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Clock drawing in spatial neglect: A comprehensive analysis of clock perimeter, placement, and accuracy

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Clock drawings produced by right-brain-damaged (RBD) individuals with spatial neglect often contain an abundance of empty space on the left while numbers and hands are placed on the right. However, the clock perimeter is rarely compromised in neglect patients' drawings. By analysing clock drawings produced by 71 RBD and 40 healthy adults, this study investigated whether the geometric characteristics of the clock perimeter reveal novel insights to understanding spatial neglect. Neglect participants drew smaller clocks than either healthy or non-neglect RBD participants. While healthy participants' clock perimeter was close to circular, RBD participants drew radially extended ellipses. The mechanisms for these phenomena were investigated by examining the relation between clock-drawing characteristics and performance on six subtests of the Behavioral Inattention Test (BIT). The findings indicated that the clock shape was independent of any BIT subtest or the drawing placement on the test sheet and that the clock size was significantly predicted by one BIT subtest: the poorer the figure and shape copying, the smaller the clock perimeter. Further analyses revealed that in all participants, clocks decreased in size as they were placed farther from the centre of the paper. However, even when neglect participants placed their clocks towards the centre of the page, they were smaller than those produced by healthy or non-neglect RBD participants. These results suggest a neglect-specific reduction in the subjectively available workspace for graphic production from memory, consistent with the hypothesis that neglect patients are impaired in the ability to enlarge the attentional aperture.

Textbook descriptions of spatial neglect are usually accompanied by patients' drawings. Right-brain-damaged (RBD) individuals with spatial neglect often depict an object with left-sided features absent. As neglect symptoms cannot be explained by sensory or motor defects (Heilman, Watson, & Valenstein, 2003), omissions in drawing may result from the degradation of left-sided representational imaging (Bartolomeo, 2007; Berti, 2004;

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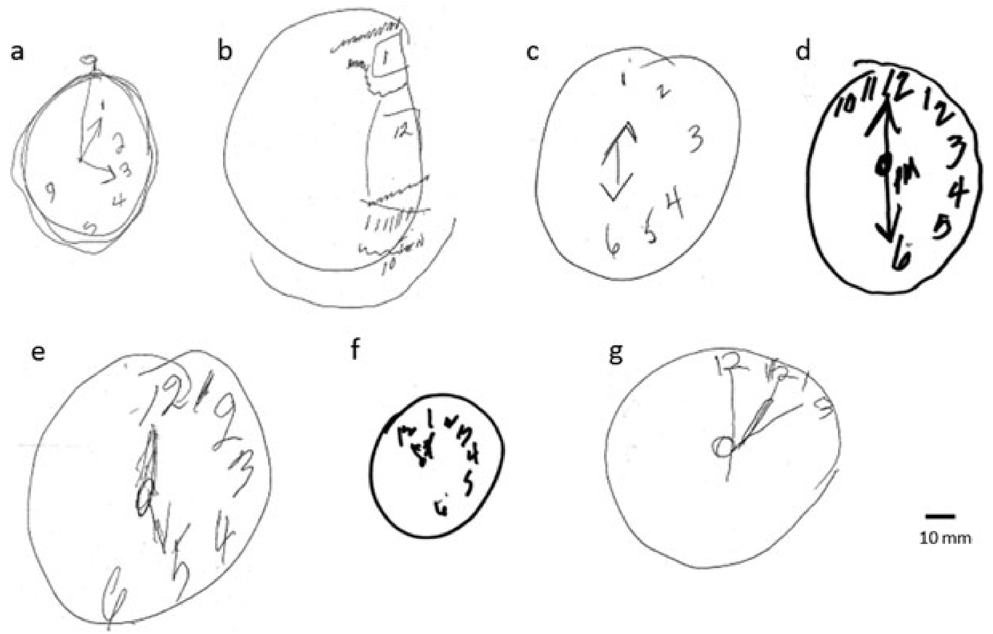

Figure 1. Examples of clock drawings produced by right-brain-damaged stroke survivors with spatial neglect. The reference scale of 10 mm is noted.

Bisiach, Luzzatti, & Perani, 1979), or the inability to deploy attention leftward in such mental imagery (Hillis, 2006), thus fading the left-sided figures into the background (Marshall & Halligan, 1994). Many have documented this phenomenon in non-artists as well as professional artists with spatial neglect (Apfeldorf, 1962; Chatterjee, 2004; Chokron, Colliot, & Bartolomeo, 2004; Halligan & Marshall, 2001; Poole, Sadek, & Haaland, 2011). Some drawings appear as having a clear and complete cut between emptiness on the left and abundance on the right as if an opaque blank covered the left side of the object; others show an absence of details or parts on the left side as if the drawing were unfinished.

Similarly, clock drawings produced by neglect patients often present a left–right asymmetry. Specifically, the asymmetrical layout of clock numerals signals the manifestation of spatial neglect (Agrell & Dehlin, 1998). Typically, these drawings contain empty space on the left, as if the clock were covered by an opaque semicircle (see examples in Figure 1). However, this metaphoric occlusion frequently leaves the rim of the clock unaffected. The circular outline is rarely compromised in neglect patients' clock drawings and is almost always the first feature produced in the task. To comment on this seemingly preserved ability to produce the clock circumference, Halligan and Marshall (1993b) suggested that 'the optimal gestalt of the circle precludes the omission of parts thereof' (p. 15).

However, there is little to no evidence as to whether the clock perimeters produced by neglect patients are normal. The standardized scoring methods for clock drawing are focused on the clock face: number sequencing and allocating, and hand placement (Cohen, Ricci, Kibby, & Edmonds, 2000; Lessig, Scanlan, Nazemi, & Borson, 2008; Mendez, Ala, & Underwood, 1992; Shulman, Gold, Cohen, & Zucchero, 1993; Tuokko, Hadjistavropoulos, Miller, & Beattie, 1992). Indeed, patients may not even be asked to draw the clock perimeter, which is often provided and seldom taken into account in the scoring method. For instance, Ishiai and colleagues investigated whether neglect severity was correlated with clock-drawing accuracy (Ishiai, Sugishita, Ichikawa, Gono, & Watabiki, 1993), and addressed this question by asking neglect patients to produce a clock face within a printed circle that was provided. Another example is the Behavioral Inattention Test (BIT; Wilson, Cockburn, & Halligan, 1987), a widely used screening tool for spatial neglect. Clock drawing is part of the BIT, and examinees are instructed to draw a clock face with no circle provided. However, the scoring method emphasizes the left–right symmetry of the drawing in general, and a response with 'omission or gross distortion of any major contralesional component of the drawing' is considered incorrect (Halligan, Cockburn, & Wilson, 1991). This all-or-none scoring method is unlikely to capture any abnormality of the clock perimeter. In one of the few studies examining clock perimeters, Suhr, Grace, Allen, Nadler, and McKenna (1998) compared different scoring methods for the clock-drawing test and found that RBD stroke survivors produced smaller clock drawings than left-brain-damaged stroke survivors and healthy individuals. However, Suhr *et al.* (1998) did not provide a mechanistic explanation for their finding or whether such finding would be related to spatial neglect.

