Spatial working memory predicts re-cancellation behaviour in neglect

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Abstract

The lateralised bias of spatial neglect can be modulated by concurrent non-lateralised impairments. For instance, people with left neglect may have spatial working memory deficits that prevent them from keeping track of locations visited in visual search tasks such as target cancellation. Not only do they omit targets in some parts of the array but they may revisit and re-cancel targets in other parts, and this re-cancellation behaviour increases dramatically in 'invisible' conditions, in which touching a target leaves no visible trace. It has been proposed that spatial memory deficits are the main reason for the rise of re-cancellation errors in invisible cancellation conditions. This idea predicts that spatial memory abilities should correlate with re-cancellation behaviour; but this expected relationship has never been demonstrated. The present study takes an exploratory approach to describing the behaviour of 18 people with left visual neglect, following right hemisphere stroke, on touchscreen tests of spatial working memory and target cancellation. We show that people with neglect who are less able to remember locations in a spatial memory task tend to make more re-cancellation errors in invisible cancellation conditions. We also describe an apparent trade-off, in which some people with neglect make many more re-cancellation errors, whilst others make many more target omissions. We suggest that the influence of spatial memory deficits on invisible cancellation tasks can be more fully captured by considering both types of errors, rather than re-cancellations only.

Keywords: cancellation; spatial neglect; spatial working memory; visual search.

Introduction

The core symptom of spatial neglect is a bias of attention away from the contralesional side of space and toward the ipsilesional side. Neglect is more common, severe and persistent following right hemisphere damage, so it usually manifests as a bias away from the left and toward the right (Heilman et al., 1993; Vallar, 1993). A common class of test for neglect is target cancellation, in which the person is shown an array of targets on a sheet of paper, and asked to strike each one through with a pen. In touch-screen versions, the requirement is to touch each target once, usually marked by a change or disappearance of the target. Spatial neglect is diagnosed if targets are omitted in an asymmetrical pattern: a person with left neglect would omit targets in leftward parts of the sheet or screen. In addition, people with neglect may make errors of commission, re-visiting and re-cancelling some targets, and even cancelling the same target several times. These re-cancellation errors have been ascribed to a magnetic attraction to targets on the right (Mark et al., 1988), motor perseveration (Gandola et al., 2013; Na et al., 1999; Ronchi et al., 2009, 2012; Rusconi et al., 2002), poor executive planning of search (Olk & Harvey, 2006; Ronchi et al., 2012; Weintraub & Mesulam, 1988), and failures of spatial working memory (Husain & Rorden, 2003).

A pre-eminent role for spatial working memory is suggested by several strands of converging evidence. First, under 'invisible' cancellation conditions in which the targets do not visibly change when cancelled, so that the requirement for spatial memory is heightened, people with neglect re-cancel many more targets (Parton et al., 2006; Wojciulik et al., 2001, 2004). Second, when asked to report whenever they find a new target during visual search, they often misclassify old targets as new, indicating that they do not remember having visited them before (Husain et al., 2001; Malhotra et al., 2004; Mannan et al., 2005). Third, people with left neglect show impairments on tests of spatial working memory, even when these tests do not involve any horizontal lateralisation of stimuli (Malhotra et al., 2004, 2005; Mannan et al., 2005; Pisella et al., 2004). Within the Discussion section of their paper, Parton and colleagues (2006, p. 836) informally reported a correlation between re-cancellations in their invisible cancellation task and performance on a spatial working memory task, for seven people with neglect who had done both tasks (n = 3 from Malhotra et al., 2006; n = 4 from Parton et al., 2006). The correlation was strong (r = -.72),[1] but was based on such a small

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[1] The correlation "between target revisits and spatial memory span" was reported by Parton et al. (2006) as .72 (i.e. positively signed), but given that it was stated in favour of the idea that poor spatial memory leads to re-cancellation, we have presumed that the implied relationship is negative.

sample that it must be highly tentative. The purpose of the present study is to re-examine this correlation, which has not been demonstrated since this early, informal report.

To our knowledge, two subsequent studies have tried to test the same general relationship. Ronchi and colleagues (2009) assessed spatial memory in 14 people with left neglect using different versions of the Corsi blocks assessment for spatial memory (Corsi, 1972), in which the participant must observe and copy a sequence of taps within an array of blocks. This traditional test is unsuitable for people with neglect, because it uses a laterally-extended array of locations, so Ronchi and colleagues included a vertical version with no lateralisation. They found no reliable correlation with re-cancellation errors in paper-and-pencil cancellation tasks (Kendall's $\tau = .05$). However, these authors did not study the elevated rates of re-cancellation elicited by invisible cancellation conditions, in which the theoretical link to spatial memory is strongest. Wansard and colleagues (2014) did use an invisible cancellation condition (one trial, with a touchscreen array of 32 targets, and no time limit) and a different, digitised Corsi-type test of spatial memory. Sequences of targets were shown within a grid that was laterally and vertically extended, and the scoring method was designed to factor out errors related to the left side of space. There was still no reliable correlation with re-cancellation errors in the invisible cancellation task ($\tau = -.15$), although this could be a false negative given that the sample of neglect participants was modest at best ($n = 14$). Considering the theoretical importance of the proposed relationship, it is worth exploring further.

