent reversals of 1 and 7, and the near absence of reversals for E, F, K, L, N. Even if the National Education recommendation to also practice drawing circles to the right (clockwise) may help to reduce the frequency of reversals of some characters, especially 3, it will not eliminate all reversals, and may even favor others (e.g., those of 6 and C).

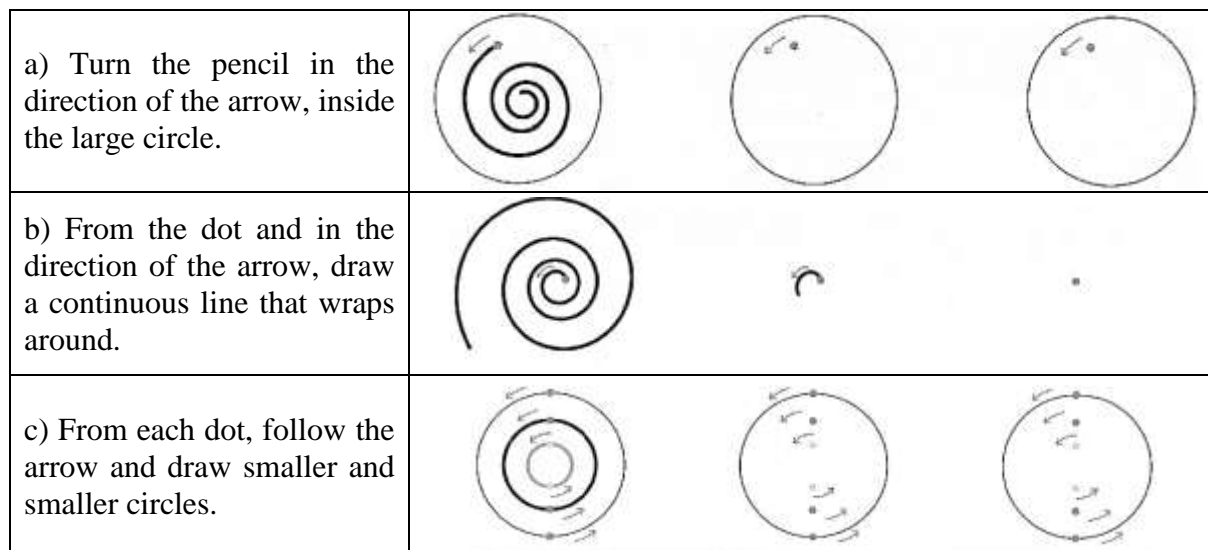


Figure 46. Circle drawing exercises proposed in a French textbook for MS kindergarten (4-5 years old). [Adapted from Spitz (2010), p. 15]. Note that the tracing is systematically counterclockwise for (a) the inner spiral, (b) the outer spiral, and (c) the concentric circles. In addition, I specify that no analogous tracing exercise is proposed clockwise.

It has been observed that, from the age of 5 years, when children start to draw a circle upwards, they most often use a counterclockwise rotation. This is consistent with biomechanical differences between extension and flexion movements, which are sometimes cited to explain this tendency in adults. However, Meulenbroek et al. (1993) found that this still only occurs in 75% of children at age 5 and that this percentage increases with age to 100% at age 9. We can therefore think that, even if a biomechanical constraint exists, the predominance of the counterclockwise direction of rotation in cursive writing is an essential factor in this principle of tracing counterclockwise a simple circle. This is all the more true because, in order to anticipate the learning of cursive writing, teachers and textbooks teach this drawing in the kindergarten years, as illustrated in Figure 46. The suggestion made by the French Department of Education therefore seems useful, but it will not solve all the problems of reversal and will create others.

7.6. Does the study of adult learning shed any light?

The effectiveness of learning to write classical characters can no longer be studied on ordinary adults, since they have known and used them for a long time. But, with a non-classical material, one can proceed to such a learning. This is what Longcamp et al. (2006) did with the characters in Figure 47.



Figure 47. The two sets of "characters" learned by the 12 participants in the Longcamp et al. (2006) study.

In the "Typing (keyboard)" condition participants had to find the appropriate key on the keyboard, and press it; in the "Writing (manual)" condition they had to write the characters on a paper sheet. The comparative assessment of learning effectiveness consisted of a recognition test (recognizing whether a character is correct or mirrored) and a discrimination test (less relevant because it could be successfully completed without learning). These tests were administered at three time points: immediately after learning, 1 week, and 3 weeks later. Participants recognized characters better in the "Writing" condition than in the "Typing" condition, but mainly in the recognition test after 3 weeks. The authors conclude that their results indicate that the writing movements produced during learning affected participants' ability to later differentiate characters from their mirror images.

This is an important result, especially as relevant learning in school is learning that takes place over time, which is the case in the observation by Longcamp et al. But the main problem, which the authors note, is the longer duration of learning through writing. For many years, French elementary school teachers asked their students to copy a short summary at the end of each lesson. An experienced third grade teacher I know, who had followed this practice, told me that this is totally impossible today: some students write so slowly that they would never finish! And he can no longer force these students to finish copying during (and instead of) the recreation period, as was done in the past! As a result, he distributes photocopied summaries.

7.7. Does learning to write (in general) reduce mirror reversal?

One may ask whether learning to write, even if not focused on the problem of character reversal, does not at the same time reduce the frequency of reversal. Indeed, it is known that learning a script with mirrored graphics is the most powerful force for breaking mirror invariance (Fernandes et al., 2021). The absence of such learning is often accompanied by indistinctness between the image of a shape and its mirror; for example, in Pederson's (2003) monolingual Tamil (a language originating in South India) participants, Danziger's (2011) Mopan Maya (a language spoken in an indigenous group of regions in Belize and Guatemala) participants, Izard et al.'s (2022) Mundurucu (an isolated indigenous Amazonian group) participants, or in Thai readers (Winkel & Perea, 2022). A necessary condition, however, is that the learning be effective! The more general problem of how best to learn to write can only be posed here very partially because it is multifaceted.