In an investigation of neglect patients' graphic production of circles, Smith and colleagues asked RBD stroke survivors to make copies of circles of various sizes, and neglect patients consistently produced circles that were smaller than the model (Smith, Gilchrist, Butler, & Harvey, 2006; Smith *et al.*, 2007). In addition, the size of drawings decreased with increasing neglect severity (Smith *et al.*, 2006). Surprisingly, size distortion in circle copying was not related to the laterality of the start position, nor was the clockwise or counterclockwise direction of the drawing movement (Smith *et al.*, 2007), suggesting that this abnormality in graphic production of circles may not be associated with the lateralized bias that is the hallmark of spatial neglect. However, with only six patients with spatial neglect (based on the BIT cut-off score), Smith *et al.*'s studies may underestimate the extent of graphic distortions, and their results only indirectly address the possibility of abnormal perimeters in clock drawing: their participants copied circles rather than producing them from memory. Thus, it remains unknown whether persons with spatial neglect produce abnormal clock perimeters when drawing clocks from memory.

Potential mechanisms of small clock drawing

In this paper, we consider several possible mechanisms of small clock drawing in spatial neglect. The possibility that we consider most plausible is that neglect patients draw small clocks because of a reduction in the available workspace for producing the clock. The clock perimeter defines the workspace for placing the other features inside the perimeter to form a clock face, but the size of the workspace for producing the clock perimeter may be limited for neglect patients due to one or both of the two separable mechanisms of spatial attention: Using the metaphor of a floodlight (Barrett, Beversdorf, Crucian, & Heilman, 1998), spatial attention can be spread over a broad area or focused on a specific location, which is the ability to scale the attentional aperture (Barriopedro & Botella, 1998); spatial attention can also be shifted from location to location, which is the ability to move attention (Posner, 1980). Abnormality in the ability to enlarge the attentional aperture may reduce the subjectively available workspace (e.g., spontaneously producing a small circular outline as the foundation for the clock face);

abnormality in the ability to move attention in space may constrain the amount of space available for creating the drawing.

In a task that required participants to judge whether two separate line segments were collinear, Barrett *et al.* (1998) found that RBD stroke survivors had difficulty in widening their attentional aperture to perform the task normally. Independent of the distance between the line segments, both RBD and left-brain-damaged stroke survivors were able to indicate the locations of the line segments in the right and left hemispaces. However, in comparison to healthy controls, RBD individuals produced significantly greater errors in collinearity judgement as the gap between the line segments increased while left-brain-damaged individuals' performance was poorer than healthy controls only in the condition with the smallest gap between the line segments (Barrett *et al.*, 1998). Such findings suggest that RBD stroke survivors may have difficulty enlarging the attentional aperture to sufficiently circumscribe both line segments with large gaps and therefore fail to judge whether the lines were collinear. Consistent with this interpretation, a functional imaging study using the collinearity judgement task to investigate the ability to scale the attentional aperture in healthy adults showed that the right inferior frontal gyrus was differentially activated when the gap between the line segments was increasing rather than decreasing, and that the right posterior temporal parietal areas were critically associated with switching size of the attentional aperture (i.e., zoom-in to zoom-out or zoom-out to zoom-in; Chen, Marshall, Weidner, & Fink, 2009). Thus, the phenomena of small clock drawings in spatial neglect may be related to right-brain damage impairing the ability to widen attention for determining the subjectively available workspace for creating the clock perimeter.

Alternatively, the reduced size of clock drawing in spatial neglect may result from the limited ability to move attention around. It is known that persons with left-sided neglect typically start exploring a predetermined workspace (e.g., a page) from the right hemispace (Chen *et al.*, 2008; Fong *et al.*, 2007; Nurmi *et al.*, 2010) as well as from the distal/upper portion of the entire workspace (Chatterjee, Thompson, & Ricci, 1999). This spatial bias may be due to deficits in the perceptual–attentional or the motor-intentional spatial systems (Barrett & Burkholder, 2006; Heilman *et al.*, 2003; Lau, Rogers, Haggard, & Passingham, 2004; Na *et al.*, 1998). Therefore, when exploring the available workspace to initiate the graphic production of a clock face, neglect patients may be abnormally constrained to the upper right portion of the page. Constraining the clock to the upper-right portion of the page may limit the amount of space available for producing the clock drawing and thus neglect patients may draw a small clock.

In addition to a potential reduction in the available workspace, we consider three other mechanisms for the small clock drawings produced in spatial neglect. However, these three accounts are less plausible explanations for the small clock perimeters. First, it is possible that neglect patients produce smaller clocks because of hypometria (i.e., an abnormally reduced amplitude of manual movements towards contralesional space). However, no evidence supports that the initial direction (leftward or rightward) affects the amplitude of a circular movement (Smith *et al.*, 2007). Furthermore, hypometria in neglect patients is observed mostly with the contralesional limb (left) moving in the contralesional space without visual feedback (Meador *et al.*, 2000; Meador, Watson, Bowers, & Heilman, 1986). Second, making a graphic production, by drawing from memory or copying from a model, is related to constructional abilities, which is vulnerable to right-brain damage (Laeng, 2006). Thus, it is possible that reduced constructional abilities in neglect patients affect the size of the clock drawing. However, in Smith *et al.*'s study (2007), the size of circles copied was predicted by neglect severity, but it was independent of constructional abnormalities. This suggests that graphically producing a stand-alone circle may not be related to constructional abilities. A third possibility is that small clock drawing is due to representational neglect. That is, it is the mental imagery of the clock, rather than the attentional aperture, that is reduced in size and reflected in the drawing. Given, however, that Smith *et al.* (2006) found that neglect patients produced smaller drawings even when copying circles, we consider this alternative unlikely too.

Is the clock perimeter in normal shape?