For the measurement of spatial working memory, we took inspiration from a method developed by Malhotra and colleagues (2005), which used a vertical column of locations at the midline of a touch-screen. Their first version of the test followed the traditional Corsi-style observe-and-reproduce structure, but they noted that this involves memory for temporal sequence rather than isolating memory for spatial location. In a second, refined version, the participant had to observe the sequence and then, after a short delay, report whether a single highlighted location had been part of the sequence. This second test was found to discriminate people with neglect very cleanly from brain-damaged and healthy control participants ($n=10$ per group). The authors argued that the impairment exposed by the test was a 'pure' problem of spatial working memory, not working memory in general, because the neglect group performed well in the digit span sub-test of the Wechsler Adult Intelligence Scale, which tests verbal memory for sequences (Wechsler, 1955).

The above method evidently exposes impaired functions in neglect, but the presentation of stimulus locations in sequence is time-consuming, and the yes/no response structure is inefficient; given binary responding, random guessing would be correct on 50% of trials, so many trials are needed to estimate spatial memory ability. Malhotra and colleagues ran 100 trials per participant, 20 at each of five sequence lengths. This lengthy repetitive task makes heavy demands on sustained attention, so its specificity as a test of spatial memory might be questioned. It has long been known that many people with neglect have problems sustaining attention and arousal, and that these non-lateralised impairments shape the expression of their symptoms, for instance increasing cancellation omissions (Husain & Rorden, 2003; Robertson, 1993). In this context, it may not be surprising that scores on the above task correlated with target cancellation omissions in the neglect group (r > .7; Malhotra et al., 2005). In the present study, we follow the columnar arrangement of Malhotra and colleagues' task but aim to estimate spatial memory more efficiently, by changing both the stimulus presentation method and the mode of responding. Following Pisella and colleagues (2004), we added a control task with the same general structure and response requirements as the spatial task, but testing visual memory for colours, which seems like a more relevant comparison task than digit span. We also included invisible cancellation tasks, so that the correlation of theoretical interest, between spatial memory and re-cancellation behaviour, could be assessed. This correlation should follow from the assumption that spatial memory impairments are the major driver of re-cancellation behaviour under invisible cancellation conditions.

Methods

Participants

Clinical participants were recruited from an acute stroke unit in Edinburgh and a neurological rehabilitation unit in Milan. The sample size was determined by the number of suitable participants that could be recruited given the time and resources for the study. Inclusion criteria (*a priori*) were: unilateral right hemisphere stroke, as confirmed by neurological assessment and clinical brain imaging; cognitive capacity to understand and participate in the tests; evidence of visual neglect, operationalised by performance on a line bisection task, and on the visible and invisible conditions of the cancellation task (see procedures below for details). Cut-offs for left neglect were derived from control participants using a one-tailed criterion based on Crawford and Howell's (1998) modified t-formula for case-control comparisons, with an alpha level of .016 to account for the three comparisons made per clinical participant.

Exclusion criteria (*a priori*) were: previous medical history of head injury or stroke; other neurological disease or dementia; psychiatric disorders for which medication had been prescribed; inability to understand the study information and provide informed written consent. One clinical participant was excluded *a posteriori* because they showed disordered engagement with the cancellation task, making a very high number of touches to empty parts of the screen (see below). Table 1 shows demographic and clinical information for the 18 participants in the Neglect group.

Eleven right-handed older adults, with no previous neurological history, were tested as a healthy control group at the University of Edinburgh. This sample size was considered sufficient to define cut-offs for the detection of neglect on the tasks of interest, which was the main role of the Control group. We did not attempt to age-match the control participants precisely to the Neglect group (who had very varied ages, see Table 1), but recruited volunteers within the older adult range from a local participant panel (6 Female, 5 Male, aged 57-78 years).

Materials and procedure

The participant was seated at a table with the touchscreen at a comfortable distance. They performed all tasks with the index finger of the right hand, with the other hand off the table.

The viewing distance was around 50 cm but was not strictly controlled. Neglect participants were tested in a private room at the hospital, and usually completed the tasks across two sessions, but individual tasks were never split across sessions. Control participants completed all tasks in a single session in a laboratory at the University of Edinburgh.

At the Edinburgh sites, participants performed the tasks on a 17” touchscreen monitor (3M™ MicroTouch™; active display area 340 x 270 mm) in an upright orientation. At the Milan site, participants performed the tasks on a slightly smaller tablet laptop (Toshiba Model Portégé M780; active display area 260 mm × 163 mm) laid flat on the table. In this arrangement, the ‘vertical’ axis of the screen lies in the depth dimension with respect to the body, but the head was tilted toward the tablet so that the visual projection was similar. The tasks were executed by custom software written in the LabVIEW programming environment (National Instruments, Emerson). Participants completed the following tasks, in order.

Touchscreen familiarisation (~5 mins)

To familiarise the participant with the touchscreen interface, they were presented with a black screen and invited to touch it at different locations. Each touch resulted in visible feedback in the form of a white circle (slightly larger than the fingertip) and a short high tone. In a first run, the participant was asked to touch the screen 20 times, and the circle remained at each touched location, with the screen clearing after 20 trials. In a second run, the participant was asked to touch the screen 20 times, with each feedback circle disappearing when a new location was touched. The aim was to familiarise the participant with the touchscreen, and with the idea that the persistence of the visual feedback from touches could vary.

