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Writing and drawing tilts after right hemisphere stroke are signs of a wrong verticality representation

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1 **Writing and drawing tilts after right hemisphere stroke are signs of a wrong**
2 **verticality representation**

3
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1 **Abstract**

2 *Background*

3 Many signs of spatial dysgraphia and drawing errors after right hemispheric stroke (RHS) have
4 been attributed to spatial neglect or impaired sensory feedback. [Counterclockwise \(contralesional\)](#)
5 [tilts of graphomotor productions remained to be explained.](#)

6 *Objective*

7 [To test whether graphomotor tilts stem from a tilted representation of verticality transposed to the](#)
8 [top/bottom axis of the sheet of paper, from data of the DOBRAS cohort.](#)

9 *Methods*

10 Handwriting and drawing orientations were measured from the writing of three lines and the
11 drawing of the Gainotti Figure (house roof lines). Verticality perception was measured with the
12 visual (VV) and postural (PV) verticals. Severity of extra-body (EBN) and body (BN) neglect were
13 each quantified with composite scores (battery of 8 tests).

14 *Results*

15 We analyzed data of 133 individuals: 64 healthy individuals (median age 63 years) and 69 with a
16 subacute RHS (median age 68 years). With respect to normal cut-offs (writing -5.4° ; drawing -
17 8.1°), 26/69 (38%) individuals with RHS showed at least one graphomotor tilt (median[IQR] of
18 writing tilt: $-6.8^\circ[-9.7;-1.7]$; drawing tilt: $-10.9^\circ[-17.6;-6.4]$). Compared to individuals without
19 graphomotor tilts, those having both writing and drawing tilts showed greater contralesional tilts in
20 verticality perception (VV: $-1.4^\circ[-4;0.6]$ vs $-7.9^\circ[-11.5;-7.5]$; PV: $-1^\circ[-2.4;0.2]$ vs $-8^\circ[-9;-5.4]$, P_s
21 $\leq .001$) and more severe spatial neglect (EBN: $4.2[1.8;9.3]$ vs $16.6[10.2;20.4]$; BN: $22.7[17;28.2]$
22 vs $37.8[35.9;39.7]$, $P_s \leq .01$). Composite graphomotor z-scores on writing and drawing correlated

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23 both with verticality estimates (VV+PV, $r_s=.46$, $p < 10^{-4}$) and spatial neglect scores (EBN+BN, $r_s=-$
24 $.36$, $p < .01$).

25 *Conclusion*

26 Contralesional tilts of writing and drawing after RHS are primary related to a tilted representation
27 of verticality, and secondary related to spatial neglect. They are easy to detect and could be
28 considered as a first step to perform early, before conventional tests of verticality perception.

29 **Keywords**

30 Right hemisphere stroke; graphomotor tilts; spatial dysgraphia; verticality representation; spatial
31 neglect

32 **Abbreviations**

- 33 a.u.: arbitrary unit
- 34 BN: body neglect
- 35 CBS: Catherine Bergego Scale
- 36 DOBRAS: Determinants of Balance Recovery After Stroke
- 37 EBN: extra-body neglect
- 38 RHS: right hemispheric stroke
- 39 SCP: Scale for Contraversive Pushing
- 40 VP: postural vertical
- 41 VV: visual vertical

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42 Introduction

43 Manifestations of spatial dysgraphia and drawing errors after right hemispheric stroke (RHS) have
44 revealed the contribution of the right hemisphere to the spatial organization of graphomotor
45 behaviors, such as handwriting and drawing [1–6]. Spatial dysgraphia refers to various handwriting
46 difficulties distorting the spatial layout of writing. It encompasses letter or word omission/iteration,
47 overwriting, writing only in the right margin, and sloping lines [1,4,6,7]. Spatial dysgraphia has
48 been mainly associated with damage to the right parietal lobe [1,4,5], as well as to subcortical grey
49 and white matters [8,9]. Drawing errors typically comprise line omission/iteration, perspective loss
50 or abnormal location, wrong proportions, and tilted orientation [2,3,6]. This constructional disorder
51 has been frequently associated with damage to the right temporo-parietal lobes and adjacent white
52 matter [10–13].

53 The brain areas involved in spatial dysgraphia and drawing errors explain why pioneer clinical
54 observations reported a strong association between these graphomotor errors and spatial neglect
55 [3,4,6,14]. This association is causal for lateralized graphomotor errors such as left omissions and
56 right-page preference, plainly explained by attentional/representational deficits underlying the left-
57 right gradient characterizing spatial neglect [15]. In contrast, spatial neglect does not easily explain
58 — and was found dissociated from — non-lateralized errors such as letter duplication in the writing
59 (e.g., [7]) or altered spatial relations in the drawing (e.g., [3]). These graphomotor errors could be
60 rather explained by impaired visual/kinaesthetic feedbacks [6,7] or impaired spatial remapping
61 [12].

62 But, none of the above-mentioned mechanisms hold for the counterclockwise tilts of
63 graphomotor productions, which are frequent and remain to be explained. We hypothesized that
64 they might result from a contralesional tilt in the representation of the vertical, transposed to the
65 sheet of paper referring to the top and bottom. A recent single case study [5] supports this
66 hypothesis, that we tested here, in a substantial series of right-handed individuals examined at

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67 the early subacute stage after an RHS. We investigated the associations between contralesional
68 graphomotor tilts, verticality estimates, and other relevant clinical deficits such as spatial neglect.

69 **Methods**

70 Data and analysis codes of this study are available on reasonable request from the corresponding
71 author. The reporting follows STROBE recommendations [16].

72 **Study design and regulatory considerations**

73 This study was performed in compliance with the Declaration of Helsinki and regulatory rules for
74 human research in France. It was registered at the national committee for informatics and freedom
75 (Commission Internationale Informatique et Liberté, no. 2014874 v1). All individuals were informed
76 orally and in writing about the study and gave their informed consent. All participants, controls and
77 with RHS, were blinded to the study hypotheses.