In addition to size, spatial neglect may alter the shape of clock perimeter as well. Literature on representational neglect does not indicate whether the contour of an object image would be affected. Since the drawing is produced from memory, and the circular outline is the first component produced, it may be least affected by immediate visual input, and thus may reflect how the stereotypical image of a clock is represented in the mind (Anderson, 1993; Chokron *et al.*, 2004). Alternatively, converging evidence suggests that in comparison to the radial dimension, the horizontal dimension is more likely to be underestimated, and thus misperceived or misrepresented in spatial neglect (Guariglia & Piccardi, 2010; Halligan & Marshall, 1993a, 1995; Harvey, Gilchrist, Olk, & Muir, 2003; Heilman & Valenstein, 1979; Irving-Bell, Small, & Cowey, 1999; Milner & Harvey, 1995). Therefore, underestimation of the horizontal dimension may result in the imprecise production of a circle as a radially extended ellipse, namely an oval shape with the height longer than the width (see Figure 1a–f).

Current study

Few studies have comprehensively analysed the perimeter of clock drawings in spatial neglect. Suhr *et al.*'s report (1998) suggested that right-brain stroke may be related to small clock drawings but treated it as an 'error' in clock drawing without much elaboration. Smith *et al.* (2006, 2007) studied neglect patients' graphic production of circular shapes via copying models, but the results may not be directly related to graphic production of clock perimeters from memory and they had a small sample of neglect patients ($n = 6$). With a large sample of RBD neglect, RBD non-neglect, and healthy participants in the present study, we addressed the question of whether the size and shape of the clock perimeter were abnormal in spatial neglect, and whether any distortions were associated with known characteristics of spatial neglect. We performed a comprehensive analysis of the clock-drawing performance, assessing the horizontal and radial extensions of the drawing, the overall size of the drawing, and placement of the drawing on the page. We also performed a comprehensive assessment of clock-drawing accuracy, as typically employed for dementia screening (Lessig *et al.*, 2008). Lastly, to understand the potential mechanisms that may underlie abnormal clock perimeters, we investigated the relation between participants' clock-drawing characteristics and their performance on the BIT subtests, each of which may detect different manifestations and mechanisms of spatial neglect (Halligan *et al.*, 1991; Halligan, Marshall, & Wade, 1989).

Table 1. Characteristics of RBD neglect participants (BIT < 129), RBD non-neglect participants, and healthy participants

	RBD neglect ($n = 31$)	RBD non-neglect ($n = 40$)	Healthy ($n = 40$)
Men/women	15/16	23/17	14/26
Age, years	68.1 ± 15.8	62.7 ± 13.5	65.0 ± 9.9
Education years***	12.9 ± 2.9	14.0 ± 2.9	16.3 ± 3.1
Post-stroke days	21.9 ± 9.3	26.2 ± 16.9	NA
MMSE (out of 30)***	23.1 ± 3.9	28.5 ± 2.1	29.7 ± 0.8
BIT total score (out of 146)***	67.6 ± 39.8	139.4 ± 5.5	144.9 ± 1.2
BIT subtests			
Line crossing (out of 36)***	21.1 ± 12.3	35.8 ± 0.7	36.0 ± 0.0
Letter cancellation (out of 40)***	17.0 ± 12.3	37.4 ± 2.6	39.4 ± 0.9
Star cancellation (out of 54)***	24.9 ± 16.1	52.6 ± 1.7	53.8 ± 0.5
Figure and shape copying (out of 4)***	0.9 ± 1.0	3.2 ± 0.7	3.9 ± 0.4
Line bisection (out of 9)***	2.7 ± 2.3	7.7 ± 1.8	8.9 ± 0.3
Representational drawing (out of 3)***	1.1 ± 1.0	2.7 ± 0.6	3.0 ± 0.2
Stroke etiology (Hem/Isc)[a]	7/22	14/25	NA
Right-brain lesion location[b]			
Frontal cortex	15	6	NA
Parietal cortex	13	7	
Temporal cortex	7	6	
Occipital cortex	1	1	
Insular cortex	5	5	
Basal ganglia	11	23	
Thalamus	3	8	
Subcortical WM	13	14	

Note. RBD, right-brain-damaged; MMSE, Mini-Mental State Examination; BIT, Behavioral Inattention Test; NA, not applicable; Hem, haemorrhage or haemorrhagic conversion; Isc, ischaemic; WM, white matter.

[a]Two neglect patients and one non-neglect participant's radiology records were unavailable, but right-brain strokes were noted in their charts.

[b]Multiple cytoarchitectonic sites may be involved in individual participants.

*** $p < .001$ from one-way ANOVA.

Method

Participants

Participant characteristics are summarized in Table 1. All information was obtained in compliance with the regulations of the Institutional Review Board (IRB) of the authors' organization. Seventy-one consecutive stroke survivors, admitted to one of the collaborating rehabilitation hospitals after an ischaemic or haemorrhage stroke in the right cerebral hemisphere, were included. All were right-hand dominant pre- and post-stroke (determined by a 17-item handedness questionnaire; Raczkowski, Kalat, & Nebes, 1974); had no history of a stroke in the left hemisphere; and completed the Mini-Mental State Examination (MMSE; Folstein, Folstein, & McHugh, 1975) and the conventional subtests of the BIT within 100 days post-stroke ($M = 24.3$; $SD = 14.2$). There were 38 men and 33 women, between 34 and 91 years of age ($M = 65.1$; $SD = 14.7$) who had 6–20 years of education ($M = 13.5$; $SD = 2.9$). MMSE scores ranged from 15 to

30 of 30 (M = 26.1; SD = 4.0), and BIT scores from 11 to 146 of 146 (M = 108.0; SD = 44.5). Because the BIT total score is frequently used to diagnose spatial neglect in clinical practices and research (e.g., Cherney, Halper, Kwasnica, Harvey, & Zhang, 2001; Fong *et al.*, 2007; Hartman-Maeir & Katz, 1995; Luukkainen-Markkula, Tarkka, Pitkanen, Sivenius, & Hamalainen, 2009), we used the standardized cut-off (Halligan *et al.*, 1991) to group the stroke survivors into neglect and non-neglect RBD participants. Thirty-one of the RBD participants met the criterion for having spatial neglect (BIT total score <129).