Cancellation tasks (~20-25 minutes)

The cancellation array comprised 48 white upright T-shaped targets against a black background. The targets were distributed across the screen within a virtual grid of eight columns and six rows, with one target positioned randomly within each cell. The T-shaped targets were either filled (Figure 1a) or unfilled (Figure 1b), and there were no distractor items. The cancellation condition was either visible, so that the target changed from filled to unfilled (or vice-versa) when touched, or invisible, so that the target did not change. In all cases, a successful touch to a target was registered with a short high tone. The participant was instructed to touch each target once, and to state when they had completed the task. The requirement to touch each target *once and only once* was emphasised. The trial ended when the participant indicated completion, or after 90 seconds had elapsed.

Each participant performed 16 trials, with four in each of the four cancellation conditions, in the following internally-counterbalanced order: Filled-Visible (x2); Unfilled-Visible (x2); Unfilled-Invisible (x2); Filled-Invisible (x4); Unfilled-Invisible (x2); Unfilled-Visible (x2); Filled-Visible (x2). A break was given after the eighth trial, and additionally as required. Note that, in the visible cancellation conditions, the target fill factor created a difference in relative salience between cancelled and uncancelled targets. Cancelled targets became relatively low salience in the Filled-Visible condition, and relatively high salience in the Unfilled-Visible condition. If attraction to salient items on the right is a major cause of re-cancellation behaviour, there should be many more re-cancellation errors in the Unfilled-Visible than in the Filled-Visible condition. This allows us to explore the influence of magnetic attraction to salient targets (cf. Parton et al., 2006).

The dependent measure for the diagnosis of neglect on this task was the Centre-of-Cancellation (CoC) index, which is the mean horizontal coordinate of cancelled targets, expressed as a proportion of the display half-width (Binder et al., 1992; Rorden & Karnath, 2010). The CoC provides a continuous, robust index of neglect, which can be readily extracted from the coordinates of successful touch responses. CoC score ranges from a theoretical minimum of -1 (extreme left bias) to +1 (extreme right bias) with a symmetrical distribution of cancellations giving a score of zero. For instance, a left-neglect participant touching all the targets on the right of the screen, and none on the left, would have a CoC index of around 0.5.

The main dependent measures of experimental interest were the number of first touches to targets, and the total number of touches to targets, which can be re-expressed as the number of target omissions (= number of targets – number of first touches) and the number of re-cancellations (= total number of touches – number of first touches). The analysis also logged but excluded 'misses' (touches to blank parts of the screen) and 'bounces' (re-touches of the same target within 1000 ms). One clinical participant showed very disordered engagement, with 69% of their touches being misses, and was excluded from the study on this basis. One trial for a control participant was excluded from the cancellation analysis because it had been terminated accidentally within 10 seconds.

Spatial and colour working memory tasks (~10-15 minutes)

The memory task was performed at the horizontal midline of a grey screen, to avoid stimulus lateralisation. The array was a vertical column of 17 virtual cells (45 px square), the top and the bottom cells of which were never used, leaving 15 possible active locations. The stimuli were solid dots (20 px diameter), presented in the centre of selected cells.

The basic trial sequence is sketched in Figure 1c. An initial set of dots was presented, accompanied by a short high tone, and the participant was required to memorise the dots and to inform the experimenter when they had done so. The experimenter then pressed a key, and the dots disappeared, leaving a 1500 ms blank interval, after which the dots re-appeared, with one dot added, and the participant was required to touch the new dot. The touch was accompanied by a short high tone, and a white noise screen was shown for two seconds before the next trial began. The participant was instructed to treat each trial as separate from all the others.

In the *spatial memory task*, the dots were black and the participant had to remember their locations. When the dots reappeared, they were in the same locations as before, and the participant had to touch the extra dot that occupied a new location. In the *colour memory task*, the dots were defined by colour, and the participant had to remember their colours. When the dots reappeared, they occupied a newly randomised set of locations, and the participant had to touch the new dot that had a different colour.

The colour memory task was designed to replicate the general demands of the spatial memory task for sustained attention and manual responding, and to control for general (non-spatial) visual memory requirements, and any vertical attention biases. Fifteen possible colours were used, many of which were not easily nameable, to discourage verbal strategies. Before beginning the task, the experimenter informally checked that the participant did not have any form of colour blindness.

In each task, the first five trials were at load level 1, in which there was a single dot in the memorised array (with an extra dot added after the delay). If the participant responded correctly on at least two of the five trials at load level 1, they progressed to level 2, in which there were two dots in the memorised array (with an extra dot added after the delay). Again, if they responded correctly on at least two of the five trials, they progressed to the next load level. The task ended when the participant responded correctly on fewer than two trials at any load level, up to the highest load level 6. The final score for the task was the total number of correct responses, giving a maximum possible score of 30 (five trials at six levels).

Line bisection task (~5 minutes)

A line bisection task was also included to screen for neglect. This was a shortened touchscreen version of the 'endpoint weightings' design of McIntosh and colleagues (2005, 2017), which has been found to be more sensitive to neglect than is the traditional line bisection task and scoring method (McIntosh et al., 2005, 2017; McIntosh & Ishiai, 2022).

The participant placed the right hand on the table in front of the body midline, and the experimenter initiated stimulus presentation. The screen was black and, on each trial, a 2 mm thick white horizontal line appeared at the vertical midline, in one of four configurations created by combining two possible endpoint positions on the left (-40, -80 mm from screen centre) with two possible endpoint positions on the right (40, 80 mm from screen centre). The participant was required to touch the line at its midpoint. The touch was registered by a short high tone, the line disappeared and the participant returned their hand to the start position. Each line configuration appeared once within each epoch of four trials, randomly ordered, and there were six epochs in a block of 24 trials. The block was preceded by two practice trials, with line configurations selected at random.

