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Mirror man: a case of skilled deliberate mirror-writing

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Abstract

Mirror-writing is a striking behaviour that is common in children, and can re-emerge in adults following brain-damage. Skilled *deliberate* mirror-writing has also been reported, but only anecdotally. We provide the first quantitative study of skilled deliberate mirror-writing. KB can write forward or backward, vertically upright or inverted, with the hands acting alone or simultaneously. KB is predominantly left-handed, but writes habitually with his right hand. Of his writing formats, his left hand mirror-writing is by far the most similar in style to his normal handwriting. When writing bimanually, he performs better when his two hands make mirror-symmetrical movements to write opposite scripts, than if they move in the same direction to write similar scripts. He has no special facility for reading mirrored text. These features are consistent with prior anecdotal cases, and support a motor basis for KB's ability, according to which his skilled mirror-writing results from the left hand execution of a low-level motor program for a right hand abductive writing action. Our methods offer a novel framework for investigating the sharing of motor representations across effectors.

Introduction

Mirror-writing, put simply, is writing back-to-front (McIntosh & Della Sala, 2012). Partial mirror writing can occur when individual letters are formed back-to-front, but complete mirror writing entails spatial reversal of the whole script. The writer begins with the first letter of the word, and proceeds through to the last, but production flows in the opposite direction to normal with each of the letters individually back-to-front. For a dextrad language like English, mirror-writing is right to left; it can be read normally when held to a mirror. Mirror-writing has three cardinal forms: 'spontaneous', 'involuntary', and 'deliberate' (Lebrun, Devreux & Leleux, 1989). *Spontaneous* mirror-writing is common amongst pre- and early school age children undergoing literacy development (Gordon, 1920; Cornell, 1985). *Involuntary* mirror-writing refers to the production of mirrored script by adults following brain damage (Balfour, Borthwick, Cubelli & Della Sala, 2007; Critchley, 1927, 1928; Della Sala & Cubelli, 2007). Mirror-writing can also be *deliberate*, and skilful. This form has been described anecdotally, but never studied experimentally. In this paper, we provide the first quantitative case study of skilled deliberate mirror-writing.

The most-celebrated deliberate mirror-writers, name-checked routinely in any overview, are Leonardo da Vinci and Lewis Carroll (e.g. Schott, 1999, 2007). Mirror-writing with the dominant left hand was Leonardo's habitual script when writing for himself, though he wrote for others in a forward direction. Schott (1999) has commented on the striking stylistic resemblance between Leonardo's mirrored and forward handwriting. Contrariwise, Lewis Carroll usually wrote with his right hand, and his mirror-writing was recreational rather than habitual, albeit highly skilled. It has been speculated that Carroll was a natural left-hander, schooled to write with his right hand (see Schott, 1999), though there is no direct evidence for this. Indeed, with a logical circularity that Carroll himself might have enjoyed, his mirror-writing is one of the most common arguments in favour of his left-handedness (personal communication, Chairman of Lewis Carroll Society, 2012).

A less illustrious, but better-documented case of deliberate mirror-writing is that of Frank James Allen, a Professor of Physiology who described his experience in *Brain* in 1896. He reported himself to be ambidextrous, and had discovered 'accidentally', at thirteen, that he could write backward fluently with his left hand. His reversed productions, when viewed in a mirror, are very similar to his normal handwriting (Figure 1 of Allen, 1896). Allen offered several interesting observations: that it was easy to write the same word simultaneously with both hands (presumably in opposite directions); that a sign language alphabet learned with his right hand could be executed easily with his left; that reversed writing movements could be made with the left foot; that visual feedback did not aid performance; and that he had no facility for *reading* mirrored-script, even self-penned. He speculated that everyone has the ability to mirror-write, to some degree, but that it is usually undiscovered, surfacing mainly in conditions where injury or disease obliges the unaccustomed hand to pick up a pen.

Allen's interpretation was that mirror-writing demonstrates the super-ordinate nature of the relevant graphic representations. He proposed that a high-level command can direct writing with any effector, with lower-level processes translating into an appropriate sequence of muscle contractions. His idea foreshadowed the concept of a generalised motor program, developed more fully during the latter half of the twentieth century (e.g. Bernstein, 1967; Lashley, 1951; Rosenbaum, 1980; Salzman, 1979; Schmidt, 1975). Generalised motor programs code for action in relatively abstract, effector-independent terms. For instance, the spatial path of an unspecified end effector may be coded initially in environmental coordinates. Such generalised programs occupy the top of a motor control hierarchy, with lower-levels becoming effector-specific and more detailed, translating the movement plan into joint movements, and ultimately into the precise muscle activations required for that effector. Several approaches to human and robotic motor control adopt this general hierarchical structure (e.g. Bernstein, 1967; Hollerbach, 1982; Salzman, 1979).

Handwriting (in a forward direction) has become a textbook example to illustrate the concept of effector-independence in action (e.g. Tresilian, 2012). At least some aspects of person's handwriting style are recognisably preserved when using unpracticed effector systems, such as the shoulder and elbow when writing very large (Merton, 1972), the non-dominant hand, or even using a pen taped to the foot or held in the teeth (Raibert, 1977). The two influential sources just cited compared individual writing samples produced by different effectors, interpreting similarities of shape to imply the involvement of a common, generalised motor program. However, these analyses were limited to a qualitative evaluation of the static shape of the writing, and did not consider dynamic aspects of its production. These limitations were highlighted by Wright (1990), using the analogy of signature forgery: the forger may fool us quite easily if she need only produce something that looks like the target signature, but her job is much harder if we also compare her sequence of pen-strokes against those that produced the original. For evidence that graphic representations are shared at an interestingly deep level of the motor control hierarchy, written words should not only look similar, but be produced in similar ways.

Wright (1990) compared normal writing with the dominant hand, against writing very large with the dominant arm, and writing with the non-dominant hand, analysing static and dynamic features across multiple writing samples in each condition. Whilst confirming broad qualitative similarities between conditions, he also identified systematic changes in the letter shapes, and in the dynamic sequence of pen-strokes. The non-dominant hand's writing diverged more from normal writing than did the dominant arm's, leading Wright to suggest that the two hands share only rather high-level abstract spatial representations for writing, whilst writing with the dominant hand and arm share representations at a deeper level in the motor hierarchy. Wright's work implies that we can differentiate degrees of relatedness between different formats of writing. The closer the relatedness, the deeper down the control hierarchy are the shared motor representations.

Wright's insights can be extended to the study of mirror-writing. For instance, FJ Allen's (1896) deliberate non-dominant hand mirror-writing, when viewed in a mirror, may look stylistically similar to his dominant hand forward writing, but we could assess the true relatedness more deeply by considering the dynamic and not just the static character of the writing, across multiple samples. This would more formally test Allen's intuition that mirror-writing with the non-dominant hand reflects the sharing of motor programs between effectors. The predictions for this test will be drawn out in due course, but for now we should note that Allen's hypothesis of deliberate mirror-writing converges with a classical motor account proposed to explain cases of *involuntary* mirror-writing following brain damage. The core idea of (at least some) classical motor accounts is that a skilled action developed by one hand will most naturally be executed by the opposite hand in mirror-reversal, since homologous muscles would be activated in the same sequence (Critchley, 1928; Erlenmeyer 1879, cited in Critchley, 1928; Vogt, 1880). In a right-handed, dextrad language culture, mirror-writing may be the natural 'unthinking' script of the left hand.

To transpose these classical ideas onto a more modern motor control hierarchy, we might suggest that motor plans for writing are associated with the hand that has learned them, so become represented strongly at an effector-relative level of the motor hierarchy. At this lower level of representation, there is no explicit specification of how the pen should move, but rather of how the joints should move, for instance specifying horizontal arm movements as abductive (away from the body midline) or adductive (toward the body midline) rather than as rightward or leftward through the environment (e.g. Salzman, 1979). Thus, for right handers in dextrad language culture, handwriting is ingrained as a low-level abductive motor plan for the right hand. If this abductive plan is then sent to the left hand instead of the right, the movement will flow from right-to-left, producing mirror-writing. This might arise through some sort of disinhibition in patients with brain damage, or as an innate and/or cultivated ability in deliberate mirror-writers. In either case, fluent mirror-writing should be strongly associated with the non-dominant hand; and provided that this hand is reasonably dexterous, the mirror-writing (when viewed in a mirror) should be similar to normal writing in both static and dynamic features, because it derives from a shared representation at a low level of the motor hierarchy. Indeed, the similarity should be stronger than that between forward writing for the two hands, which share only a higher-level, environment-relative representation (Wright, 1990).