Vinci-Booher et al. (2016) studied functional connectivity with 4- to 6-year-old children after learning capital letters and shapes through handwriting, tracing, or typing. They showed that functional connections between visual and parietal regions increased after all training conditions. Specifically, interaction analysis revealed that for trained letters (regardless of training), functional connections between the left fusiform gyrus and the right parietal lobe were stronger during their perception than for untrained letters. Although the motor component is

very different in the typing condition from that in the other two conditions, it could be thought that it is the one that makes all three learning modalities effective. In particular, one might think that this motor experience provides information specific to learning to write letters by hand, thereby improving letter recognition more than the visual experience. But subsequent research by Zemlock et al. (2018) showed that this effect is not specific to training with letters. Since digit writing also improves letter recognition, we see that the improvement does not result from memorizing a specific motor pattern for each letter. This may then suggest that handwriting facilitates general gains in visual-motor coordination.

Cohn and Stricker's (1979) observation of first-grade students in reading provides an answer to the question raised in this section for writing. In this research, students, tested in the first two months of the school year, were asked to read letters, specifically from the set {b, d, p, q}. Although the authors use a more general notion of inversion than ours (and in reading), we can observe in their data that inversion errors are proportionally over-represented in the group of the most competent students in reading. For example, for the letter d, while students in the "high proficiency" group make only inversion errors (100%), inversion errors account for only 58% of errors in the "low proficiency" group. Inversion errors thus seem to be very "resistant", at least in reading, and of a higher level than other form errors. This observation is consistent with the idea that reversal, in writing, has some value (see Section 4.4).

7.8. Delaying learning to write is not the answer!

My experience has taught me that one of the solutions, which comes most easily to the mind of some pedagogues when a difficulty appears at the time of teaching a notion, is to delay the learning of this notion. I have seen this occasionally in connection with the teaching of subtraction at the end of the 1970s, in France. Indeed, the teaching of subtraction was placed after that of multiplication in 2nd grade. Yet, this indirect delaying of teaching subtraction, which is naturally taught before multiplication, was quickly abandoned. A delaying of a much larger scale was set up at the beginning of the 1970s, in France, with the reform known as "Maths modernes". The delaying strategy consisted of waiting until the child is mature to understand the notion of number. The main argument for implementing this strategy was that kindergarten children did not pass the Piagetian test of conservation of number (see Bideaud et al., 1993). As a consequence, all numerical activities—even purely verbal numerical counting—were excluded from kindergarten (Fischer & Bocéréan, 2004). This reform was such a fiasco that no one wanted to take responsibility for it in the 1980s/1990s.

Recently, however, Mather (2022) has suggested that frequent letter reversals accompany dyslexia and that premature learning to write may be its cause. Consequently, Mather suggests delaying writing instruction until 7-8 years of age to prevent these errors and as well as the development of dyslexia. But Mather's argument remains purely theoretical. He only makes recommendations for empirical evidence of premature writing as a cause of dyslexia. Yet, Mather had such empirical evidence at hand. Unfortunately, despite more than 100 other references, he fails to mention his 2012 research (Mather, 2012). In this research, he specifically obtained empirical evidence by observing a Waldorf school, a type of school where handwriting instruction is delayed until age 8. The omission of this research is likely due to the fact that it showed that Waldorf school students produce more mirror writing errors than public school students (see section 7.3), exactly the opposite of what Mather expects from delayed handwriting instruction. More generally, Mather's suggestion seems at odds with his 2012

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claim, by reference to Della Sala and Cubelli (2007) and Cubelli and Della Sala (2009), that "children's mirror-writing has been found to be less related to age than to writing practice" (Mather, 2012, p. 175).

Both the failure of the 1970 'Modern Maths' reform, which significantly delayed the learning of counting, and the negative effect of the delay in learning to write observed in Mather's (2012) data, lead me to be totally skeptical about the implementation of such a delay in school.

8. Some surprising consequences

8.1. Writing and recognizing a reversed digit have little in common

When children have to recognize a correct digit in competition with its reversed writing, do they apply the same rule of preference of the digit oriented in the direction of the writing (i.e., the right)? To answer this question, we projected three sets of 2 x 2 matrices of digit writings, such as the set in Figure 48, to GS kindergarten students. The students were simply asked to show the correctly written digit. In Figure 48 the target digit is specified in writing, but with the children it was exclusively stated orally.

1	4	5	9	7	6	5	1	2	3	2	3
2	1	9	2	6	7	4	3	1	3	3	5
“four”	“two”	“six”	“seven”	“nine”	“five”	“one”	“three”				

Figure 48. Students were asked to point with a stylus to the digit requested by the experimenter in Fischer & Luxembourg (2020).

We anticipated that some students will be embarrassed to make a choice between two scripts if they feel both are valid. Indeed, each matrix contains not only the correct writing of the target figure, but also its mirror (diagonally opposite in the series of Fig. 48), as well as another digit and its mirror. This embarrassment should then be reflected in the back and forth of the gaze between the target digit and its mirror. We tried to verify this with an eye tracker.

The processing software associated with the device allowed us to produce numerous heat maps (by summing data from a group of children) attesting that the gaze is indeed focused on these two digits. Figure 49 shows two of these maps. The warm yellow and orange colors show that the children's gaze did indeed focus primarily on the target digit and its mirror, 6 for the left matrix and 3 for the right matrix.



Figure 49. Warm (collective) maps obtained for the third and eighth digit matrices in Figure 48.

It also allowed us to obtain, at the individual level, the detailed path of the saccades of each child. Figure 50 reproduces an individual path generated by the last matrix of Figure 48. In this sort of visualization, the successive fixations of the child's gaze are numbered from 1, generally almost at the center, which allows us to verify that the child was indeed fixing the center at the beginning of the projection, up to the maximum (here 8); but they are sometimes difficult to read because of the superimpositions of the disks whose size is modulated according to the duration of the fixation.