78 Writing and drawing productions of individuals with RHS were analyzed from data of the
79 DOBRAS cohort (Determinants of Balance Recovery After Stroke), approved by our institutional
80 review board (CHU Grenoble Alpes), which validated the ClinicalTrials.gov registration
81 (NCT03203109). According to French law, eligible individuals were informed about the DOBRAS
82 study (orally and in writing) and use of their data; those who did not want to participate signed an
83 opposition form. Studies of the DOBRAS cohort focus on the recovery of balance and gait
84 disorders after a first-ever hemispheric stroke, particularly in relation to spatial cognition deficits,
85 such as impaired verticality perception and spatial neglect (for the first results, see [17–19]).
86 Writing and drawing tasks were part of the routine assessment of spatial neglect.

87 The recruitment of healthy controls, selected to be matched to individuals with RHS, was
88 approved by the ethical review board of Grenoble-Alpes University (CERGA-2019–04–09–1).

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89 They were recruited from the relatives of authors and from the relatives of patients hospitalized in
90 our ward.

91 Their writing and drawing data have partly been reported in a previous methodological study
92 intending to identify reliable criteria to measure writing and drawing orientations [20]. The goal of
93 the present study was to understand graphomotor tilts after RHS, by identifying their clinical
94 determinants.

95 Participants

96 We extracted from the DOBRAS database only the observations for right-handed individuals
97 (Edinburgh inventory score ≥ 0.4) with a first-ever RHS, to focus on individuals potentially
98 presenting spatial representation disorders, spatial dysgraphia, and drawing errors [3,6,21]. All
99 individuals were able to write and draw with their non-paretic right upper limb. Among the three
100 evaluations performed at 30, 60, and 90 days (D30, D60, D90) after the RHS, we selected the
101 earliest and most complete evaluation in terms of writing, drawing, and other spatial cognition
102 tests.

103 Exclusion criteria common to all DOBRAS studies were recurrent or complicated stroke,
104 unstable medical condition, previous disability interfering with balance and verticality perception,
105 psychiatric problems, or dementia (e.g., [18]). Additional exclusion criteria for this ancillary study
106 were severe comprehensive impairment (due to aphasia, even if rare after RHS in right-handers),
107 not French-speaking (as a native language), limb apraxia (Test of Upper Limb Apraxia score < 9 ;
108 [22]), and altered ability to remain seated (Postural Assessment Scale for Stroke score < 8 ; [23];
109 see flowchart in Fig. 1).

110 We planned to recruit about 60 individuals with RHS to build multivariate models and test the
111 effects of impaired verticality perception and spatial neglect on graphomotor tilts against each

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112 other.

113 Healthy controls were recruited to be matched to the individuals with RHS in manual laterality
114 (right-handers), age, sex ratio, and education level (1 = primary school certificate, 2 = ninth-grade
115 certificate [“brevet”], 3 = bachelor’s degree). They were asked about their medical history, had to
116 not have neurological disorders, and had to have preserved abilities to draw and write legibly. No
117 specific clinical examination or complementary investigation was performed.

118 Writing and drawing tests: orientation criteria

119 For writing, the material was the French battery for neglect assessment (*Batterie d’évaluation de*
120 *la négligence*; [24]; see Fig. 2a). Individuals were asked to manually write personal details on three
121 lines on the blank sheet of paper in portrait format. For drawing, the material was the Gainotti
122 Figure, representing a landscape with four trees and one house oriented vertically and horizontally
123 [25]; see Fig. 2b). The Gainotti Figure was printed on the top of a page in landscape format, and
124 individuals were instructed to manually copy it just below. For both tasks, the neuropsychologist
125 checked that the sheet of paper was centered on the individual’s trunk but never gave instructions
126 regarding the disposition, orientation, or speed of writing and drawing.

127 To measure writing and drawing orientation criteria, all graphomotor productions were first
128 digitized. Then, a home-made electronic protractor was used to compute the orientation of
129 segments (e.g., the drawing of one of the house roof lines) defined from landmarks (e.g.,
130 extremities of the drawn segment) positioned by the operator (RL). The accuracy was set to 0.1°.
131 RL was blinded to data from tests of verticality perception and spatial neglect. More details are
132 given in our recent methodological paper [21], which showed that among various graphomotor
133 criteria tested, the two best were the mean tilt from the horizontal of the three written lines (“writing
134 orientation”, Fig. 2a) and of the two drawn roof lines of the house (“drawing orientation”, Fig. 2b).
135 These two graphomotor criteria have excellent clinimetric properties and are the most suited to

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136 detect and quantify contralesional (i.e., counter-clockwise) tilts in individuals with a RHS [20]. Of
137 note, the “horizontal” orientation refers here to the width of the sheet of paper. By convention,
138 negative signs indicated contralesional orientations.

For both writing and drawing criteria, we determined the thresholds of abnormal contralesional
tilt from data distribution (mean \pm 2 SD) obtained in the 64 healthy controls. These distributions
were approximatively Gaussian according to visual inspection and Kolmogorov-Smirnov tests
(writing: $p = .64$; drawing: $p = .10$). These thresholds were [-5.4°; 1.7°] for the written lines and [-
8.1°; 2.2°] for the drawn roof lines. With regards to ipsilesional graphomotor tilts, we found that
only 2/69 (3%) individuals had a writing tilt > 1.7° (of a small magnitude: 3.1° and 3.4°) and 0/69
had a drawing tilt > 2.2°. These two individuals with a marginal ipsilesional writing tilt (without
contralesional drawing tilt) had normal VV (-0.7°, -1.8°) and normal/quasi-normal PV (1°, -2.8°),
and no spatial neglect. Because we planned to analyze whether contralesional graphomotor tilts
were related to contralesional VV/PV tilts, we pooled these two individuals with those who had a
normal graphomotor orientation, and a similar clinical profile without bias in verticality
representation or spatial neglect (see Table 1 in Results).