The scoring of line bisection followed the endpoint weightings method (McIntosh et al., 2005, 2017), to derive an index of asymmetry, the Endpoint Weightings Bias (EWB). A negative EWB indicates a stronger influence of the left endpoint and a positive EWB indicates a stronger influence of the right endpoint.

Data analysis strategy

The sample size of neglect participants tested here is modest (n=18), albeit larger than in previous relevant reports (Parton et al., 2006; Ronchi et al., 2009; Wansard et al., 2014), and so we cannot expect to make a high-powered critical test of the hypothesised association.[2] Moreover, it is not entirely clear which metrics of (invisible) cancellation behaviour are the most relevant for testing the theoretical question at stake (see Results). Thus, although the study is strongly motivated from theory, our analytic approach is exploratory, focusing on the description and estimation of relevant relationships rather than on binary hypothesis-testing.

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[2] A sample of 18 participants with neglect would provide > .75 power to detect a true correlation ≥ .50, using a one-tailed (directional) test.

Results

Cancellation tasks

Figure 2 shows descriptive profiles of touches to targets across space for each group performing in each cancellation condition, conforming to the expected global pattern that the omission of leftward targets by participants with neglect was exacerbated in the invisible cancellation condition, along with a dramatic rise in the number of re-cancellation errors (Parton et al., 2006; Wojciulik et al., 2004). Control participants also made a few re-cancellations in the invisible condition. The patterns were very similar between Filled-Visible and Unfilled-Visible target conditions, suggesting that the influence of magnetic attraction to salient targets was not an important determinant of performance in our task. For brevity, subsequent analyses will be collapsed across the factor of target fill.

The Neglect group mean patterns in Figure 2 should not be taken as representative of the individual patterns of response to the visibility manipulation, which differed quite substantially from participant to participant. Three main types of profile can be distinguished, illustrated by selected examples of individual neglect performance in Figures 3a-3c. Figure 3a shows a participant (NEG08) who made many more omissions in the invisible condition relative to the visible condition, with only a few re-cancellations. Figure 3b shows a participant (NEG09) who made dramatically more re-cancellations, but with little change in the number of omissions. Figure 3c shows a participant (NEG18) with a more intermediate pattern of moderate increases in re-cancellations and omissions. In this particular instance, the invisible condition provoked re-cancellations on the right side, which were accompanied by more omissions on the left side, consistent with a pattern described by previous authors (Wojciulik et al., 2004).

Overall, we can consider each person’s response to the invisible condition in terms of two primary dimensions: how much did omissions increase, and how much did re-cancellations increase? Figure 3d shows a scatterplot that locates each participant in this two-dimensional space (the participants plotted in panels a-c are labelled on this plot for clarity). The distribution of Neglect participants follows a rough L-shape (or banana) such that, when the invisible condition led to a large increase in errors, this tended to manifest *either* as increased omissions *or* as increased re-cancellations: *the Neglect participants that made increased omissions were not generally the same participants that made increased re-cancellations*. A few participants (such as NEG18) showed an intermediate pattern with moderate rises in both types of error, but the Neglect group as a whole showed essentially no correlation between increased omissions and increased re-cancellations (Spearman's ρ = -.00; Kendall's τ = -.05).

These results would be consistent with the adoption of different strategies in the invisible condition, depending on whether the participant prioritises the instruction to cancel all targets, or to cancel each target only once. If the participant prioritises the former, they may adopt a liberal strategy, touching any target unless they are sure they have already visited it, which would tend to limit their omissions at the cost of more re-cancellations. If the participant prioritises the latter, they may adopt a conservative strategy, touching only targets they are sure they have not visited, which would tend to limit re-cancellations at the cost of more omissions. This dynamic would imply that re-cancellations alone may not fully reflect impaired spatial working memory, which could alternatively promote increased omissions. We suggest that a better measure to capture the hypothesised impact of impaired spatial memory might be the sum of the increase in re-cancellations *and* omissions between the visible and invisible conditions; we call this index the total 'Invisibility Cost' (see below).

Spatial and colour working memory tasks

Neglect participants performed more poorly than Control participants in both spatial and colour working memory tasks (Figure 4a). Performances in the two tasks were tightly related in Control participants (r = .85), and more loosely in Neglect participants (r = .58). An overall positive correlation between tasks is consistent with them tapping overlapping resources, related to general memory capacity and attention to the task. However, almost all Control participants (ten of 11) did worse in the colour task than the spatial task, perhaps in part because the colour task required them to ignore the salient but irrelevant spatial locations of the dots (see Figure 1d). By contrast, most Neglect participants (13 of 18) did worse in the spatial task, indicating a differential deficit for memory of locations.

Is spatial memory associated with re-cancellation behaviour

The main question of interest is whether there was an association of impaired spatial memory with increased re-cancellation behaviour. Like Wansard and colleagues (2014), we assessed the association of spatial memory with re-cancellation behaviour in the invisible cancellation condition. We also considered the effect of invisible conditions on cancellation errors more broadly, represented by the total Invisibility Cost, calculated as the summed increase in re-cancellations *and* omissions (relative to the visible condition).

Table 2 shows the association of spatial and colour memory scores with performance in the invisible cancellation condition (re-cancellations, and Total Invisibility Cost), estimated by two non-parametric methods (Spearman's ρ, and Kendall's τ). The magnitude of relationship estimated by Kendall's τ is smaller, but both methods support similar conclusions: there is a reliable, albeit modest, association between spatial memory and re-cancellation errors, which is somewhat stronger when using Invisibility Cost as the metric of re-cancellation behaviour; Figures 4b and 4c show scatterplots of these relationships.