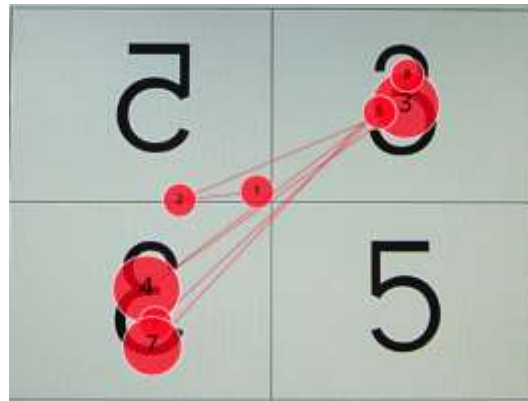


Figure 50. Visualizations of a participant's fixations for the last digit matrix in Figure 48.

Note that these images also suggest that children virtually ignored the non-target digit and its mirror. This was verified quantitatively with percentages of choices of these two writings being almost zero, an unsurprising result since children of this age readily recognize the shape (without orientation) of digits (see Section 4.4).

But the key quantitative result concerned participants' choice when they did not recognize the target digit. In a recognition task, the morpho-kinetic component of character writing has basically disappeared. As a result, it can no longer oppose the topo-kinetic component, an opposition that is at the origin of the reversed writing of the characters when the morpho-kinetic does not coincide with the topo-kinetic. Our theoretical answer is therefore that the topo-kinetic component, i.e. the general direction of writing/reading in our culture, remains the only one to dictate its law. This should lead participants who do not yet know the orientation of the digits to choose the writing in the right column, whether it is reversed, like the 6 in the left matrix of Figure 49, or correct, like the 3 in the right matrix of Figure 49. This is what we observed: participants chose the digit (target or its mirror) in the right column in nearly 62% of the possibilities (in one of the three series, the target digit and its mirror were in the same column, making such a choice impossible). This percentage can be compared to 50%, the percentage that would be expected if participants who could not distinguish a target digit from its mirror had randomly answered the digit in the left or in the right column. This percentage could also have been increased by the position of the experimenter, usually to the right of the participants. Indeed, Corballis and Beale (1976, 1993) pointed out that this position can serve as a cue to orientation so that the child does not need to use an internal sense of it. In any case, an almost direct consequence of participants' choice based on spatial position is that this choice does not result from the orientation of the digits. As a complement, we verified that left-facing digits (1, 2, 3, 7, 9) generate neither more nor less choice of their mirror than other digits (4, 5, 6).

8.2. Mirror writing has little to do with reversal in reading

Reading, especially its major dysfunction, dyslexia, is certainly the most widely discussed subject in the psycho-pedagogical literature. The abundance of documents that a conscientious researcher should analyze and synthesize is such that I have long hesitated to venture into the field. Nevertheless, the French 1st grade national assessments, at the beginning of the school year 2020, offered material that was suitable for the study of the relationship between the reversal of digits in writing and reading, at least in recognition of letters.

In these assessments, students were asked to answer tests involving the recognition of different correct writings of several letters. Among these, we are particularly interested in the writing of [be] and [de]. These two letters have indeed given rise to an abundant literature: just look at the titles of Brault-Foisy et al. (2017), Davidson (1935), Smith and Lovitt (1973), or Soares et al. (2019), which are only a few among other articles dealing with the reversal of b into d (and vice versa). The different forms of writing offered in the assessments are: printed lowercase (b, d), cursive (*b*, *d*), and capital (B, D). Students were asked to circle the writings of [be] in the sample of writings shown in Figure 51. This allows us to identify students who do not differentiate between b and d in line 1. Instructed to recognize the writing of [be], these students could make two types of errors: either circle the d only, or circle the d and b, without circling any other writing. The same is true for the letter d.

Line 1: E b a o C d
 Line 2: *b* O A e D c
 Line 3: o e B c a d

Figure 51. The sample of different letter writings from which French students were asked to recognize all writings of [be] or [de] (the lines are numbered in our text but were not shown in the students' assessment booklet; students were encouraged to work line by line through an example using an untested letter).

In another test, the children were asked to write the ten Arabic digits and the number 10 under dictation, always in the same order: 3, 5, 1, 4, 2, 6, 9, 0, 8, 10, 7. Figure 52 shows the writings of two children. The idea that some children would have a propensity for reversal leads quite naturally to the hypothesis that the pupils who reverse the writing of the numbers are essentially the same as those who do not distinguish b from d, or who take b for d and vice versa. But we have already suggested that such an idea is false (see section 2.6). Moreover, since the reversal in writing comes from the fact that students have to give an orientation, which they do not yet know, to the digits, it will be noted that they do not have to make the same choice during a character recognition task since they see the orientation. Our interpretation of digit reversal thus leads to the prediction that there is no link between it and the confusion between b and d. In other words, digit reversal and reading confusion of the letters b and d would be two different and somewhat independent processes. Statistically, this should translate into the lack of correlation of the b and d confusion rate with the digit reversal rate.

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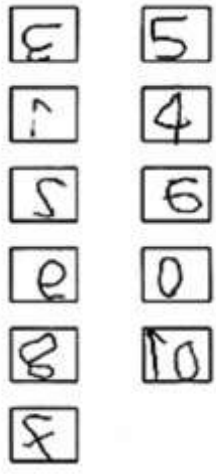
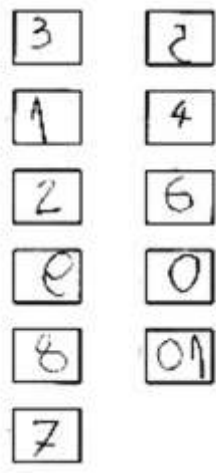
	
Boy, 6 years 5 months old	Girl, 6 years 1 month old

Figure 52. The number writing subtest, completed by two students at the beginning of first grade, during the French national assessments.

In our article in *Reading and Writing*, a fitting journal since we were dealing specifically with the link between writing and reading, we defined such rates of reversal (of digits) and letter confusion (b/d). This definition is made more complex if we want to include the writing of 10 because, as Figure 52 shows, 10 can lead to partial reversals: the boy has reversed the number 1 in his writing, whereas the girl has written it correctly but has swapped the digits 1 and 0. It is also complicated by the fact that the error of a child who mistakes b for d (and vice versa) is different from that of a child who simply does not differentiate the two writings. Regardless of how the data were treated, we found that the correlation is negative, as shown in Figure 53. This finding is surprising with respect to our hypothesis of no correlation. But, on the one hand, the correlation is not very strong ($r_s = -0.37$), on the other hand, and more importantly, it shows at least that the idea that students who reverse numbers are likely to be those who also confuse two mirror letters like b and d is completely false. This last point then raises the question of the origin of this confusion. We will simply note the graphical similarity of both of b and d (see Section 4.10), and the phonic similarity of [be] and [de] in French (see also Jee et al., 2022, who suggest that graphics and pronunciation should be reconciled). More generally, we can refer to the extensive literature on developmental dyslexia for this search of an origin (e.g., Lachmann, 2018, or the book from which this article is taken).