We also computed a composite “graphomotor z-score” to serve as a robust index of the global
magnitude of writing and drawing tilts in individuals with RHS. For this, their writing and drawing
orientations were each z-scored from the means and standard deviations obtained in healthy
controls, then averaged.

Clinical deficits

Impaired verticality representation

The representation of verticality was assessed with two well-validated measures, the visual
vertical (VV) and postural vertical (PV), described in detail elsewhere [26].

VV was measured in darkness by binocular visual adjustment of the orientation of a luminous

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160 line (visual angle = $5.7^\circ \times 0.1^\circ$) presented on a computer screen at eye level, about 1.5 m from
161 the nasion. In case of hemianopia, the computer screen was adequately translated toward the
162 non-hemianopic side. Individuals were seated with their head and trunk maintained upright and
163 were asked to adjust the line to the vertical by giving verbal instructions to the examiner. The
164 starting orientation of the line, randomly ranging from $\pm 5^\circ$ to $\pm 30^\circ$, was balanced to the right or
165 left following a sequence fixed across individuals.

166 PV was assessed in darkness with the wheel test (see [26]). Individuals were seated,
167 restrained in a wheel-like device that was slowly and manually turned by the examiner and were
168 asked to adjust their body to the vertical by giving verbal instructions to the examiner. The starting
169 orientation of their body, ranging from $\pm 15^\circ$ to $\pm 45^\circ$, was balanced to the right or left following a
170 sequence fixed across individuals.

171 For both tasks, individuals performed 10 trials. All measures started after 2 min of darkness.
172 The examiner never gave a time limit or feedback. Data from all 10 trials were averaged to
173 calculate individual mean VV and PV orientations. In addition, we calculated “transmodal” vertical
174 estimates (means of VV and PV) to get a unique measure of verticality representation (i.e.,
175 independent from a specific vestibular or somaesthetic modality of gravity sensing). According to
176 standards, negative and positive VV or PV values corresponded to contralesional (i.e., counter-
177 clockwise) and ipsilesional (i.e., clockwise) orientations, respectively. VV and PV tilts were
178 diagnosed according to well-established ranges of normality (-2.5 to 2.5° ; [26,27]).

179 *Spatial neglect*

180 Extra-body neglect (EBN) and body neglect (BN) were evaluated by trained neuropsychologists
181 and occupational therapists with a battery of eight well-validated tests routinely used in clinical
182 practice [24]. EBN was evaluated with (1) the Bells cancellation test [28], (2) the overlapping figure
183 test [29], (3) the reading test [24], and (4) four EBN items of the Catherine Bergego Scale (CBS;
184 [30]). BN was evaluated with (5) the Bisiach test [31], (6) the Fluff test [32], (7) the Comb and

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185 Razor test [33,34], and (8) four BN items of the CBS [30]. Participants completed these tests with
186 their sound right upper limb (see [18,19] for more details about these eight tests).

187 Spatial neglect was diagnosed from at least two abnormal test results, whatever the spatial
188 neglect domain. We also evaluated EBN and BN severities by calculating composite scores. For
189 this, raw scores for all eight neglect tests were converted to percentages based on their respective
190 ranges (0% = no neglect, 100% = maximal neglect). These percentages were then averaged to
191 calculate EBN and BN scores, as well as a “global” spatial neglect score (mean of EBN and BN
192 scores). [More details about these composite scores are provided in Appendix A.](#)

193 *Disability and other deficits*

194 [Gait and disability were evaluated with the modified Fugl-Meyer Assessment gait score \[35\],](#)
195 [ranging from 0 arbitrary unit \(a.u.\) = no gait, to 6 a.u. \(= normal gait\) and the Functional](#)
196 [Independence Measure \[36\], ranging from 18 a.u. \(= very severe disability, a.u.\) to 126 a.u. \(=](#)
197 [total independence\). Lateropulsion, which refers to an abnormal postural behavior against gravity,](#)
198 [was evaluated with the Scale for Contraversive Pushing \(SCP; \[37\]\), ranging from 0 a.u. \(= upright](#)
199 [body orientation, a.u.\) to 6 a.u. \(= active pushing of the body toward the contralesional side\).](#)
200 Lateropulsion was considered moderate or severe with an SCP score > 0.5 [18, 27]. These three
201 scales are detailed in previous DOBRAS reports (e.g.,[18,26]). Hemianopia was manually
202 evaluated by trained physicians.

203 **Statistics**

204 Descriptive statistics are first presented for each graphomotor criterion, both for orientation
205 magnitude and prevalence of abnormal tilt. Data were analyzed with non-parametric tests, as
206 residual plots from parametric tests revealed assumption violations and outlying data.

207 To identify the main determinants of contralesional graphomotor orientation, we first compared
208 the clinical profile of three groups of individuals with RHS: (1) those having normal graphomotor

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6 210 having both contralesional writing and drawing tilts. Differences between groups were tested with
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8 211 Kruskal-Wallis (omnibus) tests for continuous measures, and with chi-squared tests for categorical
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10 212 measures.

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13 213 Then, we conducted two-tailed Spearman correlations and Pearson and Filon' z tests to test
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15 214 whether the graphomotor z-scores were more associated with the transmodal vertical estimates
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17 215 (mean of VV and PV) than with the global spatial neglect scores (mean of EBN and BN).