Healthy participants consisted of 40 right-handed individuals with no history of brain injury or neurological disease. They were recruited via flyers and e-mails in the authors' organization and collaborating rehabilitation hospitals. Healthy participants (14 males; 26 females) aged from 50 to 86 years (M = 65.0; SD = 9.9) with 12–26 years of education (M = 16.3; SD = 3.1). Their MMSE and BIT total scores were 29.7 $\pm$ 0.8 and 144.9 $\pm$ 1.2, respectively. Between healthy and stroke participants, there were no group-level differences in sex (Fisher's exact: p = .076) or age (independent samples t-test: p = .975). Healthy participants had more years of education than stroke participants and better scores on the MMSE and BIT (all p < .001).

Procedure for clock drawing

Participants sat at a desk and used their right hand for the task. Following the standard procedure for administering the BIT (Wilson *et al.*, 1987), the examiner asked participants to draw a clock, while presenting participants with a blank letter-sized sheet of paper (215.9 mm $\times$ 279.4 mm), of which the shorter edge was parallel to participants' coronal plane and centred at body midline. Head and eye movements were not constrained. Moving the sheet was not permitted. Drawing was untimed, and no time limit for completion was imposed.

Measurements

The height (radial diameter; H) and width (horizontal diameter; W) of the clock drawing were measured in millimeters (mm) to determine drawing distortion in terms of size and shape. We created an area index by multiplying height by width ($H \times W$) to convey the size of the clock perimeter. We created a shape index that was the height-to-width ratio (H/W). A shape index of 1 indicates a perfect circle, greater than 1 indicates a radially extended ellipse, and less than 1 a horizontally extended ellipse. Both area and shape indices were values with no unit.

Placement bias was measured horizontally and radially from the paper centre to the clock centre in millimeters. Horizontal placement was the distance right (coded positive) or left (coded negative) to the paper centre. Radial placement was the distance above (coded positive) or below (coded negative) the paper centre. We also calculated the overall displacement, which was the distance, regardless of the directional bias, between the clock centre and the paper centre.

Lastly, to quantify accuracy in clock drawing, 19 items (scored as correct = 1 or incorrect = 0) were selected from the clock scoring technique described by Lessig *et al.* (2008), incorporating three popular methods (Mendez *et al.*, 1992; Shulman *et al.*, 1993; Tuokko *et al.*, 1992). Five error types from Lessig *et al.*'s method were excluded because they were irrelevant to the standard BIT instruction, which did not require participants to set a particular time or provide a second try. An independent rater scored all clock drawings. The Appendix lists the 19 scoring items for clock-drawing accuracy. The clock-drawing accuracy score was the total number of items correct.

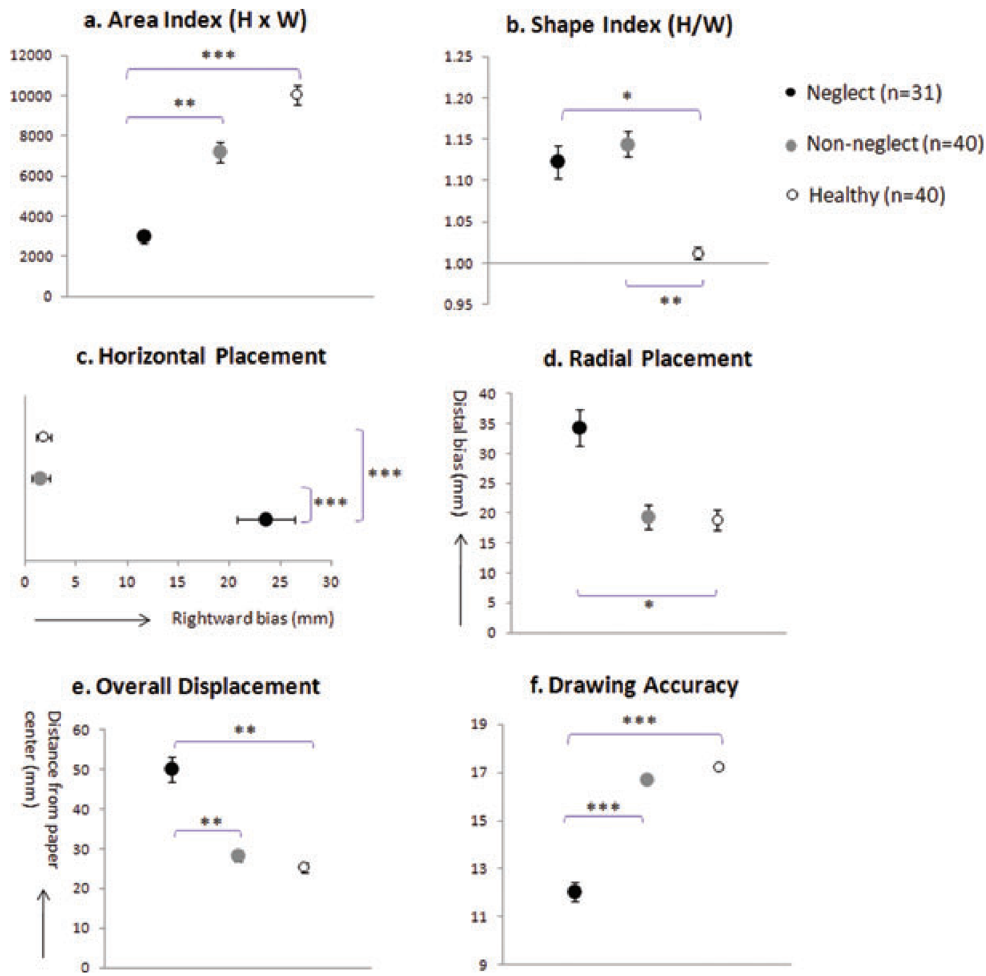

Figure 2. Means and standard errors (presented in error bars) of clock-drawing geometry in right-brain-damaged (RBD) participants with or without spatial neglect, and healthy participants. (a) Area index (denoted on the *y*-axis). (b) Shape index (denoted on the *y*-axis): horizontal line at 1 indicates the shape of a circle; values greater than 1 indicate shapes of vertical ovals. (c) Horizontal placement (denoted on the *x*-axis): vertical line at zero indicates clock centre overlapping paper centre on the horizontal dimension; positive values denote clock centres on the right side of paper. (d) Radial placement (denoted on the *y*-axis): zero indicates clock centre overlapping paper centre on the radial dimension; positive values denote clock centres on the upper part of paper. (e) Overall displacement (denoted on the *y*-axis): zero indicates clock centre overlapping paper centre. (f) Drawing accuracy. Asterisks ($^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$) indicate significant differences in pairwise comparisons (Tukey's HSD tests) post the one-way ANOVA.