Motor accounts of mirror-writing have been formulated in various ways (see Discussion). As a class of explanation, they can be contrasted with perceptual accounts, according to which mirror-writing is guided by reversed perceptual representations of words and letters (e.g. Orton, 1928; Heilman, Howell, Valenstein & Rothi, 1980). These reversed perceptual representations would give rise to high-level effector-independent plans for writing reversed words and letters, inducing mirror-writing with either hand. As with motor hypotheses, the perceptual accounts can take various specific formulations, but all predict that mirror-writing should be associated with a facility for perceptual recognition of mirrored letters and words. Two clinical observations strongly favour a motor over a perceptual account of mirror-writing. First, *involuntary* mirror-writing is typically confined to the non-dominant hand; and second it is not normally accompanied by mirror-*reading* (Critchley, 1927, 1928; Della Sala & Cubelli, 2007; for possible exceptions, see Durwen & Linke, 1988, and Heilman et al, 1980). Similarly, *deliberate* mirror-writing is, at least anecdotally, associated with the left hand, especially amongst amdibextrous or left-handed people schooled to write with the right hand. In a letter to *Nature*, Smetacek (1992) mentioned four such 'corrected' sinistrals who mirror-wrote fluently with the left hand. One woman apparently drafted her master's thesis by mirror-writing onto transparent paper with her left hand, editing it later on the flip side with her right.

However, whilst skilled deliberate mirror-writing has long attracted interest, the literature lacks any objectively-described case. We provide the first such data, concerning a German academic, who practises as an amateur artist under the pseudonom Kasimir Bordihn (KB). KB has a more than 50 year history of mirror-writing, and has developed this ability to a flamboyant degree. He writes, apparently quite fluently, with either hand, forward or backward, upright or inverted, and unimanually or bimanually (see Figure 1). Although it will be impossible to separate out, retrospectively, innate ability from the effects of practice, we aim to provide an objective characterisation of KB's mirror writing skills, and to assess how these bear upon perceptual and motor hypotheses of mirror-writing. The specific predictions will be detailed alongside our methods, following a brief description of this unusual man.

Case report

KB describes himself as ambidextrous; but on examination with the Edinburgh Handedness Inventory (Oldfield, 1971), he reports a left hand preference for all manual activities except for writing, for which he has a strong right hand preference. His laterality quotient (-64%) therefore reflects incomplete left hand dominance; and he is left eye dominant, as assessed by the Porta test (Porta, 1953). This pattern suggests that KB is a natural left-hander, schooled to write with his right hand, a practice common in Germany (and elsewhere) at that time

(Smetacek, 1992). However, he does not recall having been required to write right-handed, so this inference cannot be certain. In addition to his first language, German, KB is fluent in English, which he studied from the age of 12. He also studied French at school, and later some Spanish.

KB 'discovered' mirror-writing at the age of nine, finding that he could reduce his time writing lines for a teacher by writing forward with his right hand and simultaneously backward with his left. He went on to practice writing backwards and forwards with either hand, unimanually and bimanually. He revived these amusements in his early twenties. For instance, when paying a parking fine, he wrote a cheque and letter in mirror-reversal as a humorously subversive act. He also posted himself mirror-addressed envelopes, to see if they would be delivered. They were.

As a University lecturer in Veterinary Medicine, from the age of 35, KB found a more practical outlet for these abilities. He used mirror-writing of words and letters to illustrate the concept of knot chirality, teaching that a compound surgical knot will be strongest if its component knots are of alternating chirality. This novel demonstration proved popular with students, and he was invited to perform at University events. For these, he developed more elaborate tricks, adding vertical inversions to his forward and backward writing (Figure 1). As an amateur artist, he incorporated these reflections and inversions into a distinctive 'mirror-art', which deals with concepts of symmetry and asymmetry (Figure 2).

At the time of testing, shortly before his 65th birthday, KB was able to write in eight ways: forward and reversed combined with upright and inverted, executed with either hand (Figures 1 and 3). He reports that left hand mirror-writing has always felt natural to him, but that other non-standard writing patterns have required more practice.

Methods and predictions

Reading tasks

A cardinal prediction of the perceptual hypothesis is that, since the ability to mirror-write implies access to reversed perceptual representations of words and letters, it should be associated with a facility for mirror-reading. However, like FJ Allen (1896), KB reports that he does not find it easy to read mirrored-text, and is unable to read his own mirror-writing without the aid of a mirror.

We attempted to test this more formally by presenting KB with short abstracts from *Current Biology* news articles, such as he might read in his academic life, to be read aloud under timed conditions. He was first presented with a 109 word abstract, printed normally, which he read without error in 38 seconds. Next, given a mirror-printed abstract, he struggled severely, reading four words correctly and two incorrectly before refusing to continue after 25 seconds. This was considered sufficient to establish that KB does not have any special facility for mirror-reading, and we did not press him further with this task that he did not enjoy.

Writing tasks

KB's writing, in its various formats, was assessed by single-word writing. All words were written with a pen-like stylus on the touch screen (260*163 mm, 1280*800 pixels, 60 Hz refresh) of a Toshiba Portégé tablet laptop, with the screen in the flat landscape orientation. The tasks were controlled by customised LabVIEW software, which sampled the stylus coordinates every 13 ms (+/- 3 ms).

Unimanual writing task

KB has eight unimanual writing formats. Figure 3 shows examples of these eight formats, and illustrates the terminology used to refer to them, and the symbol shapes that will denote them on our data figures.

KB performed four blocks of unimanual trials, with hand and vertical orientation blocked in the order: right hand upright, left hand upright, right hand inverted, left hand inverted. In each block, he wrote each of nine words in each of four ways: forward with visible trace, forward with no trace, reversed with visible trace, reversed with no trace. On visible trace trials, the stylus left a black line, two pixels thick, on the screen, mimicking writing with a normal pen. Each word was a legal six letter word in English and German (butter, design, editor, farmer, finger, garage, hammer, helium, isomer). Trial order was randomised within blocks.

Each trial was preceded a grey rectangular box (300*150 pixels), stating the trial number, at the bottom centre of a white screen. KB touched the box with the stylus to initiate the trial. The box disappeared and 500 ms later the target word appeared in normally-oriented, black, lower case, 138 point Times New Roman font at the top centre of the screen. The word was underlined or not, indicating visible trace and no trace trials respectively. After 3000 ms, the word disappeared, and a grey triangle (325*465 pixels) appeared at the left or right of the screen, pointing to a grey circle (475 pixels diameter) on the other side. The two shapes were centred vertically, and separated by 1060 pixels of blank space, within which KB was required to write the word in the direction indicated by the triangle, touching the circle with the stylus to end the trial. His instruction was to write each word at a comfortable pace. Consistency of handwriting style, not speed or neatness, was emphasised as important.

Unimanual writing: scoring procedures and dependent measures

To index how similar each of KB's non-standard writing formats is to his standard right hand upright forward handwriting, we used three scoring procedures. *Static similarity* of the final written forms was derived from the subjective ratings of multiple naive observers, who did not know the purpose of the study or the provenance of the stimuli. *Dynamic similarity* was derived from a rule-based comparison of the sequence of pen-strokes by an observer who did not know which writing condition he was scoring. *Fluency cost* was calculated as the amount of extra time required to write each non-standard format, relative to the standard.

Static similarity to the standard was rated by 20 naive observers (13 women, 7 men; mean age 27.7 years, SD 3.61), each of whom completed a booklet of 18 A4 rating sheets, bound with a cover sheet of instructions. There was one sheet for each of the nine words in the visible trace and no trace conditions separately. Figure 4a shows an example rating sheet. On every sheet, a standard word was shown within a central box, with eight target formats of the same word arranged around it. The eight target words were from KB's eight unimanual formats, and the central standard was from KB's right hand upright forward format for the same trace condition (visible trace or no trace). Observers were required to rate each target word for similarity to the standard by using a numerical scale underneath the target (where 1 is totally dissimilar, and 5 is identical). To facilitate this, every word had been digitally reflected and/or inverted as required to normalise to the canonical orientation. The spatial assignment of writing conditions to the eight target word positions was varied across sheets, to offset any rating biases related to word position. Note that the right hand forward format appears twice on each sheet, once as the standard and once as a target. This provides a check on the validity of the observer ratings, as this target should be rated as identical to the standard.

Dynamic similarity was scored by an experimenter (RDM) replaying the sequence of pen strokes, moment by moment, comparing each target word side-by-side with the same word produced in the standard right hand forward condition of the corresponding trace condition (visible trace or no trace). To facilitate comparison, every word was normalised digitally to the canonical orientation. To reduce subjectivity, a set of rules was followed. Each letter within each word was rated as different from the standard only if any of the following differences were identified: (i) a major feature (e.g. decorative loop) was missing or added; (ii) a cursive link to the next letter was missing or added; (iii) the direction of a major pen-stroke differed categorically (e.g. an anticlockwise vs clockwise loop, a leftward vs. rightward or upward vs downward stroke); (iv) the orientation of a major pen-stroke differed by more than 45 degrees; (v) there was a difference of stroke order (typically, crossing a ‘t’ or dotting an ‘i’ at a different point during the word formation). For each word, the number of letters recorded as different was subtracted from six to produce a similarity score from zero to six. Dynamic similarity has some overlap with static similarity, as it is affected by major (though not minor) differences of shape, but it provides a complementary measure that is sensitive to differences in the sequence of pen strokes.

Fluency cost was the time taken to write the target word minus the time taken to write the standard, with writing time calculated from the onset of the first pen-stroke to the offset of the last.