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19 216 Continuous data are presented as median [Q1; Q3] and categorical data as number (%).
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22 217 Standardized effect sizes were calculated by using the r_s (rho) value of the Spearman test, the $\sqrt{\eta^2}$
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24 218 value of the Kruskal-Wallis test, the r value of the Mann-Whitney test, and the Cramer's w of the
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26 219 chi-squared test. Effect sizes > 0.1 , 0.3 , or 0.5 were considered small, medium, or large,
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28 220 respectively [38]. The significance level was set at $p < .05$ and Bonferroni-corrected when needed.
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30 221 All data analyses were conducted with R 4.0.3 [39].
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34 223 Results

35 224 Participants

36 225 A total of 133 individuals took part in this study (see flowchart in Fig. 1): 69 with RHS and 64
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38 226 healthy controls, matched in age (median 68 years [62; 73] vs 63 years [59; 71]; Mann-Whitney,
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40 227 $p = .24$, $r = 0.10$) and sex ratio ($n = 43/69$ [62%] vs $35/64$ [55%] males; χ^2 , $p = .47$, $w = 0.06$). With
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42 228 regards to education levels, no difference was found between individuals with RHS and healthy
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44 229 controls (χ^2 , $p = .10$, $w = 0.19$): level 1, 27/69 [39%] vs 14/64 [22%]; level 2, 18 [26%] vs 21 [33%];
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46 230 level 3, 24 [35%] vs 29 [45%]). Clinical data were collected mostly at D30 ($n = 48$, 70%), sometimes
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48 231 at D60 ($n = 13$, 19%), and more rarely at D90 ($n = 8$, 12%). The stroke was mainly a cerebral
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50 232 infarct ($n = 61$, 88%). The individual disability was moderate, with a median FIM score of 102 [75;
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52 233 114]; the median mFMA gait score was 5 [2; 6], indicating that half was able to walk without
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234 technical aid; the median SCP score was 0.25 [0; 1.5], indicating that most of them were either
235 upright or showed mild lateral body tilt with respect from gravity.

236 **Missing data**

237 Only 9/4200 (0.21 %) data points were missing in the whole dataset. For clinical deficits, 3 (4%)
238 PV tests and 2 (3%) VV tests were missing because of participant uneasiness or dizziness in the
239 dark. Two (3%) other PV tests were missing because of technical problems or the inability of a
240 participant to sit in the device because of a pelvic fracture. For the drawing test, roof lines were
241 not drawn by 2 (3%) individuals. Data imputation was not required given these few missing data.

242 **Distribution of graphomotor orientations in participants with RHS**

243 Figures 3a and 3b present data distribution for each graphomotor criterion. Orientations were
244 mostly contralesional for both criteria: -1.8° [-4.5; -0.6] for the writing and -4.4° [-8.3; -2.5] for the
245 drawing. The frequency of contralesional (abnormal) tilts were comparable for the writing ($n =$
246 $15/69$, 22%) and the drawing ($n = 18/69$, 26%). Overall, $43/69$ (62%) individuals did not show any
247 contralesional graphomotor tilt, $19/69$ (28%) individuals showed a contralesional tilt for at least
248 one criterion (writing tilt = -2.6° [-8; -1.1]; drawing tilt = -9.6° [-15.1; -4.6]), and $7/69$ (10%) a
249 contralesional tilt bearing on both criteria (writing tilt = -9.5° [-13.1; -7.4]; drawing tilt = -17.6° [-
250 23.7 ; -11.2]). Writing and drawing orientations were nonetheless not significantly correlated
251 (Spearman test, $r_s = .20$, $p = .10$). As highlighted in Fig. 3, there were cases of dissociations: $8/69$
252 (12%) individuals showed an isolated contralesional writing tilt, whereas $13/69$ (19%) showed an
253 isolated contralesional drawing tilt.

254 Figure 3c shows data distribution for the graphomotor z-scores, representing the mean severity
255 of writing and drawing tilts. Important variations were noted: range = -8.3 to 1.5 SD, median = -0.4

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256 SD [-2; 0.3]).

257 Verticality perception, spatial neglect, and hemianopia

258 For VV, abnormal contralesional tilts were found in 34/67 (51%) individuals. In others, VV was
259 either normal in 25/67 (37%) individuals or more rarely subjected to a light ipsilesional tilt ($n =$
260 8/67, 12%). For PV, abnormal tilts were found in 27/64 (42%) individuals, always toward the
261 contralesional side, otherwise was normal in 37/64 (58%). Contralesional tilts were transmodal
262 (VV and PV) in 20/64 (31%) individuals. See [Appendix B](#) for details on associations and
263 dissociations.

264 Spatial neglect was diagnosed in 41/69 (59%) individuals, with 29 (42%) individuals having
265 EBN, 36 (52%) having BN, and 24 (35%) having both. Left hemianopia was diagnosed in 23/69
266 (33%) individuals.

267 Determinants of graphomotor tilts

268 Table 1 shows the clinical profile of individuals with RHS according to their [graphomotor](#)
269 [orientations](#) ([normal graphomotor orientation](#) or [light ipsilesional tilt](#) [$n = 43/69$, 62%],
270 [contralesional writing or drawing tilt](#) [$n = 19$, 28%], [contralesional writing and drawing tilts](#) [$n = 7$,
271 10%]). As for verticality estimates, the severity and frequency of contralesional VV and PV tilts
272 gradually increased with the number of contralesional graphomotor tilts (all p -values $\leq .01$,
273 moderate effect sizes). Whereas VV and PV estimates were in normal ranges (-2.5 to +2.5°) in
274 individuals without graphomotor tilts, they raised to -8° (about 6 SD) in individuals with writing and
275 drawing tilts. These latter had 2 to 4 times more tilts in verticality perception. Congruently, they
276 also showed greater lateropulsion. The severity and frequency of spatial neglect (EBN and BN)
277 also increased with the number of contralesional graphomotor tilts. This was specially the case for
278 EBN (p -values $\leq .01$, moderate effect sizes), found in 28% of individuals without graphomotor tilts,

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279 and in 100% of individuals with writing and drawing tilts (Table 1). In contrast, the three
280 graphomotor groups did not differ for hemianopia and demographic features.

281 Figure 4 shows that graphomotor z-scores were moderately correlated with transmodal vertical
282 estimates ($r_s = .46, p < 10^{-4}$) and global spatial neglect scores ($r_s = -.36, p < .01$), without significant
283 difference between these two correlations (Pearson and Filon's z test on absolute values, $z = 0.85,$
284 $p = .39$).