Analyses and Results

Clock drawings characteristics

Throughout, we used an alpha of .05 and performed *post hoc* pairwise comparisons using Tukey's Honestly Significant Difference (HSD) after significant one-way ANOVAs.

Clock size

The ANOVA showed a significant difference among the three groups of participants, $F(2, 108) = 14.03$, $p < .001$. As seen in Figure 2a, and consistent with our prediction, the drawings of neglect participants (mean area index = 2,988.4 ± 3,834.2) were smaller than those of non-neglect RBD (7,187.9 ± 6,230.9; $p = .006$) and healthy participants (10,044.5 ± 5,981.9; $p < .001$), who did not differ from each other.

Clock shape

All participants drew the clock with an elliptical contour rather than any other shape such as rectangle or triangle. However, the ANOVA, revealed a significant difference in the shape index of the three groups, $F(2, 108) = 6.44$, $p = .002$ (see Figure 2b). Both neglect and non-neglect RBD participants had shape indices greater than that of the healthy participants ($p = .025$ for neglect vs. healthy; $p = .003$ for non-neglect vs. healthy). However, there was no statistical difference between neglect and non-neglect RBD groups on the measure of clock shape ($p = .870$). The healthy participants' clock perimeter was very close to a circle with a shape index of 1.01 ± .09 (one-sample t-test comparing to value of 1: $t(39) = .82$, $p = .418$). However, both neglect and non-neglect RBD participants' clock perimeters were radially extended ellipses with shape indices of 1.12 ± .22, $t(30) = 3.07$, $p = .005$, and 1.14 ± .19, $t(39) = 4.69$, $p < .001$, respectively.

Horizontal placement

As illustrated in Figure 2c, neglect participants' clock drawings were placed more rightward than those of non-neglect participants' and healthy participants'. These impressions were confirmed with the one-way ANOVA, $F(2, 108) = 15.45$, $p < .001$. On average, neglect participants placed clock drawings more rightward (23.6 ± 31.2 mm) than those of non-neglect RBD (1.8 ± 9.3 mm) and healthy participants (0.4 ± 13.6 mm; $p < .001$ for both comparisons). Neglect participants also placed the clock right of the paper centre (one-sample t-test: $t(30) = 4.21$, $p < .001$). Both non-neglect RBD participants' and healthy participants' clock drawings were not significantly deviated from the paper centre ($p = .407$ and $p = .234$, respectively).

Radial placement

The ANOVA indicated a significant difference among the groups, $F(2, 108) = 3.64$, $p = .030$: As illustrated in Figure 2d, neglect participants drew clocks more distally than did healthy participants ($p = .044$), with a trend towards the same difference when compared to non-neglect RBD participants ($p = .055$). There was no difference between non-neglect RBD participants and healthy participants ($p = .995$) in radial placement. However, all three groups placed the clock centre in the upper portion of the paper, confirmed by one-sample t-tests: neglect participants: 34.4 ± 33.7 mm, $t(30) = 5.68$, $p < .001$; non-neglect RBD participants: 19.4 ± 25.3 mm, $t(39) = 4.84$, $p < .001$; healthy participants: 18.8 ± 21.7 mm, $t(39) = 5.48$, $p < .001$.

Overall displacement

As would be expected from the results of the radial and horizontal placement biases, the one-way ANOVA yielded a significant difference among the groups in the distance of the

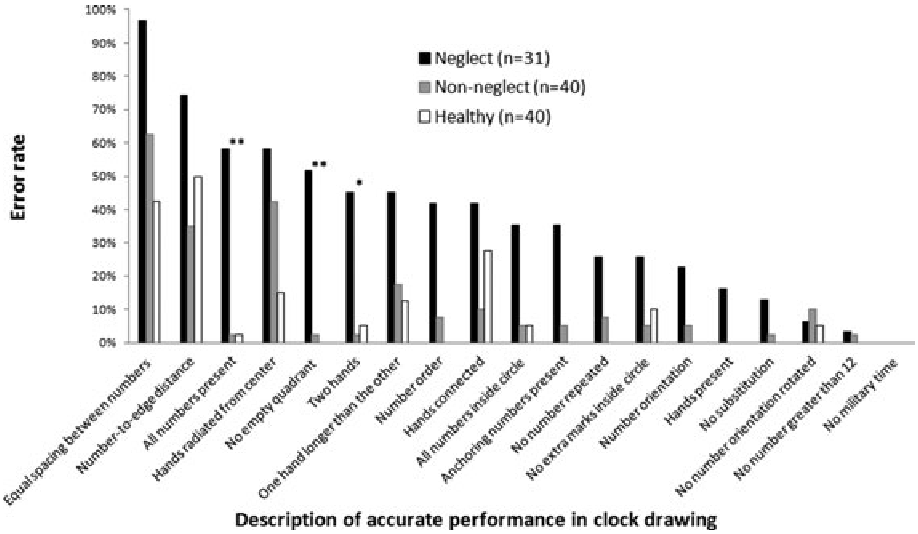

Figure 3. Error rates in clock-drawing items (see Appendix for scoring description). Asterisks (*$p < .05$; **$p < .01$) indicate significant differences in the error rates of the neglect and non-neglect right-brain-damaged (RBD) groups, controlling for Mini-Mental State Examination (MMSE).

clock from the paper centre, $F(2, 108) = 10.54, p < .001$. Shown in Figure 2e, neglect participants drew their clocks farther from centre (50.03 ± 36.22 mm) than healthy (25.26 ± 16.37 mm; $p = .001$) and non-neglect RBD participants (28.33 ± 18.23 mm; $p = .001$), who did not differ from each other ($p = .836$). All three groups displaced their clocks significantly away from the centre of the page, confirmed by one-sample *t*-tests: neglect, $t(30) = 7.69, p < .001$; non-neglect RBD, $t(39) = 9.83, p < .001$; healthy participants, $t(39) = 9.76, p < .001$.

Clock-drawing accuracy

The one-way ANOVA revealed a significant difference in the clock-drawing accuracy of the groups, $F(2, 108) = 38.34, p < .001$. Neglect participants had lower accuracy (12.0 ± 4.4) than both non-neglect RBD (16.7 ± 1.8; $p < .001$) and healthy participants (17.3 ± 1.4; $p < .001$), who did not differ from each other (Figure 2f). Figure 3 depicts the error rate of each group on each item.