Unimanual writing: predictions and analysis strategy

Our predictions for the unimanual task are predicated on Wright’s (1990) analysis, which states that writing acts will be more similar to one another if they share a motor representation at a lower level of the control hierarchy. A highly simplified motor hierarchy for writing is shown in Figure 5, to illustrate the critical predictions of the perceptual and motor hypotheses. These predictions are specifically for upright writing.

According to the perceptual hypothesis, forward writing with either hand would depend on a common high-level plan, and reversed writing with either hand would depend on a different common high-level plan. The perceptual hypothesis therefore predicts that left hand forward writing would be more similar to normal writing than would left hand reversed writing. A more speculative, and thus less critical prediction of the perceptual hypothesis is that, if mirror-writing is guided by a reversed perceptual representation of how the word should look, then its accurate production might require visual monitoring of the written form, so the visible trace condition should aid reversed writing disproportionately.

According to the motor hypothesis, left hand reversed writing would derive from the left hand executing the low-level effector-relative plan for right hand forward (abductive) writing. The motor hypothesis thus predicts that left hand reversed writing should be more similar to normal writing than is left hand forward writing. Figure 5 also implies that right hand reversed writing *could* be produced by right hand execution of a left hand adductive plan for forward writing. However, this is highly speculative, and is not a critical prediction of the motor hypothesis (which properly concerns only left hand mirror writing). Left hand adductive writing is not any more primary or canonical than right hand adductive writing, so it is not obvious that the latter should be derived by co-opting the former. An alternative might be that right hand reversed writing descends from a separate high-level motor plan for reversed writing. The only firm prediction of the motor hypothesis for right hand reversed writing is that it should be more distantly related to normal writing than is left hand reversed writing. Finally, the motor hypothesis provides no reason to think that the provision of a visible trace should aid mirror-writing disproportionately.

To target these predictions, for each dependent measure, we will run a repeated-measures ANOVA by condition (left hand reversed, left hand forward, right hand reversed) and trace visibility (visible trace, no trace), with Huyhn-Feldt corrections to the degrees of freedom to compensate for violations of sphericity. Planned contrasts will be used to compare left hand reversed writing against the other two formats. The perceptual hypothesis predicts that left hand forward writing will have the greatest similarity to normal writing, and that trace visibility may aid the reversed writing conditions disproportionately. The motor hypothesis predicts that left hand reversed writing will have the greatest similarity to normal writing, with no specific influence of trace visibility. In order to save degrees of freedom for these critical questions, we will not include inverted writing in any inferential statistical analyses. Indeed, at this stage, we make no specific predictions for inverted writing, except that it could not be produced by co-opting normal writing programs at any level of the motor hierarchy, so presumably requires a distinct high-level plan, in which case it should bear little if any resemblance to KB’s upright writing (Figures 3 and 4 suggest that this is the case).

Bimanual writing task

Bimanual writing was assessed on the day after the unimanual task. The bimanual task used two matching tablet laptops, with trial sequences synchronised. All words were written upright, with a visible trace. KB performed two blocks of 40 trials. In each block, each of five words was written unimanually or bimanually in each of the eight possible combinations of script: left hand task (inactive, forward or reversed) crossed with right hand task (inactive, forward or reversed), excluding the double inactive combination. The trial procedure was similar to that of the unimanual task, except that KB worked on the two directly adjacent laptops, with a stylus in each hand. He initiated each trial by touching the starting box on each screen simultaneously. Trials in which one hand was inactive were indicated by a single grey circle (475 pixels diameter) at the centre of that screen. The words were always the same for the two hands in bimanual trials, and each was a legal six letter word in English and German (Block 1: jaguar; karate; kitsch; magnet; minute; plural. Block 2: puzzle, quasar, radius, satire, bitter). Trial order was randomised within blocks. Consistency of handwriting and simultaneity of bimanual writing were emphasised as important.

Table 1 lists the eight writing conditions. Note that we class each bimanual condition as either *perceptually congruent* or *motorically congruent*. When the two hands write the same word in the same environmental direction (both writing forward, or both writing reversed), the condition is perceptually congruent, because a matching perceptual representation of the word could guide both hands. When the two hands write the same word in environmentally opposite directions (one writing forward and the other reversed), the condition is motorically congruent, because the same effector-relative representation (abductive, or adductive) could guide both hands.

Bimanual writing: scoring procedures and dependent measures

The scoring procedures were similar to those for the unimanual task, with minor differences.

Static similarity to KB's normal writing was rated by 20 naive observers (13 women, 7 men; mean age 26.7 years, SD = 2.86), each of whom completed a scoring booklet of 20 A4 sheets. Figure 4b shows an example rating sheet. The central standard word was always from the unimanual right hand forward condition, with six target formats of the same word arranged around it. The six target formats were from the same hand (right or left), and came from the six writing formats for that hand (unimanual forward, unimanual reversed, bimanual forward perceptually congruent, bimanual forward motorically congruent, bimanual reversed perceptually congruent, bimanual reversed motorically congruent).

Dynamic similarity was rated according to the same rules as for the unimanual task, with the experimenter (RDM) unaware of which writing format he was rating. For each word, each writing format was compared against the standard (unimanual right hand forward).

Fluency cost was the time taken to write the target word minus the time taken to write the standard, with writing time calculated from the onset of the first pen-stroke to the offset of the last.

Bimanual writing: predictions and analysis strategy

The bimanual task includes unimanual writing conditions, which replicate the critical upright conditions from the unimanual task. To test for replication of results, we will conduct a repeated-measures ANOVA, separately for each dependent variable, by unimanual writing condition (left reversed, left forward, right reversed), with Huyhn-Feldt corrections to the degrees of freedom to compensate for violations of sphericity. Planned contrasts will be used to compare left hand reversed writing against the other two formats.

The eight bimanual writing conditions provide a further exploration of KB's writing abilities, and allow an additional assessment of the relative importance of perceptual and motor representations. If a perceptual representation is critical to performance, then the bimanual task should be easier when the writing direction is the same for the two hands, since a single perceptual representation could guide performance. If effector-relative motor plans are more important, then performance should be aided when the hands act in opposite directions. For each dependent measure, we will conduct a repeated measures ANOVA by hand (left, right), direction (forward, reversed), and congruence (perceptual, motoric). The perceptual hypothesis predicts an effect of direction such that forward writing is closest to the standard, and an effect of congruence such that perceptually congruent conditions are performed better (more fluently and/or more similar to the standard). The motor hypothesis predicts an interaction of hand by direction such that abductive writing (right hand forward, left hand reversed) is closest to the standard, and a main effect of congruence such that motorically congruent conditions are performed better.

Results

Unimanual writing task: main analysis of upright formats

Figure 6 shows the mean scores for *static similarity*, *dynamic similarity* and *fluency cost* in each of the non-standard writing conditions. Inferential analyses are restricted initially to the upright writing conditions (left panels); the inverted conditions (right panels) are included for descriptive purposes;

A repeated-measures ANOVA by upright condition (left hand reversed, left hand forward, right hand forward) and trace visibility (visible trace, no trace) found a significant main effect of condition, for *static similarity* [$F(2,16) = 75.23$, $p < 0.0005$; $\eta\rho^2 = 0.90$], *dynamic similarity* [$F(1.88,15.07) = 14.20$, $p < 0.0005$; $\eta\rho^2 = 0.64$], and *fluency cost* [$F(2,16) = 12.96$, $p < 0.0005$; $\eta\rho^2 = 0.62$]. Planned contrasts confirmed that, for all three measures, left hand reversed writing was significantly closer to the standard than was left hand forward or right hand reversed writing ($p < 0.005$ in all cases). Trace visibility had no significant effect, nor significant interaction with condition ($P \geq 0.15$). These results are closely concordant with the predictions of the motor hypothesis.

Unimanual writing task: supplementary analysis of right hand reversed writing

Figure 5b suggested that right hand reversed writing could be produced by co-opting a low-level motor plan for left hand adductive writing. This is not a critical prediction of the motor hypothesis, which properly concerns mirror-writing with the non-dominant hand. Nonetheless, we explored whether KB's right hand reversed writing conforms to the scheme depicted in Figure 5b. To do this, we performed an analysis of *dynamic similarity* for upright writing, using left hand forward writing as the standard[1].

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[1] Although not reported last, this was the final analysis conducted. We did not include *static similarity*, because this would have required recruitment of a further group of observers, and because prior analyses suggested that *static similarity* provides relatively little unique

The motor hypothesis predicts that right hand reversed writing will be more similar to this standard than will right hand forward, or left hand reversed writing. An ANOVA was performed by upright condition (right hand reversed, right hand forward, left hand forward) and trace visibility (visible trace, no trace). Trace visibility had no significant influence either as a main effect or in interaction ($p > 0.68$). The analysis of the effect of condition was compromised by a severe violation of sphericity, with consequent reduction in the degrees of freedom, and the effect of condition was not significant [$F (1.16, 9.25) = 3.05$, $p = 0.11$; $\eta\rho^2 = 0.28$]. However, the pattern of means did qualitatively follow the predictions of the motor hypothesis, with right hand reversed writing having a higher mean *dynamic similarity* to the left hand forward standard that did right hand forward or left hand reversed writing (4.06 vs 3.28 and 2.89 respectively). This intermediate result does not confirm, but neither does it rule out, the motor account of KB's right hand reversed writing depicted in Figure 5b.