285 Overall, these results showed the importance of spatial deficits, tilted verticality representation
286 and spatial neglect, in contralesional graphomotor tilts of individuals with RHS.

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Discussion

Our main objective was to test whether contralesional tilts of writing and drawing after an RHS were associated with a tilted verticality representation, transposed to the top/bottom axis of the sheet of paper. For this aim, individuals with a subacute RHS were asked to write three lines and to draw the Gainotti Figure in the framework of clinical routine practice. Two reliable criteria of graphomotor orientation were extracted: the three lines for the writing, and the two roof lines for the drawing. Our results reveal that tilted writing and drawing orientations were primarily correlated to an impaired verticality representation, and secondary correlated to spatial neglect severity. Congruently, individuals with a contralesional writing and drawing tilt differed from others by more severe and frequent contralesional VV and PV tilts, greater lateropulsion, and more severe spatial neglect. These findings support the hypothesis that spatial cognition deficits, and notably tilts in verticality representation, may manifest in the orientation of graphomotor productions after an RHS.

Tilted verticality representation: the primary determinant of writing and drawing tilts

Altogether, our results show that contralesional graphomotor tilts were associated to all measures of verticality estimates (visual, postural, and transmodal). This suggests that writing and drawing tilts are not related to a specific graviceptive modality (vestibular or somaesthetic) but rather to a higher-order representation of verticality. Of note, the VV mainly tests the processing of gravity-related *vestibular* information (conveyed by the otolith organs; [27,40]), whereas the PV mainly tests the processing of gravity-related *somesthetic* information (conveyed by proprioceptive, tactile, and visceral receptors; [41,42]). These two sources of information would be integrated into and pondered by the multisensory thalamo-vestibular network to represent the vertical [26,43,44].

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4 312 The RHS could disturb these multisensory mechanisms, leading to abnormal contralesional tilts
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6 313 not only in VV and PV estimates, but also in graphomotor tasks involving an implicit representation
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8 314 of the “upright”. Of interest, very severe tilts in verticality representation might even be able to
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10 315 manifest in various graphomotor tasks. Indeed, the most severe tilts of VV and VP were found in
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12 316 individuals having both writing *and* drawing tilts, two tasks that yet differ in terms of instructions,
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14 317 materials, and mechanisms (generation [writing] vs copy [drawing]).
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17 318 Is the association between graphomotor tilts and tilted verticality representation *causal*?
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19 319 Experimental investigations in healthy individuals have established that verticality representation
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21 320 is used for various sensorimotor tasks such as body orientation, catching, grasping, or pointing
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23 321 movements (for recent reviews see [45,46]). The brain might also use a representation of
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25 322 verticality during the execution of graphomotor tasks involving spatial orientation skills in 2D. This
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27 323 view is supported by Jolly et al. (2020), who recently showed that a short-term modulation of
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29 324 verticality perception in the patient JW (PV, -10° before vs 0.5° after) was congruently associated
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31 325 with a significant diminution of his writing tilts (-10° before vs. -6° after).
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35 326 In the current series, the association between verticality estimates and graphomotor tilts was
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37 327 less strong than that reported by Jolly et al. (2020) in their case-study (i.e., moderate vs. strong
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39 328 effect sizes). This finding may be explained first by the multi-determined nature of graphomotor
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41 329 behaviors. Writing and drawing involve a large range of cognitive operations, encompassing
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43 330 spatial attention, spatial remapping, coordinate transformation, object recognition, executive
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45 331 functions, and motor control [1–3,6]. The disruption of one of these mechanisms after an RHS
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47 332 could induce graphomotor tilts on their own, independent of an impaired verticality representation.
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49 333 [This could be notably the case in individuals showing a dissociation between writing and drawing](#)
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51 334 [tilts \(about 30%\). For example, an impaired spatial remapping might disturb writing and drawing](#)
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53 335 [orientations in a non-systematic way, depending on the trajectory of the saccadic eye movements.](#)
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55 336 [The Gainotti task requires numerous up and down saccades between the model and the drawing](#)
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57 337 [space, whereas the writing task requires horizontal saccades between the letters and words. An](#)
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4 338 impaired motor control might also influence the writing and drawing in different ways, as these
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6 339 tasks require different motor planification and motor commands. Second, the moderate effect
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8 340 sizes we observed could also be explained by the use of the paper sheet's borders, or drawing
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10 341 model, as a visual allocentric frame of reference. Indeed, individuals with an impaired integration
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12 342 of gravity-related vestibular or somaesthetic cues showed increased reliance on visual cues to
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14 343 estimate verticality [47,48]. Despite a severe tilt in verticality representation, individuals with an
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16 344 RHS using this allocentric strategy might compensate for their deficit in such conditions and exhibit
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18 345 upright graphomotor orientations. This allocentric strategy could have been used especially in the
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20 346 drawing task, as the Gainotti Figure provides numerous visual landmarks.
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27 347 Spatial neglect: a secondary determinant of writing and drawing tilts? 28 29 30

31 348 Contrary to our expectations, we found that graphomotor tilts were also moderately related to
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33 349 spatial neglect severity and frequency. Although spatial neglect is an important determinant of
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35 350 many signs of spatial dysgraphia or drawing errors [1,4,6], how it would induce graphomotor tilts
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37 351 remains still difficult to conceive.
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40 352 The more plausible interpretation is that the association between graphomotor tilts and spatial
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42 353 neglect is mediated by concomitant tilts in verticality representation. Indeed, clinical studies have
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44 354 increasingly suggested that an impaired representation of verticality is a key component of spatial
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46 355 neglect [17,19,21,49], and it has been recently shown that transmodal (visual and postural) vertical
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48 356 tilts [19] and lateropulsion [17] constituted very strong proxy of spatial neglect. This mediation
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50 357 hypothesis is also supported by a recent case study, reporting a dissociated recovery between
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52 358 spatial neglect and contralesional graphomotor tilts [5].
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55 359 Might spatial neglect induce graphomotor tilts because of a distortion between the
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57 360 representation of the left and right hemispaces? A possible mechanism could involve the line
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59 361 breaking, more and more shifted to the right in individuals with spatial neglect [1,4], which results
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362 in a left margin tilt. If the orthogonality between the margin (vertical coordinate) and writing lines
363 (horizontal coordinate) is respected in these individuals [5,21], this line breaking should also
364 indirectly tilt the writing lines upward. But such a mechanism cannot explain the tilts of the drawing
365 rooflines. Thus, our data and the recent literature rather suggest that spatial neglect plays a role
366 through a bias in verticality representation.