To examine whether any of the errors were neglect specific, we performed the following analysis. Given that this assessment of clock-drawing accuracy is sensitive to dementia and general cognitive decline (Lessig *et al.*, 2008), we controlled for MMSE in separate logistic regression analyses assessing the ability of the presence of neglect among the RBD participants to predict accuracy on each item. Controlling for MMSE, the presence of spatial neglect was associated with a significantly increased error rate (over non-neglect RBD) on three of the 19 items: ‘All numbers present’, $b = -3.27$, $SE = .96$, $p = .001$; ‘No empty quadrant’, $b = -3.29$, $SE = 1.19$, $p = .006$; and ‘Two hands’, $b = -1.90$, $SE = .88$, $p = .030$. Analysis of the item ‘Equal spacing between numbers’ approached significance, $b = -2.17$, $SE = 1.19$, $p = .068$. These items all refer to errors of omission, spatial allocation, or spatial relations among numbers.

Clock drawing and BIT subtest performance

Analyses and results reported above were based on the assumption that RBD stroke survivors can be diagnosed as having neglect or not having neglect based on the BIT total score. However, spatial neglect is a very complex disorder with individual differences across domains, which may be reflected in BIT subtest scores (Halligan *et al.*, 1991). Therefore, to assess the relation between clock-drawing measures and BIT subtests, we performed an exploratory bivariate correlation analysis with the six clock-drawing measures and six BIT subtest scores of the 71 stroke survivors. Again, given that clock drawing is widely used for assessing dementia and cognitive decline, we controlled for MMSE in this analysis. The results are summarized in Table 2. Several key results emerged from this analysis: RBD participants' horizontal placement of clocks was correlated with all subtests of the BIT as well as the BIT total score, consistent with the ability of the BIT to detect lateralized biases of attention. Overall displacement was also correlated with all subtests of the BIT and the BIT total score. Radial placement was associated with letter cancellation. Interestingly, the size of RBD participants' clocks (area index) was correlated only with the figure- and shape-copying subtest, and moderately so with star cancellation. Finally, clock-drawing accuracy was correlated with all subtests of the BIT and the BIT total score.

To determine the 'best' predictor of each of the clock-drawing measures, we performed separate stepwise linear regression analyses with each of the BIT subtests and the MMSE as predictors. For area index, figure and shape copying emerged as the only predictor, adjusted $r^2 = .182$, $\beta = .44$, $p < .001$. For shape index, there was no significant predictor. Star cancellation and line bisection together significantly predicted horizontal placement, adjusted $R^2 = .447$, $\beta = -.385$ and $\beta = -.336$, respectively, $p < .001$, with star cancellation by itself accounting for 41% of variance ($p < .001$). For radial placement, letter cancellation emerged as the only significant predictor, adjusted $r^2 = .115$, $\beta = -.358$, $p = .002$. For overall displacement, letter cancellation was the only significant predictor, adjusted $r^2 = .295$, $\beta = -.552$, $p < .001$. Lastly, clock-drawing accuracy was significantly predicted by star cancellation ($\beta = .366$), representational drawing ($\beta = .324$), and MMSE ($\beta = .210$), adjusted $R^2 = .638$, $p < .001$. Interestingly, star cancellation by itself accounted for 57% of the variance while MMSE accounted for additional 2.2% variance.

We repeated the same bivariate correlation analysis in healthy participants but excluded line crossing because all the healthy participants reached the highest score in this BIT subtest. The result showed only two significant correlations, which were between area index and radial placement, $r = -.449$, $p = .004$, and between area index and overall displacement, $r = -.395$, $p = .013$. Thus, like RBD participants, healthy participants produced smaller clock drawings as they were placed farther away from the paper centre and more specifically, farther in the upper portion of the paper.

Relation between clock size and drawing displacement

To address the question of whether the size of a clock drawing resulted from its placement on the page, we further analysed the relation between area index and overall displacement. Figure 4 depicts scatter plots of area index (clock size) as a function of overall displacement (distance from centre regardless of the directional placement) for each of the three groups (Figure 4a—c) and for the groups overlaid on the same axes (Figure 4d). As the figure and the results of the bivariate correlations described earlier suggest, across all the participants, clock sizes decreased as the clocks were drawn

Table 2. Correlation matrix of BIT and clock drawing, controlling for MMSE, in all RBD participants

RBD participants ($N = 71$)	Area index ($H \times W$)	Shape index (H/W)	Horizontal placement	Radial placement	Overall displacement	Clock-drawing accuracy
Behavioral Inattention Test						
Line crossing	.136	−.040	−.440***	−.173	−.345**	.431***
Letter cancellation	.194	−.053	−.468***	−.269*	−.427***	.532***
Star cancellation	.244*	−.024	−.541***	−.192	−.347**	.567***
Figure and shape copying	.347**	.004	−.446***	−.067	−.248*	.431***
Line bisection	.154	−.008	−.525***	−.190	−.383**	.359**
Representational drawing	.129	−.091	−.443***	−.121	−.242*	.549***
BIT total score	.223	−.040	−.552***	−.228	−.411***	.569***
Clock-drawing measures						
Area index ($H \times W$)						
Shape index (H/W)	.182					
Horizontal placement (mm)	−.169	−.123				
Radial placement (mm)	−.416***	−.080	.196			
Overall displacement (mm)	−.434***	−.150	.543***	.834***		
Clock-drawing accuracy	.194	−.017	−.446***	.006	−.145	

Note. BIT, Behavioral Inattention Test; MMSE, Mini-Mental State Examination; RBD, right-brain-damaged.
* $p < .05$; ** $p < .01$; *** $p < .001$.