It should also be noted that invisible cancellation performance is numerically more strongly related to spatial memory than to colour memory (Table 2). This is consistent with spatial memory having a specific influence, over and above any general memory and sustained attention factors, which are also tapped by the colour task. Finally, although controls make many fewer errors than Neglect participants, they show broadly similar patterns of relationship between memory and cancellation tasks. This could imply that spatial working memory abilities influence invisible cancellation performance in the healthy state, even though error rates are low. Given the small size of the Control group, it is less clear that these relationships are reliable, and a larger-scale study would be required to substantiate them.

Discussion

It has been known for two decades that people with left neglect, following damage to the right hemisphere, often have impaired spatial working memory (Malhotra et al., 2004, 2005; Mannan et al., 2005; Pisella et al., 2004). This has been one of the most commonly given explanations for their tendency to revisit and re-cancel targets in areas of visual search arrays that they have already explored (Mannan et al., 2005; Parton et al., 2006; Weintraub & Mesulam, 1988; Wojciulik et al., 2001, 2004). In particular, impaired spatial memory is hypothesised to be the main driver of the dramatic increase of re-cancellations under invisible cancellation conditions, in which touching a target leads to no visible change (Parton et al., 2006; Wojciulik et al., 2001, 2004). This account is highly plausible, because avoiding previous targets that are not visually marked would seem to imply spatial memory. However, the expected relationship between re-cancellation errors in invisible cancellation and spatial memory, measured by other means, has not been confirmed by previous authors who have tested for it (Wansard et al., 2014). In the present study, we provide evidence for this expected relationship: people with neglect who were less able to remember previously viewed locations in a spatial memory task also tended to make more re-cancellation errors.

Given the relatively small sizes of the groups in which this correlation has been directly examined ($n = 18$ in the present study; $n = 14$ in Wansard et al., 2014), it is quite likely that one study would detect the correlation whilst another did not, due simply to sampling variability. The correlation estimated by the earlier study (Kendall's $\tau = -.15$) falls well within the confidence limits of the correlation here (Table 2) so the outcomes are not discrepant. Nonetheless, there may be aspects of our design that enhanced the ability to measure the relationships of interest. One is that estimates of re-cancellation rates may be more precise, because we based them upon eight trials of invisible cancellation, rather than the single trial sampled by Wansard and colleagues. Our test of spatial working memory was also more straightforward, and may have facilitated a cleaner estimate of this ability in the presence of neglect. The test had a maximum of thirty trials, and could be completed in under five minutes, so did not place unduly heavy demands on sustained attention (Husain & Rorden, 2003; Robertson, 1993). We confirmed that Neglect participants performed more poorly than controls, with very little overlap, and generally remembered locations less well than colours (cf. Pisella et al., 2004).

However, the observed correlation between spatial memory and re-cancellation errors was arguably still more modest than expected given the close theoretical link proposed between these aspects of behaviour (Spearman's ρ = -.48; Kendall's τ = -.34). One reason for this may be that the invisible cancellation conditions not only elicited more re-cancellation errors but also more omissions, *and the two types of error did not increase in tandem* (see Figure 4). Some people with neglect made dramatically more re-cancellations under invisible than visible conditions, whilst others made many more omissions. A few people showed an intermediate pattern in which both types of errors increased, albeit less dramatically. The pattern is suggestive of a strategic trade-off, akin to the inevitable trade-off between hits and false-alarms for any decision made under uncertainty. If you are uncertain about which targets you have touched, then you might play it safe and be circumspect about touching targets, which will limit re-cancellations at the cost of more omissions, or you might touch targets freely to limit omissions, but at the risk of re-cancellations. Impairments of spatial working memory could provoke mainly re-cancellations *or* omissions, depending on how each person resolves the trade-off. If so, then the total relationship of spatial working memory to cancellation errors would be incompletely reflected by re-cancellations, and we should include any increase of omissions to more fully capture the effects. In support of this, our metric of Invisibility Cost (the summed increase in re-cancellations *and* omissions) was more strongly related to spatial memory score than was the rate of re-cancellations alone (Spearman's ρ = -.63; Kendall's τ = -.45).

This apparent trade-off between re-cancellations and omissions was not anticipated from prior research. On the contrary, Wojciulik and colleagues (2004) reported a strong positive correlation (r = .74) between re-cancellations on the right of the sheet and omissions on the left side. They interpreted this to mean that increased re-exploration of ipsilesional locations exacerbates neglect of the contralesional side. Their interpretation seems reasonable, but the pattern is not present in our data,[3] or at least it is not common (there are perhaps two or three profiles that could be consistent with the dynamic, with NEG18 being the strongest example, illustrated in Figure 3c). One difference between Wojcuilik and colleagues' task and ours is that their search array contained distractor items whereas ours had targets only (similar to Wansard et al., 2014). The presence of distractors increases the attentional demands and may make it harder for people with neglect to 'escape' from the ipsilesional side. These

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[3] In the present dataset, there is no correlation between right-sided re-cancellations and left-sided omissions in the invisible conditions (Spearman's ρ = -.01, Kendall's τ = .02).

considerations highlight the complexity of cancellation tasks, which tap into many cognitive abilities, including spatial, selective, and sustained attention, as well as executive planning of search. The demands will be increased by denser and/or more extensive arrays, and by the presence of distractors. The spatial memory load of invisible cancellation tasks is not simply additive to these demands, but enters into the mix with them.