Unimanual writing task: supplementary analysis of inverted formats

Figure 6 indicates that inverted writing was always more dissimilar to the standard than was upright writing. The difference is most clear when considering *dynamic similarity*, which takes account not only of the final shapes of the letters, but the strokes by which they were produced. KB's inverted writing thus bears scant resemblance to his normal writing (see samples in Figure 3), and is produced by different pen strokes. However, this general dissimilarity is compatible with at least two interpretations. First, KB's inverted writing might be produced in a manner similar to his upright handwriting, but from a distinct high-level motor plan for inverted script. If so, although KB's inverted writing is dissimilar to his upright writing, the pattern of similarities between his formats of inverted writing should be like those observed for the upright formats. An alternative, null hypothesis is that KB's inverted writing is simply less consistently structured than his upright writing, in which case there should be no specific pattern of similarity between inverted formats.

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information, over and above *dynamic similarity*.

A supplementary analysis of KB's inverted writing was performed to address this issue. The methods of analysis followed those for the main experiment, with all words normalised digitally to the canonical orientation prior to analysis. *Static similarity* was derived from the subjective ratings of 24 naïve observers (15 women, 9 men; mean age 28.8 years, SD 4.05) each of whom completed one rating sheet for each of the nine words. On each sheet, the right hand inverted forward production was the standard, with all eight writing formats (two hands by two directions by two visible trace conditions) as targets. *Dynamic similarity* was assessed by the rule-based comparison of pen-strokes between each non-standard format and the right hand forward standard. *Fluency cost* was the amount of extra time required to write each non-standard format, relative to the standard.

Figure 7 shows the mean scores for *static similarity*, *dynamic similarity* and *fluency cost* in the non-standard inverted writing conditions. We ran a repeated-measures ANOVA by inverted condition (left hand reversed, left hand forward, right hand reversed) and trace visibility (visible trace, no trace), with Huyhn-Feldt corrections to the degrees of freedom to compensate for violations of sphericity, and planned contrasts to compare inverted left hand reversed writing against the other two formats. The effects of writing condition were compatible with those observed for upright writing in the main experiment, with a significant main effect for *static similarity* [$F(1.92,15.33) = 32.91$, $p < 0.0005$; $\eta\rho^2 = 0.80$], *dynamic similarity* [$F(1.76,14.05) = 60.25$, $p < 0.0005$; $\eta\rho^2 = 0.88$], and *fluency cost* [$F(1.71,13.66) = 10.29$, $p < 0.0005$; $\eta\rho^2 = 0.56$]. Planned contrasts confirmed that left hand reversed writing was significantly closer to the standard than was left hand forward or right hand reversed writing ($p < 0.005$), except in the case of *fluency cost*, for which left hand reversed writing was not significantly faster than right hand reversed writing ($p = 0.14$). In contrast to the main experiment, in which trace visibility had no significant effect, trace visibility did have a significant influence on *static similarity* for inverted writing [$F(1,8) = 6.29$, $p < 0.05$; $\eta\rho^2 = 0.44$], with overall greater similarity to the standard when the trace was visible.

As for the upright formats, then, the effect of inverted writing condition is consistent with a motor hypothesis, whereby inverted writing descends from a high-level motor plan for inverted script, with left hand reversed writing produced by the sharing of an effector-level motor program for right hand forward writing. It is worth emphasising that KB developed inverted writing only in mature adulthood and has given much less practice to it than to his upright formats. The fact that the motor hypothesis is supported for inverted as well as upright formats strengthens this hypothesis in general, and helps rule out the more prosaic possibility that the advantage seen for left hand reversed upright writing is simply due to this being KB's most highly practiced non-standard script. However, the relative lack of practice with inverted script may account for the improvement in *static similarity* when visual feedback is available. KB's ability to produce consistent inverted script depends partly on the ability to monitor performance visually, suggesting a less automatic execution than for upright formats.

Bimanual writing task

Figure 8 shows the mean scores for *static similarity*, *dynamic similarity* and *fluency cost* in each of the non-standard writing conditions of the bimanual task. Unimanual conditions (left panels) were analysed separately from bimanual (right panels).

The unimanual conditions were submitted to separate repeated-measures ANOVAs for each dependent variable, finding a significant effect of writing condition for *static similarity* [$F(2,18) = 20.47$, $p < 0.0005$; $\eta\rho^2 = 0.70$] , *dynamic similarity* [$F(1.64,14.79) = 3.89$, $p = 0.05$; $\eta\rho^2 = 0.30$], and *fluency cost* [$F(1.71,15.38) = 8.12$, $p < 0.01$; $\eta\rho^2 = 0.47$]. Planned contrasts confirmed that, for all three measures, left hand reversed writing was significantly closer to the standard than was left hand forward writing or right hand reversed writing ($p < 0.05$ in all cases), except that the comparison with right hand reversed writing failed to reach significance for *fluency cost* ($p = 0.06$). Overall, the pattern of unimanual performance replicates that obtained in the upright conditions of the unimanual writing task (compare left panels between Figures 6 and 8), and further supports the motor hypothesis.

The bimanual conditions were submitted, separately for each dependent variable, to repeated-measures ANOVAs by hand (left, right), direction (forward, reversed), and congruence (perceptual, motoric). There was a slight superiority overall for the right hand in terms of *static similarity* [$F(1,8) = 6.79$, $p < 0.05$; $\eta\rho^2 = 0.46$] and *fluency cost* [$F(1,8) = 9.48$, $p < 0.05$; $\eta\rho^2 = 0.54$], modified by a powerful crossover interaction of hand and direction that was significant for *static similarity* [$F(1,8) = 91.11$, $p < 0.0005$; $\eta\rho^2 = 0.919$], *dynamic similarity* [$F(1,8) = 27.27$, $p < 0.005$; $\eta\rho^2 = 0.77$], and *fluency cost* [$F(1,8) = 56.30$, $p < 0.0005$; $\eta\rho^2 = 0.88$]. For the right hand, forward writing was more similar to the standard than was backward writing, but this was reversed for the left hand.

The main effect of congruence was also significant for *static similarity* [$F(1,8)=9.02$, $p<0.05$; $\eta\rho^2=0.53$], *dynamic similarity* [$F(1,8)=19.98$, $p<0.005$; $\eta\rho^2=0.71$], and *fluency cost* [$F(1,8)=20.87$, $p<0.005$; $\eta\rho^2=0.72$], confirming better performance when the hands moved in environmentally opposite directions, despite the fact that these trials required the production of perceptually incongruent words. Figure 8 suggests that the advantage for motorically congruent conditions (black symbols) was greatest, at least for *dynamic similarity* and *fluency cost*, when the right hand wrote forward and the left hand reversed. This was confirmed by a significant three-way interaction of hand by direction by congruence for *dynamic similarity* [$F(1,8)=37.21$, $p<0.0005$; $\eta\rho^2=0.82$] and *fluency cost* [$F(1,8)=23.53$, $p<0.005$; $\eta\rho^2=0.75$]. This pattern suggests a special facilitation of KB’s mirror-writing ability when the left hand could simultaneously mirror the right hand’s normal writing movements.

As an aside, visual comparison of corresponding writing formats between the unimanual and bimanual panels of Figure 8 suggest an interesting pattern. For *static similarity*, KB’s writing in each condition was rated as closer to the standard when he wrote unimanually than when he wrote bimanually. This general unimanual advantage might arise because KB can produce a neater product when he can concentrate on writing in just one place at a time. By contrast, no general unimanual advantage is seen in terms of the sequence of pen strokes (*dynamic similarity*) or the fluency of their production (*fluency cost*). For these measures, there may instead be a specific facilitation of left hand mirror-writing under bimanual motorically congruent conditions. Thus, even for KB, a highly practiced mirror-writer, writing backward with the left hand may be most natural when writing simultaneously forward with the right. He reports this as his subjective experience, as do many people who try mirror-writing in unimanual and bimanual configurations (e.g. Allen, 1896).

Discussion

KB is a mirror-writer of exceptional skill who, across more than 50 years, has developed this ability more completely than any person previously documented. He writes forward or backwards script, upright or inverted, with either hand, and he can do this unimanually and in diverse bimanual combinations. We have assessed KB's single word writing, across his eight unimanual scripts, with and without vision of the pen trace, and for upright script across bimanual combinations. Our focus has been on the similarity of each format to KB's normal forward handwriting, in terms of the appearance of the writing, the sequence of pen strokes and the speed of execution. Here, we relate our findings to earlier anecdotal descriptions of deliberate mirror-writing, and to theories of the phenomenon.

It seems likely that KB is a natural left-hander who was schooled to write with the right hand, giving incomplete left hand dominance. If so, this is a history he shares with the four cases mentioned by Smetacek (1992), and possibly also with Lewis Carroll (Schott, 1999). As noted in the Introduction, a degree of ambidexterity may be a prerequisite for skilled mirror-writing, since either hand needs sufficient dexterity for legible writing. Also in common with prior descriptions of deliberate mirror-writing (e.g. Allen, 1896; Smetacek, 1992), and despite his extensive experience of mirrored text, KB has no special facility for mirror-reading. If he had enhanced access to perceptual representations of mirrored letters and words, then such text should be easily decipherable for him; on the contrary, his attempts to read mirror-reversed text ended in frustration. This makes a perceptually-based interpretation of his mirror-writing unlikely. KB's performance in our handwriting tasks reinforces this conclusion, as described below.