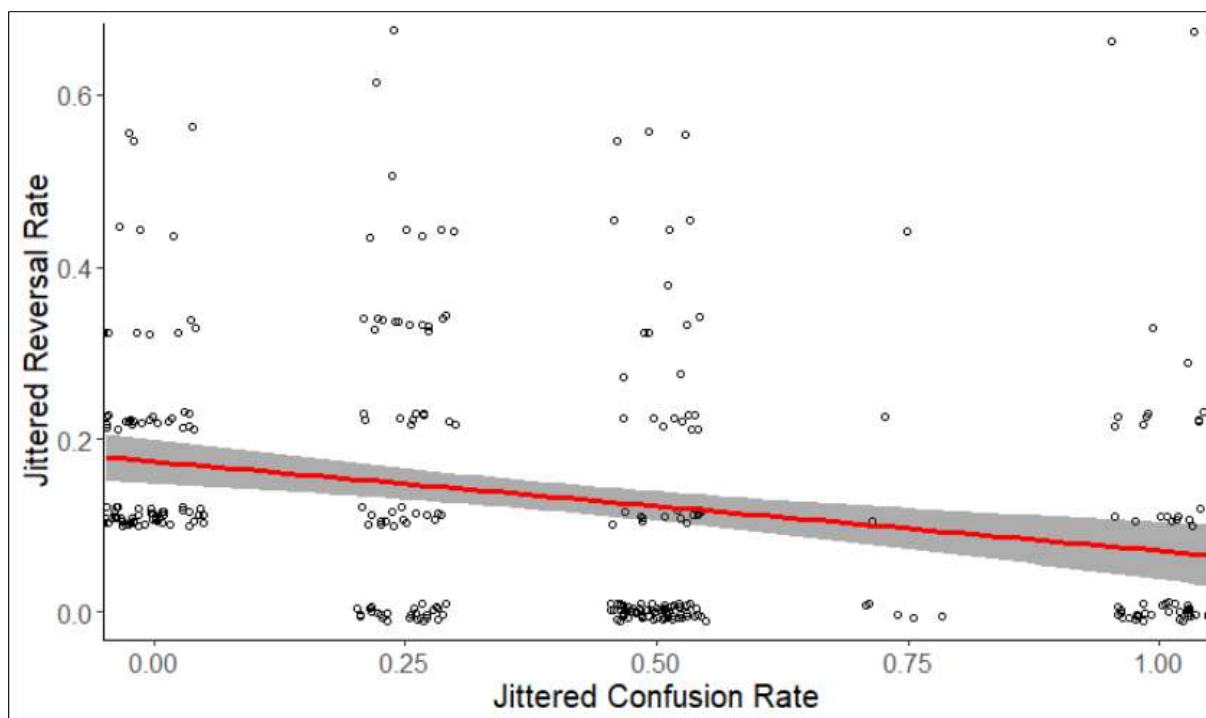


Figure 53. A jittered scatterplot of reversal rate as a function of confusion rate, with regression line (red) and 95% confidence interval (gray). [Reproduced from Fig. 3, p. 2442, in Fischer & Luxembourg (2022)].

8.3. Atypically developing children may not be more likely to make reversals

In Section 1.4 we saw that Gordon, having observed few reversals in typically developing students, presumably too old, focused on atypically developing children (mentally handicapped). This may suggest that atypical children make more reversal errors. Is this really the case? Lyle's (1969) work provides, indirectly, a first indication. His (factorial) analysis of boys with reading delays from the six grades of primary school (i.e., up to 12 1/2 years of age) did not confirm that letter and sequence (word) reversals constitute a single syndrome. More generally, it "did not shed any light on the exact nature of reversal patterns in reading and writing" (p. 842). Such conclusions lead to question the nature of the reversals, and even whether they are reversals at all. This questioning is all the more necessary as I frequently been asked, during my oral or written presentations of mirror writing, about children who continue to reverse characters beyond the age of 7-8 years.

The previous Section 8.2 suggests, however, that character reversal should be distinguished from certain confusions that may be observed in slightly older children. These confusions concern mainly the digit 6 confused with the digit 9, the digit 7 confused with the capital letter F, and the digit 9 which, in addition to being confused with the digit 6, may also be confused with P or the lower case letter e. This last confusion is reinforced by the high frequency of the letter e, which is the most frequent letter in French (Trost, n.d.) and probably in other languages. The explanation for these confusions in memory is almost obvious when one refers to the functioning of declarative memory (Ullman et al., 1997).

Declarative memory has indeed been described as susceptible to interference, or associative confusions as we prefer to call them in reference to Winkelman and Schmidt (1974). Its main brain support is the medial temporal lobe, in particular the hippocampus (Cohen et al., 1999;

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Eichenbaum, 1997; Menon & Chang, 2021; Squire, 1994). One of its essential functions is thought to be the consolidation of declarative knowledge (Squire et al., 1984). Typically declarative knowledge such as multiplicative facts (Fischer, 1992), is therefore highly susceptible to interference (De Visscher & Noël, 2014; De Visscher et al., 2018). Indeed, one multiplicative fact may interfere or be confused with another for the simple reason that both products involve the exact same digits. For example, Dotan (2022) points out that the similarity between multiplication facts—such as $8 \times 8 = 64$ and $8 \times 6 = 48$, two facts that involve the same digits—makes them difficult to remember. Thus, we see that a purely "physical" similarity, with no semantic basis, or pre-semantic as Moscovitch (1995) calls superficial medial temporal lobe outputs, can lead to associative confusions. In the same way, declarative memory must store the form of the digit writings. It therefore contains representations of a portion of a circle and a larger arc of a circle, both for 6 and for 9 and e; it also contains representations of 7 and its near-perfect horizontal mirror (when 7 is written with a second small horizontal stroke), the capital letter F. As a result, it can lead to associative confusions between the writings of 6, 9, and e, on the one hand, and 7 and F, on the other.