We have suggested a trade-off between re-cancellations and omissions under invisible cancellation conditions, and that either type of error could arise from problems of spatial working memory, depending on the strategic response to spatial uncertainty. It will be important to replicate these patterns, and it may be interesting to explore possible differences between people who show mainly an increase in re-cancellations or in omissions. There might be differences in cognitive profile, lesion location, or even in personality traits. The present dataset is small, but at the suggestion of an external reviewer, we did some further probing of the Neglect group data, finding hints that increases of re-cancellations and omissions may be associated with slightly different cognitive profiles. Specifically, increases in re-cancellation errors were more strongly related to spatial than to colour memory (Spearman's $\rho = -.47$ and $-.13$ respectively), whilst increases in omission errors correlated well with both (Spearman's $\rho = -.52$ and $-.68$). If this apparent difference is meaningful, it could suggest that re-cancellation errors are a somewhat more *specific* consequence of deficient spatial memory, consistent with the prevailing interpretation of such errors (Mannan et al., 2005; Parton et al., 2006; Weintraub & Mesulam, 1988; Wojciulik et al., 2001, 2004).

The present study, whilst strongly informed by theory and prior literature, is exploratory. We offer convergent evidence that spatial memory impairments contribute to re-cancellation errors, but this is not a critical test of the hypothesis, and nor can our correlational approach test the causal chain that the theory assumes. Furthermore, although our novel spatial memory test is valid at face-value, it requires formal validation and characterisation of test-retest reliability, both in healthy and brain-damaged samples. The ability of this test to distinguish people with neglect from healthy controls is reminiscent of previous results from a conceptually similar method (Malhotra et al., 2005). Some authors have suggested that spatial memory impairments are associated with parietal lobe lesions (Pisella et al., 2004), but our clinical imaging information is insufficient for us to comment on anatomical correlates. Finally, although we used a colour memory version to control for general task demands, and although this task correlated less strongly with re-cancellation behaviour, there is clear overlap between the two memory tasks, and both are likely to be sensitive to some general memory and alertness factors.

Overall, this study provides convergent support for the long-standing idea that spatial memory limitations contribute to re-cancellation errors in neglect, particularly when there are no visible traces on visited targets. A similar relationship may be detectable, albeit with much lower error rates, in healthy samples. There is a possible trade-off between different sorts of error (re-cancellations and omissions) when people are uncertain about which parts of a search space they have explored, and we suggest that the influence of spatial memory deficits on invisible cancellation tasks can be more fully captured by considering both types of errors. In exploring these issues, we introduce a novel test of spatial memory in neglect, adapted from previous research (Malhotra et al., 2005), which seems to be effective and efficient. These developments may aid future investigation of the role of spatial memory impairment in shaping the expression of neglect, and as a neuropsychological symptom in its own right.

Scientific Transparency Statement

DATA: All raw and processed data supporting this research are publicly available: https://osf.io/xa96p/

CODE: All analysis code supporting this research is publicly available: https://osf.io/xa96p/

MATERIALS: All study materials supporting this research are publicly available: https://osf.io/xa96p/

DESIGN: This article reports, for all studies, how the author(s) determined all sample sizes, all data exclusions, all data inclusion and exclusion criteria, and whether inclusion and exclusion criteria were established prior to data analysis.

PRE-REGISTRATION: No part of the study procedures was pre-registered in a time-stamped, institutional registry prior to the research being conducted. No part of the analysis plans was pre-registered in a time-stamped, institutional registry prior to the research being conducted.

For full details, see the *Scientific Transparency Report* in the online version of this article.

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Participant	Sex	Age (years)	Days post stroke	Lesion	Visual Field Deficit	Line bisection EWB	CoC (visible)	CoC (invisible)
NEG01	M	86	13	PCA	LH	**0.69**	**0.398**	**0.599**
NEG02	F	50	19	MCA	-	**0.21**	0.004	**0.035**
NEG03	M	59	27	MCA	-	0.08	0.001	**0.018**
NEG04	M	49	8	MCA	LLQ	**0.20**	0.005	-0.011
NEG05	M	60	10	MCA	-	-0.07	**0.033**	0.011
NEG06	M	78	7	MCA	-	0.02	0.012	**0.029**
NEG07	F	78	6	MCA	-	-0.02	0.011	**0.025**
NEG08	M	42	37	F-T-IC	LH	**0.43**	**0.026**	**0.273**
NEG09	M	49	68	P	-	**0.17**	**0.015**	**0.031**
NEG10	M	61	541	F	LH	**0.48**	**0.219**	**0.317**
NEG11	F	58	203	T-P	-	0.04	**0.018**	**0.074**
NEG12	M	50	84	F-T	LH	**0.48**	**0.039**	**0.049**
NEG13	F	44	183	F-P-T	-	**0.15**	0.008	-0.002
NEG14	M	47	80	F-P	-	0.04	**0.533**	**0.843**
NEG15	M	23	87	P-O	-	**0.37**	0.008	0.000
NEG16	M	61	27	BG	-	**0.15**	**0.021**	**0.027**
NEG17	M	43	699	P-T-O-BG-Th	LLQ	**0.17**	0.009	**0.035**
NEG18	F	56	39	F-P-Ins-BG	-	0.06	**0.125**	**0.348**