The central finding is that KB's left hand upright mirror-writing has a privileged status, being significantly more similar to his normal writing than is any other non-standard format, including *forward* writing with the left hand. This result thus undermines the claim, long-cited as a prime example of motor equivalence, that a person's forward handwriting style is invariant across effectors (Merton, 1972; Raibert, 1977, cf. Wright, 1990). Deeper equivalence may require that handwriting actions can share a lower level, effector-relative motor representation (Figure 5). The privileged status of left hand reversed writing is consistent with the idea that 'true' mirror-writing derives from non-dominant hand execution of motor programs for abductive handwriting developed by the dominant hand.

One possible counter-argument might be that left hand reversed writing is advantaged just because it is KB's earliest and most familiar format of non-standard script. However, a supplementary analysis of KB's inverted script likewise found that the left hand reversed format most closely resembles the right hand forward format, even though none of KB's inverted writing is particularly similar to his normal handwriting. His inverted writing is presumably guided by a distinct high level representation for inverted script, but the left hand mirrored format may nonetheless be produced by co-opting a low level right hand abductive motor plan. The fact that this pattern obtains even for a format of mirror-writing that KB did not develop until his late 30's, suggests that mere practice and familiarity cannot explain it. In any case, the argument from practice seems to confuse cause and effect: left hand upright reversed writing is surely the earliest format precisely *because* of its privileged status, as attested by the strong association of mirror-writing, deliberate *and* involuntary, with the non-dominant hand (Critchley, 1927, 1928; Della Sala & Cubelli, 2007; Schott, 2007).

KB's performance also accords with Allen's (1896) observation that left hand mirror-writing is not much helped by vision. In our tasks, we did not manipulate vision of the hand itself, but varied the visibility of the word written. The visible trace condition might be expected to aid mirror-writing disproportionately if mirror-writing is guided by a reversed perceptual representation of how the word should look. In fact, trace visibility conferred no differential advantage for mirror writing, offering no support for this idea. Nonetheless, trace visibility did significantly enhance *static similarity* of inverted writing in general, suggesting that visual feedback allowed KB to achieve greater consistency of shape in this relatively unpracticed task.

In the bimanual task, we pitted perceptual factors directly against motor, requiring the two hands to write the same word in the same or in opposite directions (Table 1). If the perceptual representation is critical, then this task should be easier when the writing direction is the same, since a single representation can guide both actions. If motor factors are critical, then the task should be easier when the hands act in opposite directions, since the actions are motorically congruent. Motoric congruence strongly dominated the quality of bimanual performance, consistent with a motor basis for mirror-writing. Figure 8 suggests that KB's left hand mirror writing in the motorically congruent condition may even be slightly better than his unimanual mirror writing, at least in terms of *dynamic similarity* and *fluency cost*. This accords with the common experience of non-mirror-writers who try the task; people often find it easier to mirror-write (for instance) their name backward with the left hand, if they simultaneously write it forward with the right. It may be that we can take advantage of an automatic tendency toward mirror-symmetrical movements of opposite limbs to piggy-back left hand performance upon established forward writing habits. Indeed, KB himself first discovered left hand mirror-writing in childhood via this bimanual technique.

The clear primacy of KB's left hand mirror-writing, the relative unimportance of visual feedback, and the beneficial effect of motoric congruence in bimanual conditions, are all consistent with a motor, rather than a perceptual basis for mirror-writing. Here, we have framed the motor hypothesis in terms of a motor control hierarchy, interpreting increased similarity between formats to reflect a shared representation at a relatively lower level of the hierarchy (Wright, 1990). This updating of the classical motor hypothesis (Critchley, 1928; Erlenmeyer 1879, cited in Critchley, 1928; Vogt, 1880) provides a convenient framework for deriving clear predictions in the present study. However, as flagged in the Introduction, motor accounts of mirror-writing take various forms, so there may be more than one motor account that could be consistent with our data.

For instance, Corballis & Beale (1970, 1976) have suggested that the right hemisphere contains mirror-reversed motor engrams for writing, laid down automatically by interhemispheric transfer of forward writing plans. These reversed plans would be available most directly to the left hand, which could account for the primacy of left hand mirror writing. In this scheme, a possible link between mirror-writing ability and non-right handedness might be explained by enhanced callosal function amonst non-right-handers (Haberling et al, 2011), aiding the establishment of reversed motor patterns between hemispheres. An alternative idea is that motor plans for writing are stored separately from information about the correct direction of execution, and that there is an innate preference for abductive movements of the limbs (Della Sala & Cubelli, 2007). This abductive preference might selectively advantage the right hand forward and left hand backward formats, consistent with KB’s generally faster abductive writing in the present study. Our data strongly favour a motor hypothesis over a perceptually-based account, but further work will be necessary to distinguish between alternative motor hypotheses.

This investigation is one step toward an objective account of deliberate mirror-writing. It concerns one notable individual whom we hope is representative of the phenomenon. Overall, KB's skilled mirror-writing seems like an elaborated version of that described subjectively by FJ Allen in 1896. Both men have sufficient ambidexterity for skilled writing with either hand; and neither obtains special benefit from visual monitoring of the mirror-writing act, nor finds it easy to mirror-read. Allen's abilities were confined largely to mirroring with the left hand, where KB's have been practised to include bidirectional and inverted writing with either hand. Notwithstanding these embellishments, KB's left hand mirror-writing retains privileged status; all of his other formats pale by comparison. Our interpretation has been that 'true' mirror-writing is indeed confined to the non-dominant hand, and that it reflects the sharing of low-level motor patterns associated with the dominant hand. However, other motor accounts of deliberate mirror writing are possible, and further experiments will be required to disentangle these, and to assess whether they can also be applied to involuntary mirror-writing after brain-damage. Finally, it remains to be seen whether or not there is anything neurologically unusual about skilled deliberate mirror-writers, beyond a degree of ambidexterity, and a curiosity about their own abilities.

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TRIAL TYPE	LEFT HAND	RIGHT HAND	CONGRUENCE
unimanual	●	forward	●
	●	reversed	●
	forward	●	●
	reversed	●	●
bimanual	forward	forward	perceptual
	forward	reversed	motoric
	reversed	forward	motoric
	reversed	reversed	perceptual

Table 1. The eight trial types for the bimanual writing task (note that the first four involve unimanual writing only). Bimanual trials are sub-classified according to whether the trial type is perceptually congruent (visually-matching word forms) or motorically congruent (anatomically-matching writing actions). Across two blocks of trials, KB wrote each of ten words in each of these eight ways, producing 120 written words across the two hands.