367 Clinical implications

368 In individuals showing a contralesional tilt in both writing and drawing tasks, VV and VP tilts were
369 peculiarly frequent (> 80%) and severe (median tilt > -7°), and associated with a severe
370 lateropulsion (median SCP = 3). Therefore, these graphomotor tilts, which are easy to search early
371 even in patients with a severe stroke and bedridden, should be more systematically detected in
372 individuals with a RHS [24].

373 More indirectly, our results might also suggest a role of spatial cognition disorders in 3D on
374 non-lateralized visuo-constructive deficits, which remain to be better understood. We speculate
375 that the combination of and impaired verticality representation and a representational distortion
376 on the left-right axis (spatial neglect), possibly with an impaired motor control, might alter
377 assembling segments to draw or build figures in 2D and 3D, leading to the so-called constructional
378 apraxia.

379 Limitations

380 A first limitation is the observational nature of the writing and drawing data collected from the
381 DOBRAS cohort. Hence, we could not verify that the sheet of paper was always perfectly aligned
382 with the trunk and head of the participant, although neuropsychologists carefully monitored the
383 positions of the sheet and the patient's body. Likewise, we could not investigate other potential

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384 mechanisms of graphomotor tilts, such as feedback-related errors [6,7] and impaired spatial
385 remapping [9,12,50], which still needs to be studied. Second, we did not control for the potential
386 effect of ocular torsion on graphomotor tilts, although ocular torsion is infrequent after hemispheric
387 stroke [27] and should not alter our findings. Finally, we did not investigate the representation of
388 “horizontality”, which is known to be, as with VV, tilted counterclockwise after stroke [21].
389 Nevertheless, clinical and experimental studies suggest that the VV and visual horizontal are
390 approximately orthogonal [21].

Conclusions

392 Our study supports the hypothesis that contralesional tilts of writing and drawing after RHS are
393 related to a tilted representation of verticality transposed to the top/bottom axis of the sheet of
394 paper. This may explain why these graphomotor tilts are observed in individuals with spatial
395 neglect, who are often subject to a wrong representation of verticality. These graphomotor tilts
396 should be more systematically searched, which can be done early after the stroke, even in
397 bedridden individuals having a severe RHS. Their existence may alert about the existence of a
398 wrong verticality representation which will require specific rehabilitation.

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CRediT authorship contribution statement

Rémi Lafitte: Writing – original draft, Investigation, Data curation, Formal analysis. **Flora Diaine:** Writing – original draft, Investigation, Data curation, Formal analysis. **Shenhao Dai:** Writing – original draft, Investigation, Data curation, Formal analysis. **Olivier Carré:** Software. **Eve Dupierrix:** Writing – review & editing, Conceptualization. **Caroline Jolly:** Writing – review & editing, Methodology, Conceptualization. **Céline Piscicelli:** Writing – review & editing, Investigation, Conceptualization, Methodology. **Dominic Pérennou:** Writing – original draft, Conceptualization, Methodology, Supervision, Funding acquisition.

Declaration of competing interests

None.

Data availability

The dataset analyzed during the current study is protected and not available due to data privacy laws, but is available from the corresponding author on reasonable request.

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22 559 Figure Legends

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27 561 **Fig 1.** Flowchart of participants in the study.

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29 562 DOBRAS: Determinants of Balance and Recovery After Stroke; PASS: Postural Assessment
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31 563 Scale for Stroke
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36 565 **Fig 2.** Measures of writing and drawing orientations with satisfactory clinimetric properties [20].
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38 566 **(a)** Writing criterion. **(b)** Drawing criterion. For both (a) and (b), the yellow segments defined the
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40 567 horizontal and vertical axes of the sheet. Of note, the angle values extracted by the software had
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42 568 to be reversed.
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47 570 **Fig 3.** Distribution of **(a)** writing line orientations, **(b)** drawing roof line orientations, and **(c)**
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49 571 graphomotor z- scores. Distributions are ranked by decreasing order of writing line orientations.
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51 572 The horizontal dashed lines represent the ranges of normality for each graphomotor criterion.
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53 573 Positive and negative values refer to clockwise and counterclockwise orientations, respectively.
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58 575 **Fig 4.** Effects of transmodal verticality estimates and global spatial neglect scores on the global
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4 576 magnitude (z-scores) of contralesional graphomotor tilts.
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Table 1. Univariate analyses of possible indicators determining the clinical profile of individuals showing contralesional graphomotor tilt.

Response variable	Normal orientation or ipsilesional tilt (<i>n</i> = 43)	Contralesional writing or drawing tilt (<i>n</i> = 19)	Contralesional writing and drawing tilt (<i>n</i> = 7)	<i>p</i> *	Effect size**
VV (°)***	-1.4 [-4; 0.6]	-6.4 [-9.2; -1.4]	-7.9 [-11.5; -7.5]	< .001	0.47
VV (contralesional tilt)	15/43 (35%)	13/19 (68%)	6/7 (86%)	.005	0.40
PV (°)***	-1 [-2.4; 0.2]	-3.5 [-5.3; -2]	-8 [-9; -5.4]	.002	0.41
PV (contralesional tilt)	10/43 (23%)	11/19 (58%)	6/7 (86%)	< .001	0.46
SCP (a.u.)	0 [0; 0.6]	0.5 [0; 3]	3 [1.8; 3.6]	< .001	0.45
EBN score (%)	4.2 [1.8; 9.3]	10 [4; 22]	16.6 [10.2; 20.4]	.004	0.37
EBN (yes)	12/43 (28%)	10/19 (53%)	7/7 (100%)	< .001	0.45
BN score (%)	22.7 [17; 28.2]	31.3 [18.8; 37.2]	37.8 [35.9; 39.7]	.0038	0.37
BN (yes)	19/43 (44%)	11/19 (58%)	6/7 (86%)	.11	0.26
Hemianopia (yes)	11/43 (26%)	8/19 (42%)	4/7 (57%)	.16	0.23
Education (1/2/3)	14 (33%) / 13 (30%) / 16 (37%)	9 (47%) / 4 (21%) / 6 (32%)	4 (57%) / 1 (14%) / 2 (29%)	.66	0.19
Sex (male)	27/43 (63%)	12/19 (63%)	4/7 (57%)	.96	0.04
Age (years)	66.5 [55; 72.2]	68 [63; 71]	69 [63.5; 76]	.53	0.00