Table 1. *Demographic and clinical information for the Neglect participants. NEG01-NEG07 were tested at Edinburgh, NEG08-NEG18 at Milan. Lesion location is as reported for clinical scan (MRI or CT), giving vascular territory (MCA: Middle Cerebral Artery; PCA: Posterior Cerebral Artery; NA = Not Available) or area of lesion (F = Frontal; P = Parietal; T = Temporal; O = Occipital; IC = Internal Capsule; Ins = Insula; BG = Basal Ganglia; Th = Thalamus). Visual fields were assessed by manual confrontation: LH = Left Hemianopia; LLQ = Left Lower Quadratanopia. Participants were included that showed left neglect on the Endpoint Weighting Bias (EWB) index of line bisection (cut-off ≥ 0.14), or the Centre of Cancellation (CoC) index of the visible cancellation task (cut off ≥ 0.013) or the invisible cancellation task (cut off ≥ 0.016). Cut-offs were derived from Control participants using a one-tailed criterion based on Crawford and Howell's (1998) modified t-formula for case-control comparisons, with an adjusted alpha level of .016 to account for the three comparisons made per patient. Bold values indicate left neglect.*

		Neglect group (n = 18)		Control group (n = 11)	
		Spatial memory	Colour memory	Spatial memory	Colour memory
ρ	Re-cancellations	**-.48** [-.80, -.02]	-.16 [-.61, .32]	-.48 [-.97, .25]	-.37 [-.92, .35]
	Invisibility Cost	**-. 63** [-.83, -.26]	-.43 [-.79, .09]	**-.63** [-.94, -.00]	-.39 [-.91, .30]
τ	Re-cancellations	**-34** [-.66, .00]	-.10 [-.44, .24]	-.42 [-.93, .21]	-.29[-.85, .33]
	Invisibility Cost	**-.45** [-.68, .17]	-.30 [-.64, .07]	-.49 [-.89, .08]	-.33 [-.83, .16]

Table 2. *Correlations (with bootstrapped 95% CIs) of spatial and colour memory scores with two measures of performance in the invisible cancellation condition (number of revisits, or total Invisibility Cost), estimated by two non-parametric methods (Spearman's ρ, and Kendall's τ), for Neglect and Control groups separately. Correlations in bold have 95% CIs that do not include zero.*