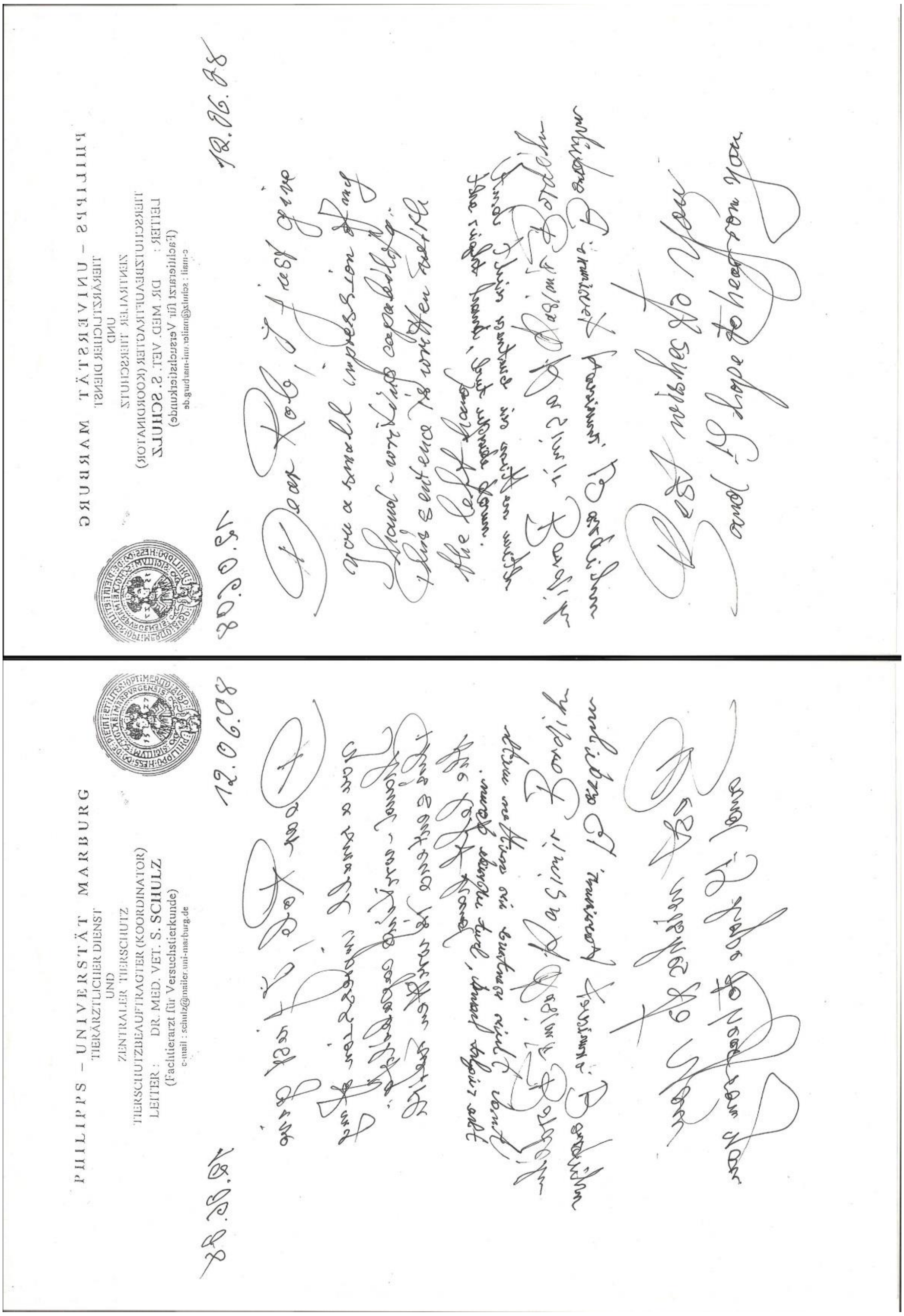

Figure 1. A letter from KB, reproduced with KB's permission, providing samples of his eight forms of handwriting. The original is on the left, and a horizontally reflected version is shown on the right.

Figure 2. An example of KB's 'mirror-art', reproduced with KB's permission.

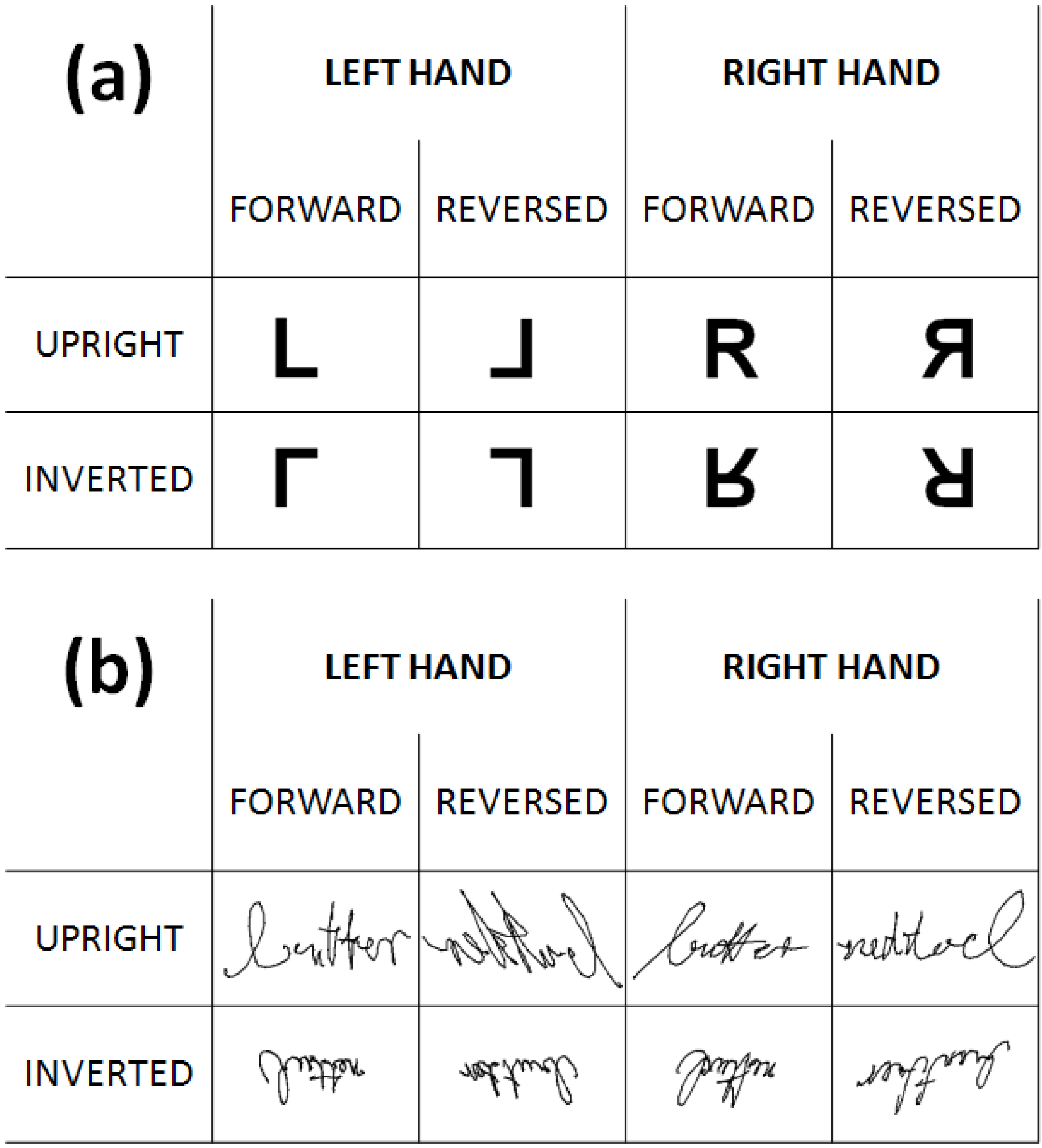

Figure 3. (a) the terminology used to refer to KB's eight handwriting formats, and the symbol shapes that will denote them on our data figures; (b) the word 'butter' as written by KB in each of the eight formats.

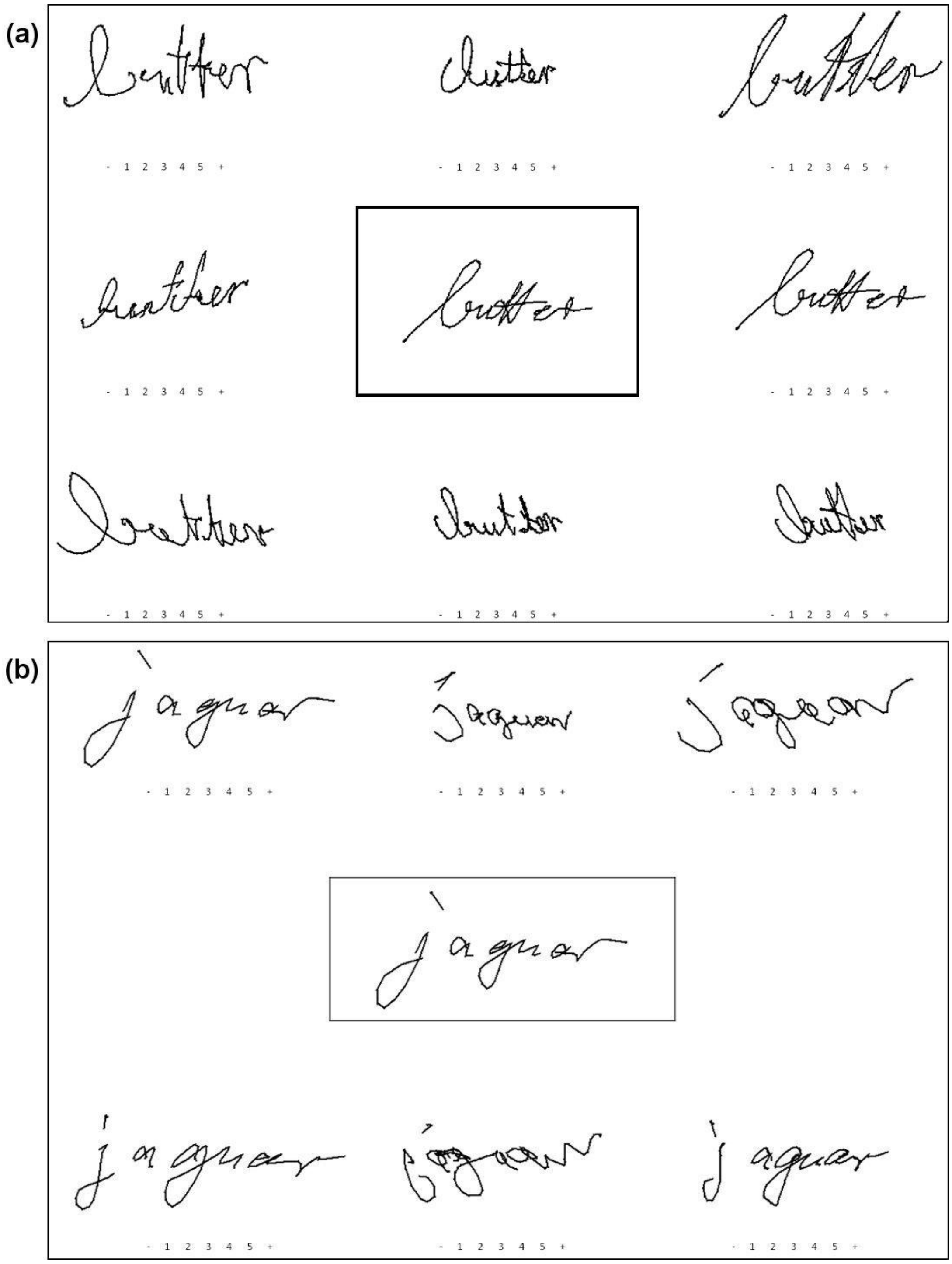

Figure 4. (a) Example sheet from a unimanual rating exercise. The standard word ('butter') is in the central box. The target words were produced with visible trace in the following conditions (clockwise from top left): left hand upright forward; left hand inverted forward; left hand upright reversed; right hand upright forward; right hand inverted forward; left hand inverted reversed; right hand upright reversed; right hand inverted reversed. (b) Example sheet from bimanual rating exercise. The standard word ('jaguar') is in the central box. The target words were produced by the right hand in the following conditions (clockwise from top left): forward unimanual; reversed unimanual; reversed bimanual motorically congruent; forward bimanual perceptually congruent; reversed bimanual perceptually congruent; forward bimanual motorically congruent.