Data are median [Q1; Q3] unless otherwise indicated.

* The alpha level was set to .0038 because of multiple tests (.05/13). Significant *p* values are shown in bold.

** $\sqrt{\eta^2}$ from the Kruskal-Wallis test for continuous variables and Cramer's *w* from the chi-squared test for categorical variables. Effect sizes ≥ 0.1 , 0.3, or 0.5 were considered small, medium, or large, respectively.

*** For VV and PV, statistical analyses involved 67 and 64 individuals, respectively, because of missing data.

a.u.: arbitrary unit, VV: visual vertical, PV: postural vertical, SCP: Scale for Contraversive Pushing, EBN: extra-body neglect, BN: body neglect

Figure 1
Eligibility

DOBRAS cohort
Individuals with a first ever
right hemisphere stroke
(*n* = 95)

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Screening

14 individuals with
feasibility issues:
10 with limb apraxia
4 unable to sit (PASS < 8)

12 individuals with
**missing writing/drawing
data due to staff absence**

Analysis

Individuals with right
hemisphere stroke
(*n* = 69)

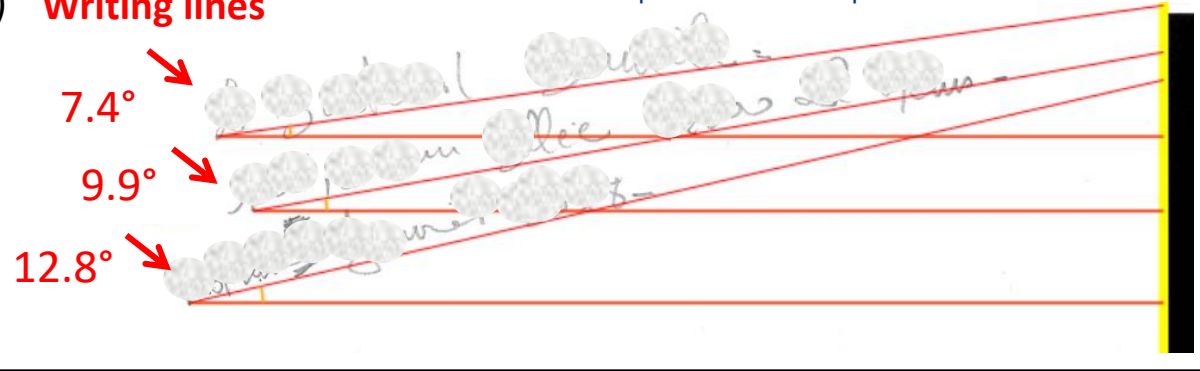
Matched healthy
controls
(*n* = 64)



Figure 2

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(a) **Writing lines**



(b)

Roof lines

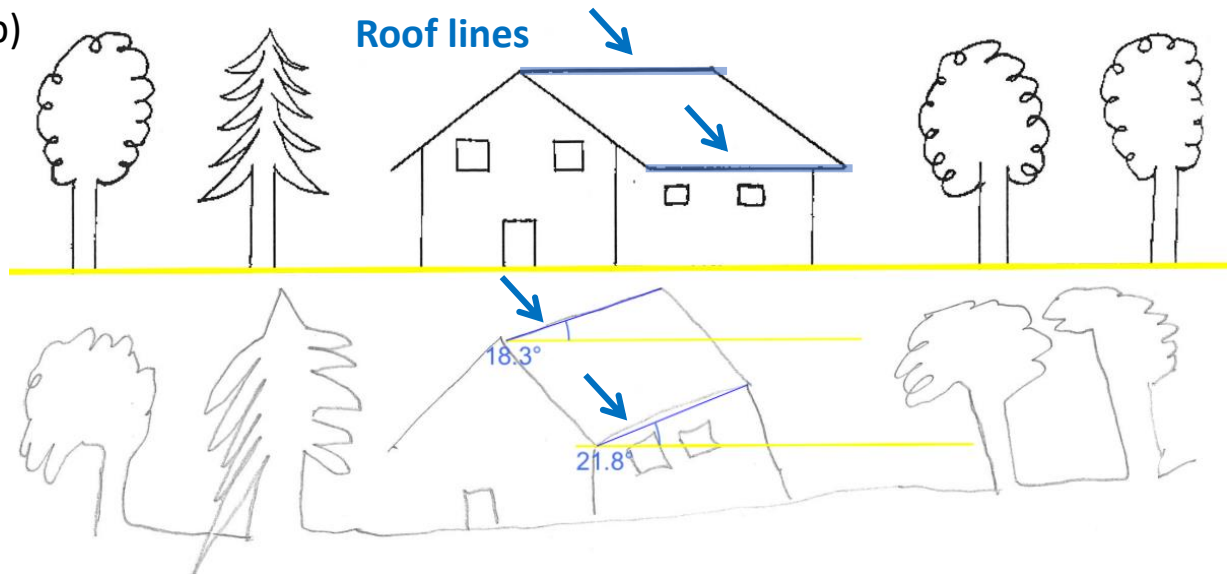


Figure 3

[Click here to access/download;Figur](#)