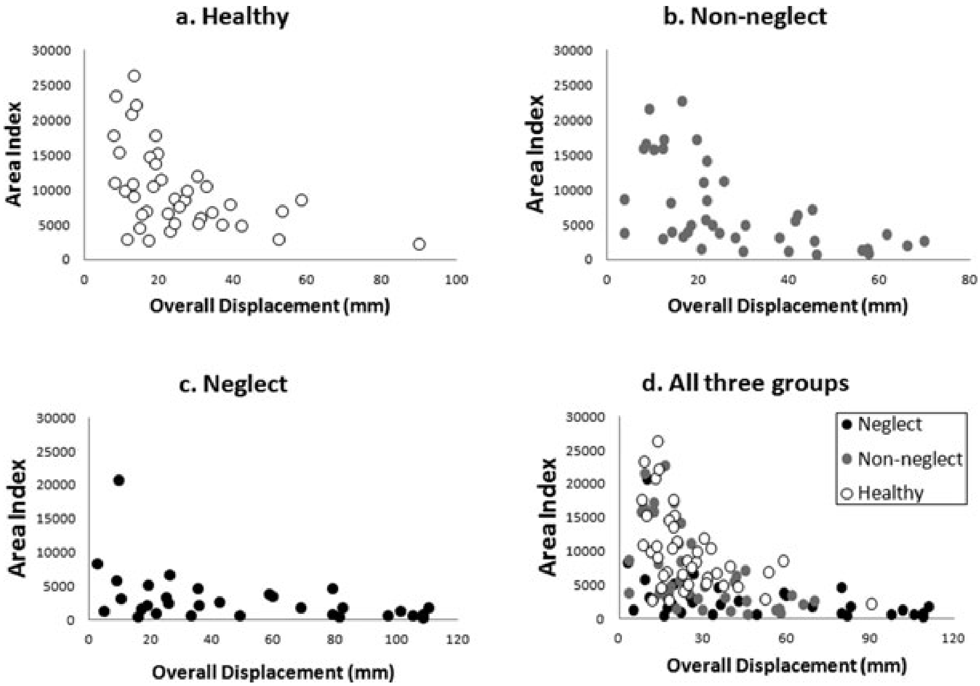

Figure 4. Scatter plots of clock size (area index) as a function of distance between the centres of page and clock drawing (overall displacement) for each of the groups individually (a–c) and overlaid on the same axes (d).

farther from the centre of the page, $r(109) = -.514$, $p < .001$. The magnitude of this relation was similar within each of the groups, although its significance varied, perhaps due to differences in sample size and range of data along the axes: $r = -.415$, $p = .020$ for neglect; $r = -.562$, $p < .001$ for non-neglect RBD; $r = -.482$, $p = .002$ for healthy participants. Collectively, these results suggest that mechanistic constraints may contribute to the size of the clock created by all participants, regardless of their neglect status.

However, we pursued the hypothesis that neglect patients may also have a reduced subjectively available workspace, in addition to any space constraint due to drawing displacement, affecting the size of clock drawing. We selected subsets of RBD participants and healthy participants who placed their clocks within one standard deviation of the mean of healthy participants' overall displacement (25.26 ± 16.37 mm). Thus, neglect ($n = 16$), non-neglect RBD ($n = 30$) and healthy ($n = 35$) participants who had overall displacement of less than 41.63 mm were included in the one-way ANOVA with *post hoc* Tukey's HSD for pairwise comparisons. Among this subset of participants, who drew their clocks in the same general region, there was a significant difference in clock size, $F(2, 78) = 6.47$, $p = .003$. Neglect participants drew smaller clocks (area index = 4,252.94 ± 4,911.23) than did non-neglect RBD participants (8,652.77 ± 6,465.74; $p = .052$) and healthy participants (10,755.23 ± 6,004.55; $p = .002$); the difference between non-neglect RBD and healthy participants did not reach significance, $p = .341$. Therefore, space constraint due to drawing displacement by itself cannot account for the small clocks produced by neglect participants.

Discussion

This study revealed abnormalities of the circular perimeter in clock drawings produced by persons with spatial neglect. Neglect participants drew smaller clock perimeters than either non-neglect RBD or healthy participants, which remained true for clock drawings produced in the same general region. Both neglect and non-neglect RBD participants tended to produce radially elongated clock perimeters relative to healthy participants, who produced close to perfect circles. In addition, neglect severity predicted the clock-drawing accuracy measured by a detailed scoring method typically used for screening dementia.

Why do neglect patients produce smaller clock drawings? One reason is that the farther away from the centre of the page the drawing response initiated, the closer it is to the edge of the page, and therefore, there is less space available for the graphic production. Our finding supports this logic in all participant groups. Neglect, non-neglect RBD, and healthy participants tended to place their clock drawings in the upper portion of the page. This behaviour may be related to a distal bias on the radial dimension that has previously been observed in neglect patients (Halligan & Marshall, 1995) as well as in healthy adults (Barrett, Crosson, Crucian, & Heilman, 2002). Such distal bias on the radial dimension as well as the overall displacement, which took both horizontal and radial dimensions into account, negatively correlated with the size of clock drawings, suggesting that at least part of the reason for small clock drawings produced by neglect patients results from the spatial bias in initiating the drawing response far away from the centre of the page and thus too close to the edge of the page to produce a clock face in a normal size.

However, this account of space constraints cannot preclude the possibility that small clock drawings result from reductions in the subjectively available workspace due to other limited abilities specifically related to spatial neglect. Indeed, when we compared the size of the clocks produced by neglect and non-neglect RBD participants who placed their clocks within the same distance from centre as did most healthy participants, neglect participants still drew significantly smaller clocks than did the healthy participants and non-neglect RBD participants. Thus, space constraints alone cannot account for the small size of the clocks produced by neglect participants, and the presence of spatial neglect is significantly associated with small clock drawings.

Even though we found some neglect specificity to the production of small clocks, small clock drawings were not significantly correlated with a number of metrics of the disorder's signature – asymmetrically lateralized bias towards the right hemispace (e.g., rightward bias in placing clock drawings and abnormalities detected by the BIT subtests including line crossing, letter cancellation, star cancellation, and line bisection). Furthermore, neglect severity (BIT total score) was not significantly correlated with the clock size (i.e., area index; see Table 2), although there was a trend for participants with lower BIT scores to draw smaller clock perimeters. Our findings differ from those of Smith *et al.* (2006) who found that neglect severity (BIT total scores) was strongly correlated with the size of copied circles. However, Smith *et al.* did not assess correlations between BIT subtests and circle size, which may yield more specific mechanistic information.

In our stepwise regression using BIT subtests to predict clock size, we found that the size of clock drawings was predicted uniquely by the figure- and shape-copying subtest of BIT, suggesting that the same mechanism may underlie the performance quantified in clock size and that detected with this BIT subtest. Figure and shape copying consists of three figures (a star, cube, and daisy) presented on the left side to be copied to the right side of a portrait-oriented page, as well as three triangle-based shapes on one landscape-oriented page to be copied to another blank page. Previous research suggests that neglect patients may be able to deploy attention to the left side of the figure-copying page but are unable to encompass each figure in its entirety, resulting in incorrect object perception and consequently half-figure production (Ishiai, Seki, Koyama, & Yokota, 1996); in the shape-copying task, neglect patients may not be able to attend to the entire page at once and fail to self-evaluate whether they copied all the shapes. If the mechanism for scaling the attentional aperture, rather than shifting it, is defective, then one would produce a clock drawing small in size regardless of where on the page it was placed and would also produce asymmetrical copies of figures. This is exactly what the present study found: Neglect participants produced smaller clocks than non-neglect RBD and healthy participants, even when those clocks were placed more centrally on the page, in the same general region as clocks drawn by most healthy participants.