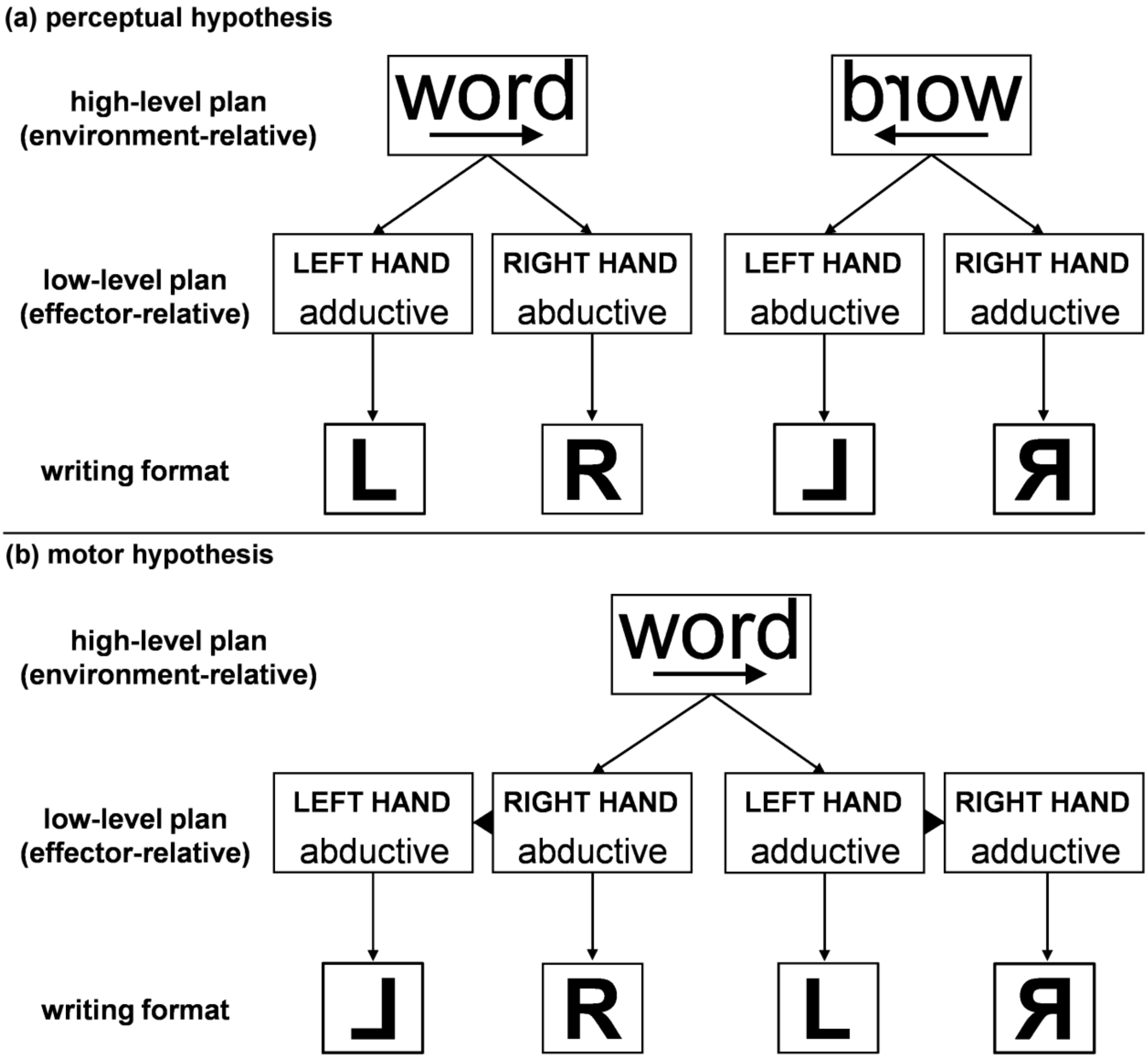

Figure 5. A highly-simplified motor hierarchy, showing routes by which the four upright writing formats could be produced under the perceptual (a) and motor (b) hypotheses. The high-level plan specifies the spatial path of the movement in environment-relative coordinates; the low-level plan specifies the movement in effector-relative (e.g. joint) coordinates. In the perceptual account, the high-level motor plan would be derived from a perceptual representation of how the word should look, so reversed-writing would descend ultimately from a reversed perceptual representation. In the motor account, left hand reversed writing would be produced by co-opting the effector-level plan for right hand abductive writing. The right side of the figure indicates that right hand reversed writing could similarly be produced by co-opting a left hand adductive motor plan, but this is not a critical prediction of the motor hypothesis (see text). The degree of similarity to normal handwriting depends on the lowest level of the hierarchy at which a representation is shared with normal handwriting. In the perceptual hypothesis, the closest relative of normal handwriting would be left hand forward writing, which shares a high-level plan. In the motor hypothesis, the closest relative of normal handwriting would be left hand reversed writing, which shares a low-level plan.

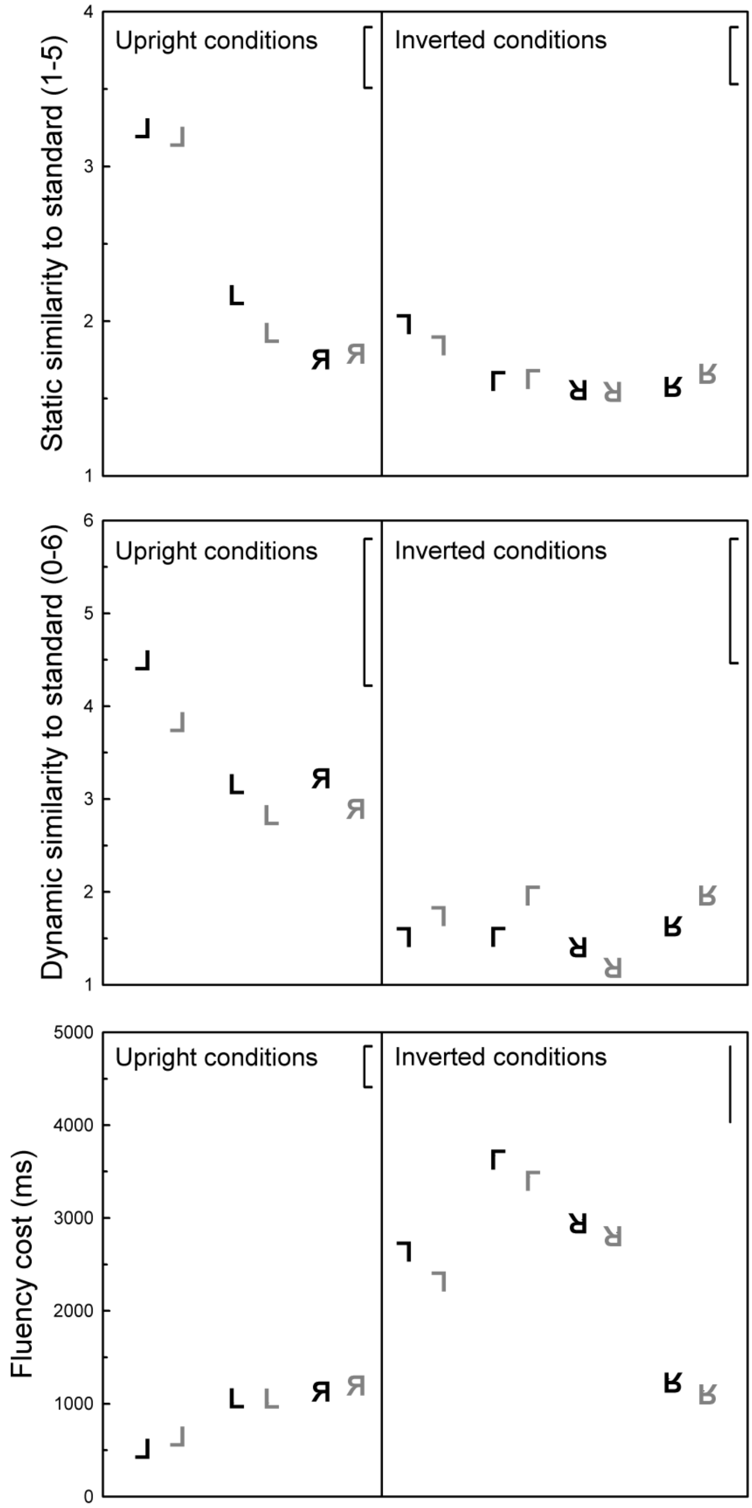

Figure 6. Unimanual task, average *static similarity*, *dynamic similarity* and *fluency cost*, relative to the right hand upright forward standard, for each non-standard writing format. The letter (L or R) indicates the hand used, its orientation indicates the writing format (forward/reversed and upright/inverted), and its colour indicates visibility of trace (black for visible trace, grey for no trace). The vertical side-bar in each panel represents the average standard deviation across the plotted conditions.