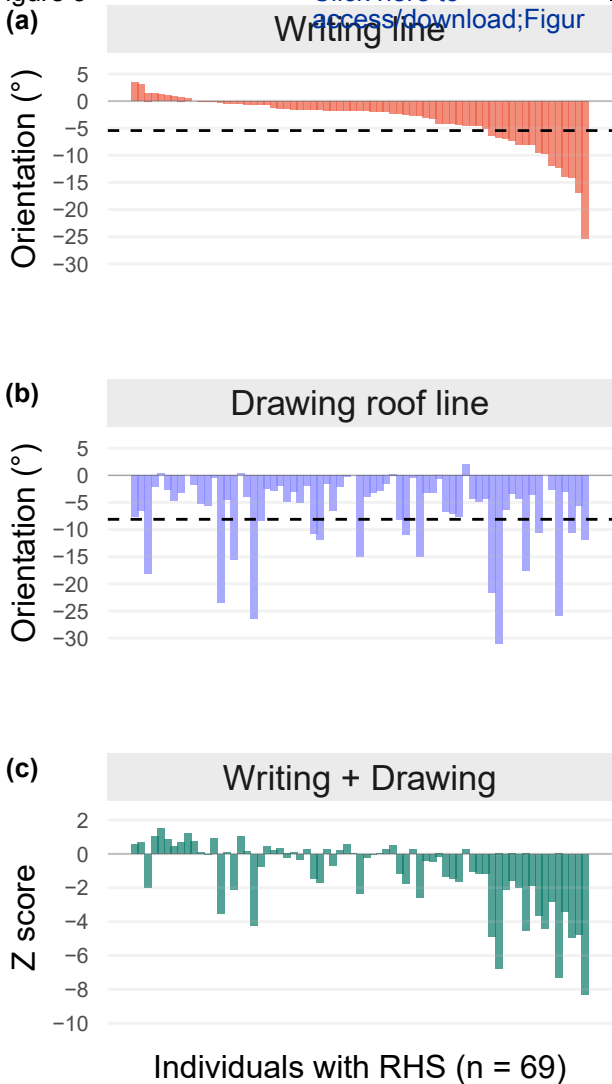
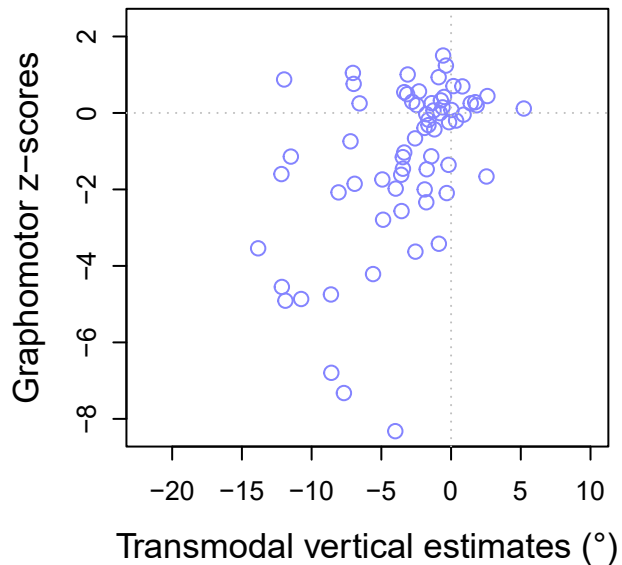


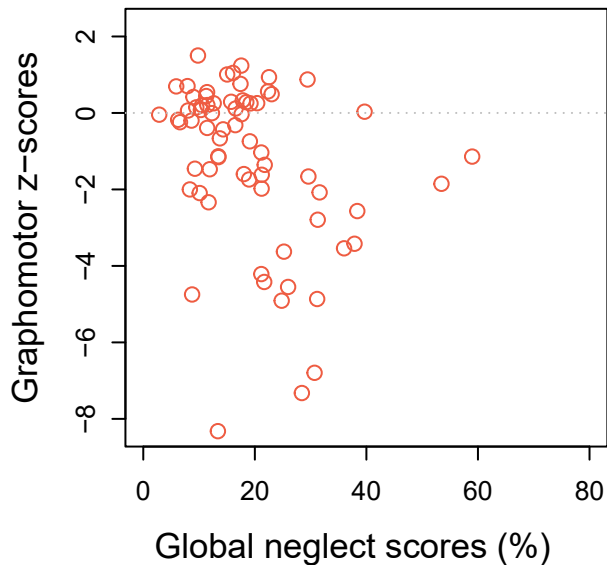
Figure 4

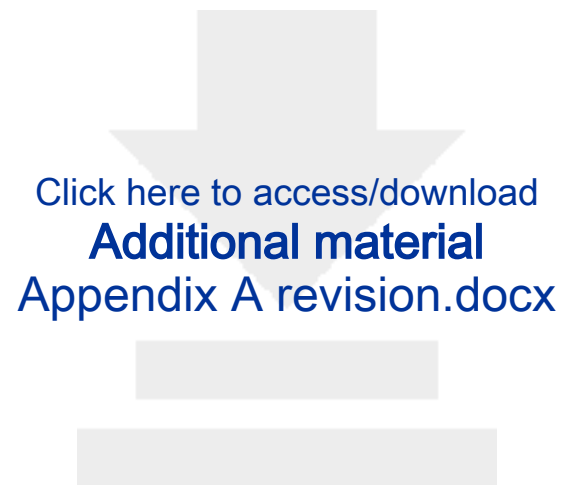
$$r_s = 0.46 \quad p < 10^{-4}$$



[Click here to access/download:Figure;Fig 4 Spearman Corr - revision.pdf](#)

$$r_s = -0.36 \quad p < 0.01$$





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Additional material
Appendix A revision.docx



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Additional material
Appendix B.docx

tilted representation
of verticality

tilted writing
and drawing