This distinction between reversal and confusion leads to the hypothesis that children with atypical development, who have been delayed in their schooling and are therefore older, should produce reversals, which are not alignments with the direction of the writing, but which belong to these associative confusions. To date, however, and to our knowledge, no research has finely studied this phenomenon of reversal or, in our opinion, associative confusion in children with developmental delay. We therefore asked, in a school situation, to write four series of 10 digits (see Fig. 54), on the one hand to pupils with an intellectual disability, attested by an IQ below 70, and on the other hand to pupils whose cognitive disability is rather of behavioral origin (aggressiveness, de-structuring, hallucinations), requiring schooling in a specialized institution. Only 13 of the 46 pupils concerned, aged between 7 and 15, produced at least one reversal. Figure 54 shows the writing of one of the mentally handicapped pupils.



Figure 54. The writings of a mentally handicapped student with his usual right hand; in the left-hand column the series of dictated digits is specified.

Overall, students made more "reversals" for the particularly confusing digits in the subset $D_p = \{6, 7, 9\}$ compared to the other digits. In addition, and partly as a result, we did not really find the usual difference in reversals between the digits in $D_l = \{1, 2, 3, 7, 9\}$ and $D_r = \{4, 5, 6\}$.

One of the teachers involved in the research provided us with a production of the writing of numbers in a school exercise of one of these students. In this exercise, the student, had to complete partially filled lines (the numbers printed in black type in Fig. 55) of a portion of a table. The latter was taken from a large 10 x 10 table showing the numbers from 1 to 100 in their natural order, i.e., the first row contains the numbers from 1 to 10, and the last row the numbers from 91 to 100. We reproduce the student's work in Figure 55, knowing that the corrections (in red, in the last column of table c) were added by the teacher.

3	4	5	6	7	3	4	5	6	F	3	4	5	6	7
13	14	15	16	17	13	14	15	16	17	13	14	15	16	17
23	24	25	26	27	23	24	25	26	27	23	24	25	26	27
33	34	35	36	37	33	34	35	36	37	33	34	35	36	37
43	44	45	46	47	43	44	45	46	47	43	44	45	46	47
53	54	55	56	57	53	54	55	56	57	53	54	55	56	67
a) 7 is always correctly written.	b) 7 is reversed before the occurrence of 37, but correctly written after.	c) 7 is always reversed (corrected by the teacher).												

Figure 55. The non-systematic reversal of 7 in a school activity by the student whose test writings are reproduced in Figure 54.

In Figure 55 it can be observed that the student, upon seeing the printed writings of 5 and 7 (in the first line of Fig. 55a), neither appears to reverse the 7 (as in the 4 lines of Fig. 54), nor to use his idiosyncratic writing of the digit 5, namely \mathcal{C} . In the first three lines of figure 55b, however, he repeats the reversal of 7 that was systematic in Figure 54. Remarkably, however, when he comes across the first printed writing of 7 (in 37, line 4 of Fig. 55b), he begins to write the digit 7 correctly in the next two lines. Finally, in the table in Figure 55c, in which there is no printed digit 7, he begins to systematically reverse the digit 7 again. Although we are talking about reversal here, for convenience, it is important to repeat that our theoretical interpretation is that of a confusion between 7 and the capital letter F.

This analysis suggests a remediation or, more generally, a teaching strategy. Indeed, as long as the student sees the correct writing, he writes the digits correctly (here the digits 5 and 7). On the other hand, when he writes them from memory, he is obliged to resort to his idiosyncratic or erroneous representation and, consequently, reproduces this idiosyncrasy or error and reinforces it in his declarative memory. To avoid such reinforcement of erroneous representations, it seems important not to force students to write numbers from memory too early, but to force them to look at the writing of a number before writing it—or at least to check it afterwards—on a clearly visible number line, for example on the student's desk.

We conclude that these students do not really reverse digits, but rather confuse them in their declarative memory. This observation extends and reinforces Fischer and Luxembourger's (2022) suggestion that reversal and confusion are two fundamentally different constructs. Even for typically developing children who still “reverse” certain characters, teachers should be

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aware that this may not be a perseveration of the tendency to reverse digits to align them in the direction of the writing, which is omnipresent in preschoolers, but probably an associative confusion arising from the physical similarity of these digits to existing writings already well consolidated in their declarative memory (such as F or e).

We have also studied the writing of digits by some hearing impaired children. But when testing hearing impaired children, the use of French Sign Language (FSL), Cued Speech Language (CSL), or even Lip Reading (LR) to dictate digits certainly disrupts the use of internal visual information. As a result, it is difficult to comment on their writing in general. On an individual level, one of the children, who was implanted and whose hearing deficit was not too profound, produced the writings in Figure 56. In the type of dictation that most closely resembles normal dictation with normal hearing students—namely lip reading (LR)—it is then interesting to observe that she reversed all the digits in the subset $D_l = \{1, 2, 3, 7, 9\}$ and none in the subset $D_r = \{4, 5, 6\}$.

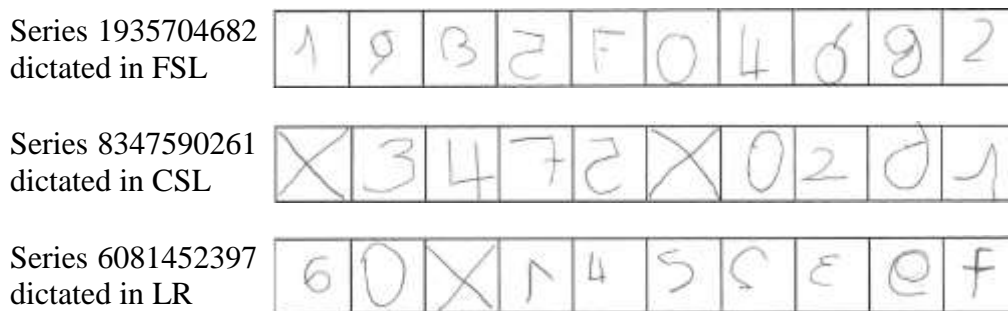


Figure 56. Three (of the 12) series written by a 5 year 8 month old student with a hearing disability (but implanted), with her usual right hand under dictation in the three languages tested.