An alternative explanation for the relation between participants' clock-drawing sizes and figure- and shape-copying performance is that both tasks rely on constructional abilities, which are impaired in neglect. Given that the scoring method of this BIT subtest is focused on whether the models are copied symmetrically instead of on whether they are produced in a well-constructed process (Halligan *et al.*, 1991), the present study produced limited evidence on participants' constructional abilities. However, Smith *et al.* (2007) found that performance on constructional subtests of the WAIS (picture completion, block design, and object assembly) were independent of the drawing size in neglect patients. Thus, a reduction in the attentional aperture may be the most likely explanation for neglect patients' reduced clock sizes. Admittedly, while extant evidence suggests the attentional aperture explanation more likely, more research is necessary to definitively decide between these alternative explanations.

Independent of size distortion, we also observed consistent shape distortions of the clock perimeters in RBD stroke survivors. Unlike previous studies that investigated spatial distortion with horizontally oriented stimuli (Harvey *et al.*, 2003; Irving-Bell *et al.*, 1999; Milner & Harvey, 1995) or radially oriented stimuli (Halligan & Marshall, 1993a, 1995), clock drawing allowed the current study to examine both extents in one response. In this task, healthy participants were able to produce a circle perimeter with the horizontal diameter (width) and the radial diameter (height) statistically equal, but RBD participants with or without spatial neglect drew circular shapes with the width shorter than the height, i.e., radially extended ellipses. Apart from right-brain damage, no other variable in the current study predicted shape index, suggesting that drawing a radially extended ellipse to represent a clock may be an independent phenomenon following damage to the right brain.

Collectively considering the results of our study and that of Smith *et al.* (2006), it is possible that the shape distortion we observed is the result of a representational deficit. Smith *et al.* failed to find any systematic distortion in the shape of copied circles, suggesting that when the image was provided, its shape was veridically reproduced. However, when drawing a clock perimeter from memory, we observed that RBD participants produced radially extended ellipses. Therefore, a shape distortion may occur either in the memory itself, or in the process of transferring the memory representation to the page. If the observed shape distortion were the result of a representational deficit, however, it is not quite clear why we would observe this same shape distortion in both neglect and non-neglect RBD participants. Regardless, future work is needed to address the source of the shape distortion that we observed.

Our discussion thus far has focused on aspects of the clock perimeter, but it is widely accepted that neglect patients demonstrate abnormality in producing a clock face (consisting of numbers and hands). However, the focus of evaluating clock drawing in spatial neglect is almost always on lateralized symmetry, ignoring other details (e.g., BIT). One exception is the work of Ishiai *et al.* (1993), who emphasized the spatial relationship between anchor numbers (12, 6, 3, and 9) and found this accuracy measure in clock drawing to be uncorrelated with the severity of spatial neglect. However, spatial neglect is associated with other errors including numbers and hands being clustered, repeatedly produced, omitted, obscured by the intrusion of irrelevant features, placed with numeral values increasing counterclockwise, or transposed from the left to the right side (Chokron *et al.*, 2004; Di Pellegrino, 1995; Lepore, Conson, Grossi, & Trojano, 2003). Using a detailed scoring method (such as those typically used for screening dementia, cognitive decline, and child development), we found that neglect participants made significantly more errors than non-neglect RBD participants and healthy individuals. More importantly, neglect severity was associated with clock-drawing accuracy (total score), which was correlated with all BIT subtests and especially predicted by star cancellation, even when controlling for MMSE. Therefore, accuracy evaluated with a detailed scoring method is sensitive to spatial neglect, and taking the size of clock drawing into account may further increase the sensitivity of this screening assessment for spatial neglect or other diseases (Rouleau, Salmon, Butters, Kennedy, & McGuire, 1992).

To conclude, RBD individuals with spatial neglect do indeed produce smaller clock perimeters than non-neglect RBD and healthy people. Our novel findings on shape distortion in clock drawing after right-brain stroke require further investigation. Our results support the hypothesis that small clock drawings in spatial neglect reflect a reduction in both objective and subjective workspaces. Furthermore, our correlational analyses support the hypothesis that the reduction in the subjectively available workspace for clock drawing is due to the limited ability to enlarge the attentional aperture after right-brain stroke, but this hypothesis requires additional investigation. The present findings also suggest that accuracy measures typically used for screening dementia may be sensitive to neglect-specific deficits.

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Appendix: Scoring Items for Clock-Drawing Accuracy

Modified from Lessig *et al.*'s method (2008), with five items excluded (see detail in 'Method').

(1) Hands present: One or more hands are present.
(2) All numbers present: Each and every number from 1 to 12 is present.
(3) No number repeated: No number appears more than once.
(4) No substitution: No placeholder (e.g., tick mark) other than numbers for representing hours is present.
(5) Number orientation: Numbers are increasing in the normal clockwise fashion.

(6) Number order: The sequence of numbers is accurate. If one number is repeated twice (violating scoring item 3) but next number's order is correct (e.g., 1, 2, 3, 4, 4, 5, . . .), this item is not violated.
(7) All number inside circle: No number overlaps the perimeter or clearly outside the perimeter.
(8) No empty quadrant: No quadrant is empty. Clocks with anchoring numbers only are considered incorrect on this item.
(9) No extra marks inside circle: Within the perimeter, no clock-irrelevant symbol or figure is present.
(10) No number greater than 12: No number greater than 12 (e.g., 13, 14, . . .) is present.
(11) Hands connected: Hands are clearly connected.
(12) Hands radiated from centre: Hands are radiated from the clock centre.
(13) Two hands: The number of hands is two.
(14) One hand longer than the other: One of the two hands (hour and minute) is longer than the other.
(15) No number orientation rotated: Each number is written right-side up as opposed to upside down or rotated.
(16) Number-to-edge distance: The distance between a number to the perimeter is constant.
(17) Equal spacing between numbers: No obvious gap or uneven spacing between numbers.
(18) No military time: The drawing represents a common use of a clock (1–12) instead of military expression (1–24).
(19) Anchoring numbers present: All the four anchoring numbers (12, 3, 6, 9) are present.