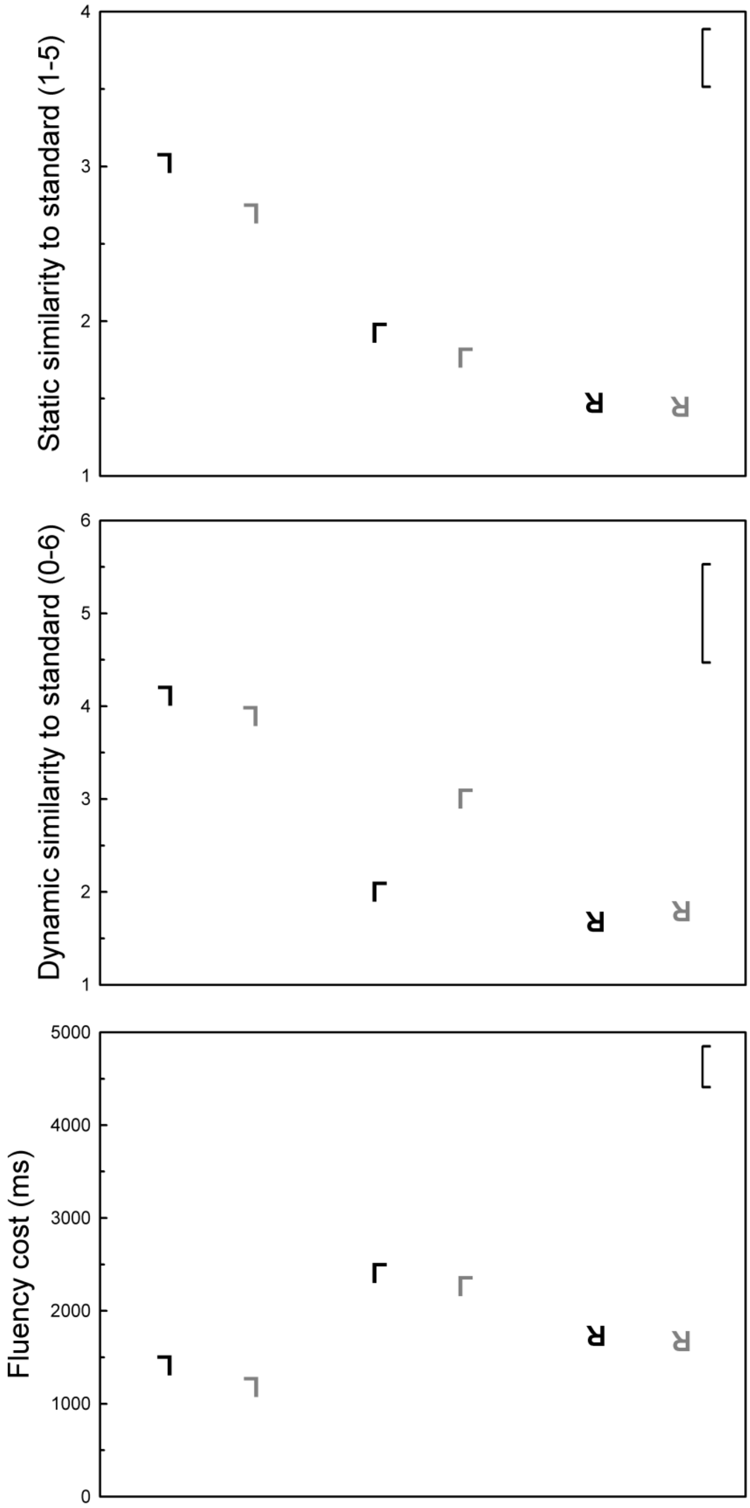

Figure 7. Unimanual task, average *static similarity*, *dynamic similarity* and *fluency cost*, relative to the right hand inverted forward standard, for each non-standard inverted writing format. The letter (L or R) indicates the hand used, its orientation indicates the writing format (forward/reversed and upright/inverted), and its colour indicates visibility of trace (black for visible trace, grey for no trace). The vertical side-bar in each panel represents the average standard deviation across the plotted conditions.

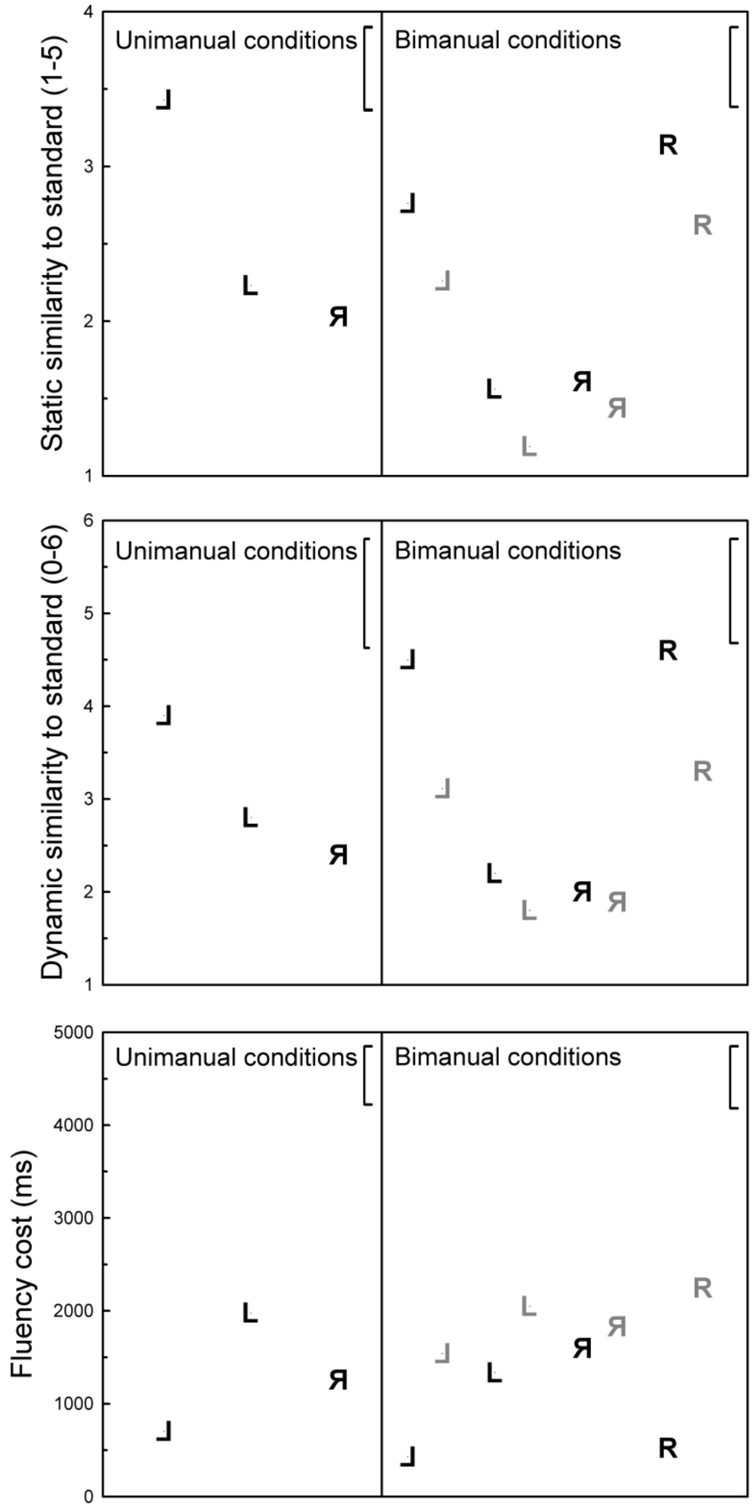

Figure 8. Bimanual task, average *static similarity*, *dynamic similarity* and *fluency cost*, relative to the unimanual right hand upright forward standard, for each non-standard writing format. The letter (L or R) indicates the hand used, its orientation indicates the writing format (forward/reversed and upright/inverted). For the bimanual conditions, symbol colour indicates congruence (black for motorically congruent, and grey for perceptually congruent). The vertical side-bar in each panel represents the average standard deviation across the plotted conditions.