8.4. An auditory indication activates a visual representation

In almost all character dictations, we (and others) have orally indicated the characters to be written. As we argue for the primacy of the visual modality (Section 4.5), it is worth pointing out how the visual written representation of characters can be activated by an oral, auditory cue. In fact, when adult participants are presented with auditory names of objects, rather than visual input, they nevertheless activate visual representations of objects (Peelen et al., 2014). How is this possible?

Several neuroscience investigations provide elements of response. Ludersdorfer et al. (2016) observed activation of the left ventral occipitotemporal cortex (vOT: ventral occipitotemporal cortex) in response to heard words. This activation could reflect access to visual-orthographic representations of whole words. In addition, activation in the posterior vOT may reflect the generation of explicit images of word-specific letter sequences. Furthermore, based on the phenomenon of cross-modality suppression, the finding of marked deactivation in response to auditory tones also supports the idea that orthographic representations of words in the left vOT are visual in nature.

Taylor et al. (2014) taught 19 adults to read 24 novel words written in unfamiliar letters and to name 24 novel objects. With an MRI scan, they observe that parietal cortices preferentially process component visual-verbal mappings, a crucial process for early reading development.

Taylor et al. (2019) found a hierarchical gradient, from posterior to anterior, in vOT cortex, in which letter representations are transformed to convey information about spoken language.

Kok and Turk-Browne (2018) observed that top-down predictions often arise from cross-modal associations, such as when a sound (e.g., a doorbell or a bark) leads to an expectation of the visual appearance of the corresponding object (e.g., a bicycle or a dog). They found that upon hearing a familiar auditory cue, the hippocampus represents visual information that had previously coincided with the cue, even when that expectation differs from what is currently visible. Given the general properties of the hippocampus, and the importance of oral knowledge of characters, it is then possible to assume that this is how the link between the oral name and the writing of characters is established. Beyond this initial learning, the participation of the hippocampus is probably no longer necessary. This is one of the great lessons learned from H.M., a famous patient who underwent a bilateral hippocampal resection and who was then tested, even beyond reason according to Hilts (1995).

8.5. Handwriting may not be very effective

I want to make it clear at the outset that I am not discussing here the contemporary and much more general problem of maintaining handwriting instruction in schools. My purpose is simply to discuss an implicit and potential consequence of my theory about the reversal of characters alone. Indeed, the theory is only logically coherent and practically relevant if the first learning of letter writing, with its vicissitudes, is of visual origin. I argue that it is. Even if the shape of an object is not a strictly visual property of the object, as is color, knowledge of the shape of the object is usually acquired through the visual modality (Peelen et al., 2014]. Indeed, kindergarten teachers and students use a visual object to refer to the writing of capital letters: they say "stick writing", with all non-curved letters appearing as a collection of sticks (A, E, F, H, I, K, L, M, N, T, V, W, X, Y and Z). But some educators may think that handwriting will help children to remember the correct orientation. As we have seen, Dehaene (2010) does not rule out the idea that motor learning can help unlearn symmetrization. But learning to write is slow (Chartrel & Vinter, 2004) and, more specifically, the constitution of motor representations can only be considered to be in place around the age of 10 (Zesiger et al., 2000).

Askov and Greff (1975) directly compared copying to tracing on kindergarten and 2nd grade students. Tracing consisted in passing with the pencil over the writing, which was first neat and then less and less inked. It turned out that copying is the most effective. This does not prove that motor training is ineffective but shows that motor learning—which is equally present in copying and tracing—is certainly not the major explanation of efficiency.

For visual letter categorization, Li and James (2016) directly demonstrated on five-year-olds that the learning condition, whether through visual-motor practice (copying typed symbols independently, tracing typed symbols, tracing handwritten symbols) or through visual-auditory practice (seeing and saying typed symbols of a single typed font, variable typed fonts, and handwritten examples) is not decisive. What is decisive is whether learning involves (or not) variable examples of a category, independent of visual-motor production. The reason handwriting supports letter recognition is that it produces perceptually (primarily visually) variable symbols in the environment that serve to enhance category understanding. The motor act involved in writing the letter, which is always fundamentally the same, does not have the same property. Moreover, in general, motor performance does not mix well with intellectual performance. Based on the study of specific connections between motor and intellectual

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functions, Jenni et al. (2013) even suggest that motor and intellectual domains in healthy children are largely independent.

Pedagogues can use sensory modalities other than the visual modality for learning to write. Although it may seem logically obvious that multi-modal learning should be more effective than single-modal learning, this is not always the case (see Madan & Singhal, 2021; Pecher & Zeelenberg, 2022). The great pedagogue Maria Montessori used rough characters that children explored tactilely (see Calo, 1956). Other pedagogues, less well known but mentioned in Section 7.1, suggested to write the characters on the children's backs. Spence et al. (2010) note that the back clearly offers great opportunities for the tactile presentation of information because nearly 50% of the skin surface is on the trunk of the body. Personally, having automated the writing of the Greek letter "epsilon" (ϵ) during my mathematics studies, I continue to fail to understand how a motor memory could tell me the correct orientation of 3.

Nevertheless, it is necessary to discuss here at least one research that has experimentally confirmed the effectiveness of manual writing learning, considering that the learning in Torres et al. (see Section 7.4) was multi-modal and only really effective by the addition of a consolidation period (sleep) just after the learning. This French research was originally published by Longcamp et al. (2005) and summarized in French by Velay and Longcamp (2005). The authors compare learning to write letters by hand with learning to type on a keyboard. This research is especially important to examine because it is often cited by advocates, nostalgic or not, of handwriting to argue that it is still useful. The research involved 76 children, aged 33 months to 57 months, who had been learning 12 capital letters for three weeks and were then tested twice, immediately after learning and one week after, with a multiple choice questionnaire test in which they had to choose the (correct) letter learned from four, one of which was a mirror image of the correct letter. Since children were likely to choose the correct letter at random and each letter was tested twice, the authors assigned a correct identification of a letter to a child only if he or she chose that letter correctly twice. The scores therefore ranged from 0 to 12. Do the results make a convincing argument for handwriting instruction?

First, we note that a floor effect affects these results since the majority of children do not exceed a score of 2 (out of 12). Second, the difference between learning by keyboarding and by handwriting (in favor of the latter) is not significant at the conventional level. On the other hand, the interaction Age x Learning mode is significant¹³: for the oldest children the difference is significant in favor of handwriting. However, one may wonder whether they did not benefit from "home" reinforcement during the three weeks of learning. The authors had certainly asked the parents not to practice handwriting at home during the experiment, but did some 4-year-olds, proud of their new learning, not want to show it to their family and friends? I don't think a grandparent—even one who knows the experimenters' instructions—would forbid his/her grandchild to show him/her how he/she can already write. And, as I am sure you will have anticipated, the children who had typed the letters on the keyboard at school (in 2005, or earlier, few 4-year-olds were expected to have a keyboard at home), had hardly any opportunity to reactivate their learning in class. In addition, it is not handwriting (learned) that is being tested but recognition, a fundamentally different task relative to character reversal (Fischer &

¹³ The authors report $p < .02$ for $F(1,70) = 4.50$. But Excel indicates $p = .037$.

Luxembourger, 2020). I therefore have reservations about the effectiveness of handwriting in overcoming reversal in writing,

Several research studies support the validity of these reservations. For example, Kiefer et al. (2015) wrote that, contrary to their expectations and previous findings (including those of Longcamp et al., 2005), "handwriting training did not improve letter recognition and letter naming performance compared with typing training" (p. 144). Duiser et al. (2022) studied 81 Dutch elementary school children (ages 4-6) assigned to one of three groups: handwriting, tactile typing, and control (traditional alphabet instruction). Although they ensured that the number of letter repetitions in all groups was higher than in Longcamp et al., they concluded that four- to five-year old children do not "learn to recognize and discriminate isolated letters better after handwriting than after touch typewriting tuition, and also not compared to regular alphabet tuition" (p. 701).

Seyll and Content (2022) have taken the investigation a step further by seeking to determine what is important for character recognition. Based on the evidence that learning new characters through handwriting leads to better recognition than learning through typing, Longcamp and colleagues proposed that the graphical motor plans acquired through handwriting contribute to character recognition. Seyll and Content's experimental research therefore also investigates the contribution of detailed visual analysis to character recognition in kindergarten children. To this end, three groups of preschoolers learned new symbols either by handwriting, typing, or composing, a method requiring detailed visual analysis but no specific graphomotor activity. After learning, the children performed a four-alternative recognition task. The same pattern of results, which these authors had previously observed in adults (Seyll et al., 2020), emerged, including the lack of evidence for the influence of motor knowledge. Thus, they confirm the importance of detailed visual analysis in learning letter-like shapes.

8.6. A child's first writing may be mirror writing

Once I was convinced that mirror writing was a phenomenon of memory, and not of perception, my observations focused on children of at least 5 years of age. For younger children, memory writing is indeed still too random, at least if one tries to test representative and unselected samples of children. Another reason why it is difficult to observe mirror writing in very young children, 3 or 4 years old, is that parents, teachers or researchers often propose models to them to copy and, as we have seen, this copy writing hardly generates mirror reversals. In the writing of the first name, we have nevertheless obtained some, even if imperfect (that of AYSEL), with our technique of sharing the sheet, in the longitudinal study of Anne-Marie Koch (see Fig. 57).

REMI : 4 years 4 months	EVANN : 4 years 5 months	SANEL : 4 years 6 months	AYSEL : 4 years 10 months

Figure 57. Mirror writing by some children under age 5. [Partial reproduction from Fig. 1 of Koch & Fischer (2013)].

In this longitudinal study, on children from a rather disadvantaged socio-economic background on average, the presence of mirroring at age 4 and the lack of change in the frequency of

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mirroring (of the first name) between MS and GS kindergarten can be seen as supporting a parallel development of mirror and correct writing. Indeed this result suggests that mirroring does not emerge "late", when children have reached a certain level of writing.

However, it is only recently that a collaborator, Christophe Luxembourger, gave me a gift that I no longer expected. ROSE, a child in his family environment, wrote her first name in mirror, spontaneously, at the age of 3 years 1 month (at school: her kindergarten teacher encouraged the children who were able to do so to sign their drawing). This signature is a complete mirror writing, i.e. from right to left and with reversal of all the reversible letters (see Fig. 58). It deserves further analysis. First, the R may appear imperfectly mirrored. But one might think that the vertical stroke is actually the secondary, diagonal, right-hand stroke of the correct R: mirrored, it is thus on the left side of the one that serves as the support for the loop of Я. The O itself, not reversable, seems to be drawn clockwise. Then the S is perfectly reversed. Finally, the E is detached, but well to the left of the other letters, respecting the mirror structuring: The hasta is well on the right, and the coda does have the three parallel strokes, even if they are imperfectly connected to the hasta.



Figure 58. ROSE's complete mirror writing, by Rose, signing her drawing at 3 years 1 month.

9. Conclusion

The current theoretical explanation of mirror writing is parsimonious and well inserted in a historical framework. We suggest that around 4-5 years of age children go through a period during which they do not know the orientation of the characters because they are symmetrized in memory. Children then orient them in the direction of the writing their culture. The current theory is only challenged by Corballis' theory, which describes a double (real and mirror) representation of characters and words in the brains of adult persons. This double representation suggests that, when writing a character or a word, children may activate the mirror representation more than the real representation. This would happen from time to time and for a reason that is not precisely known. Our research findings do not allow a general discussion of the representation of the characters in memory. However, our findings suggest that Corballis' hypothesis is not the explanation of mirror writing by typically developing children between the ages of 4 and 7.

From a broad point of view, comparison of theories can be based on two properties: their parsimony with respect to the assumptions they make and their ability to explain empirical observations (Brainerd & Reyna, 2015; see also Fig. 59). Yet, this approach for comparing theories is itself theoretical! Notably, any attempt to compare two or more theories faces the problem of their elegance, which is fundamentally subjective.

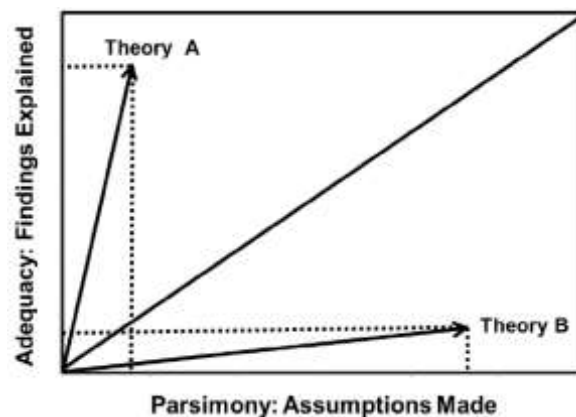


Figure 59. Vector space representing the trade-off between the explanatory adequacy and explanatory parsimony. In this space, theories are vectors: those above the diagonal represent better theories than those below, as they explain more observations with fewer assumptions. [Reproduced from Fig. 1 of Brainerd & Reyna (2015)].

Since elegance is being considered, I believe, that our description of the brain's handling of orientation awareness is itself surprisingly elegant. Indeed, children perceive correctly the orientation of characters (digits and letters) but the process of symmetrization (also called generalization) causes it to disappear in memory. Thanks to the dorsal brain pathway, the orientation of characters is then restored.

But I would like to end this essay by going back almost to the beginning, to Section 2.1. I noticed that the letters, originally left-oriented, were re-oriented to the right (mainly by their appendage next to the hasta) only 500 years before Christ when writing from left to right was established in our culture. Our distant ancestors then made the orientation of the letters coincide

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with the direction of writing. My theoretical approach to mirror writing in children, which has long seemed mysterious, thus follows Haeckel's (1907) biological principle that "ontogeny is the short and rapid recapitulation of phylogeny" (p. 310). When developing children have to choose an orientation—involuntarily because of the process of symmetrization—they choose, like their ancestors, to orient the characters in the direction of writing. By doing so, they bring the morpho-kinetic orientation of the characters into conformity with the topo-kinetic of their writing (see Fig. 60). Note that both the choices of our ancestors and those of contemporary children seem to satisfy Brekle's economic principle (see Section 2.4), or are even motivated by it.




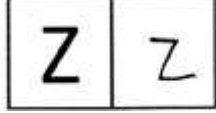


Age Task	≈ 4 years ½ in MS Kind. copy from a model	≈ 5 years ½ in GS K. writing from memory	≈ 6 years ½, 1 st grade memory, under dictation
Girl: Right hand preferred			
Boy: Right hand preferred			

Figure 60. The reversal, in the direction of writing, of the letters J and Z by 5 ½ years of age, during the developmental shift from correct copying at 4 ½ years to the management of symmetrization in memory at 6 ½ years. [Data from Fischer & Koch (2016b)].

However, our experimental procedure offered another choice to the children. When writing from right to left, they could—and a few children did—not reverse the letters of their first name. This gives a writing which, although not completely mirrored, is completely in conformity with the instructions and constraint (see the writing of ANISSA: Fig. 39). Nevertheless, most children chose to match the orientation of the characters with the direction of the writing, thus reversing the reversible letters, except possibly J and Z (see Fig. 43). Therefore, they repeat the behaviour our ancestors 2500 years later.

Certainly, Haeckel's old principle, set forth in his attractively titled book—*Les merveilles de la vie* (The wonders of life)—and its application to human children can be, and has been scientifically criticized. However, recent models of letter perception allow to come to similar conclusions. For instance, Testolin et al.'s (2017) suggest that by reusing natural visual primitives, learning written symbols requires only limited, domain-specific tuning. The model assumes that the shape of written characters has been culturally selected to match the statistical structure of natural environments. This suggests that 21st century children find "natural" what our ancestors found "natural" nearly 5 centuries BCE, namely orienting letters in the direction of writing.

More generally, the concept of perpetual knowledge, recently proposed by Geoffrey Schott (2022), can be applied to our observation of a repetition by contemporary children of the idea—matching the orientation of characters with the direction of writing—already applied by our ancestors nearly 2500 years ago. In particular, Schott offers the example of Friedrich August Kekulé's 19th-century circular representation of benzene as a snake with its tail in its mouth (see

Fig. 61). He notes that this idea of Kekulé's had already appeared about 1500 years earlier in Mesopotamia and was also used in the 17th century.

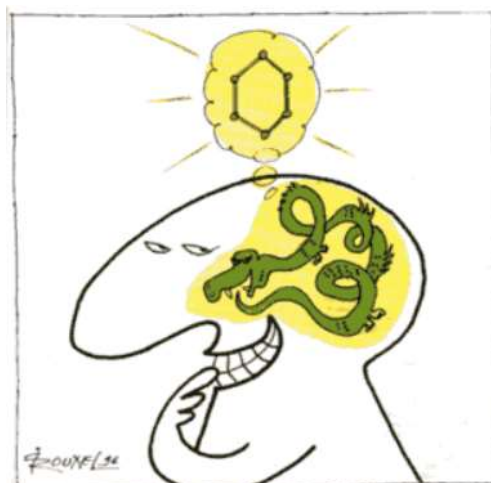


Figure 61. The Kekule snake.

[Retrieved from <http://sommeil.univ-lyon1.fr/articles/savenir/genie/serpent.php>].

How come our contemporary explanation of character reversal by typically developing 4- to 7-year olds, seems so similar to a cultural and societal shift occurring 2500 years ago? Schott attempts an answer: it might reflect the fact that the human brain has a limited creative repertoire. But one may prefer a more specific answer such as Brekle's principle of economy in writing (see Section 2.4). Especially since Jerome Bruner (1966) distinguished saving one's effort in the execution of a task as one of the three fundamental skills that govern the child's spontaneity (the other two are: directing one's attention, signifying one's intention).

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