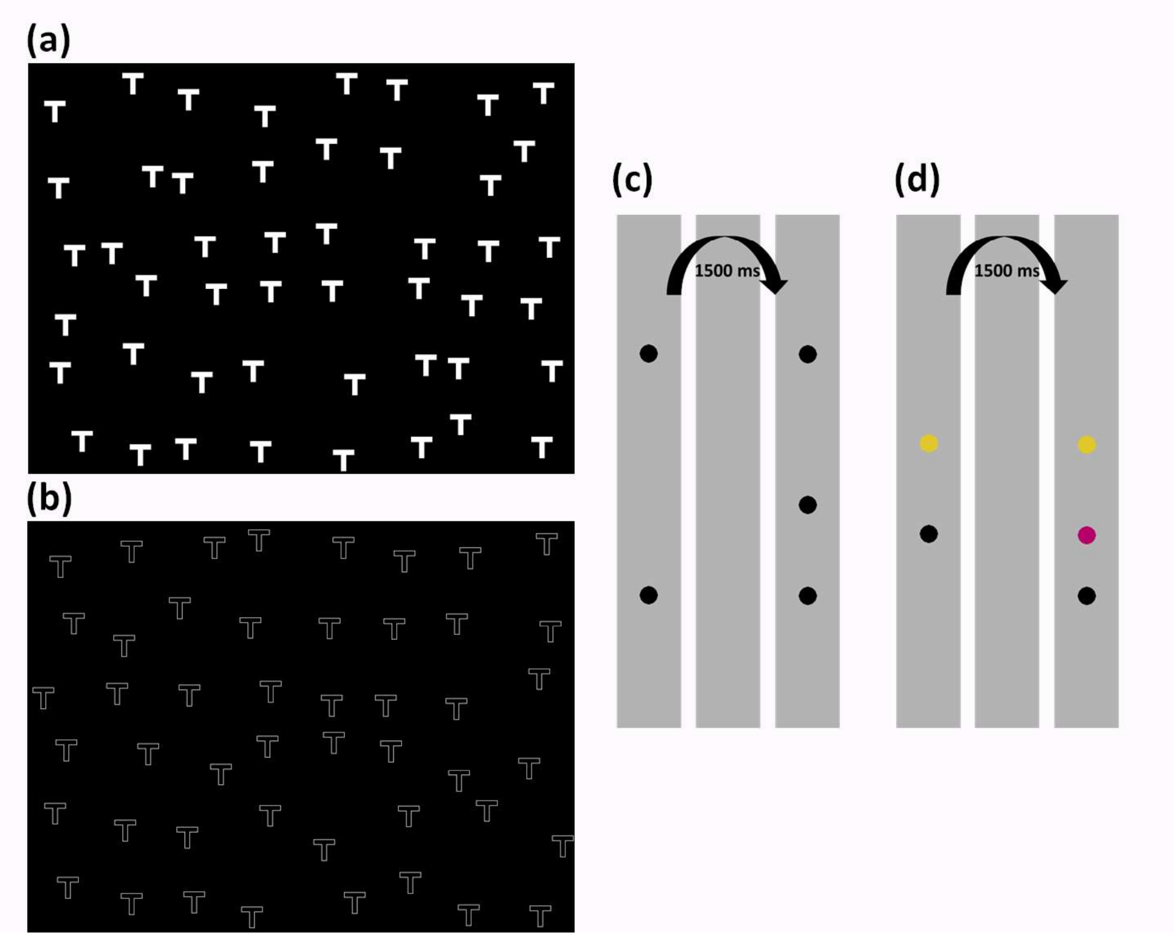


Figure 1. (a) Example cancellation array of filled targets. In the visible cancellation condition, the target would become unfilled (as in panel b) when touched; in the invisible cancellation condition, the target would not change. **(b)** Example cancellation array of unfilled targets. In the visible cancellation condition, the target would become filled (as in panel a) when touched; in the invisible cancellation condition, the target would not change. **(c)** Example of spatial memory trial at load level 2, showing the array before and after a 1500 ms blank interval. The participant is required to touch the dot added at a new position in the second array. **(d)** Example of colour memory trial at load level 2, showing the array before and after a 1500 ms blank interval. The participant is required to touch the dot added with a new colour in the second array.

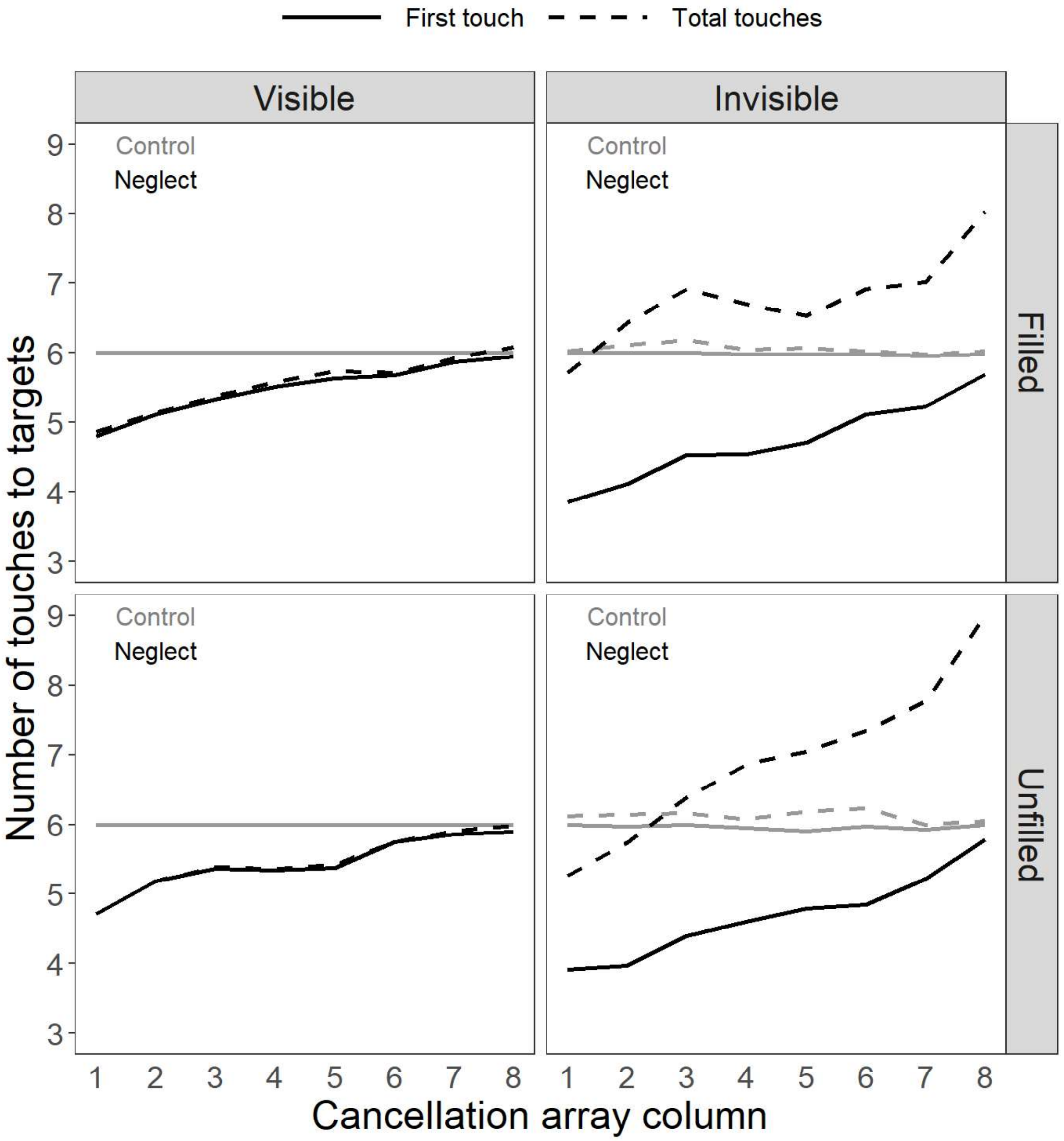


Figure 2. Group average number of first touches (cancellations) and total touches (cancellations + re-cancellations) to targets in each column of the search array (1-8, left to right). There were six targets in each column and Control participants (grey lines) cancelled them all, with a few re-cancellations under invisible conditions. The Neglect group make more omissions toward the left side, and this tendency is exacerbated in the invisible condition. The Neglect group make few re-cancellations in the visible condition (when cancellations are visibly marked), but many re-cancellations in the invisible condition (when they are not). It makes negligible difference to performance whether targets are filled or unfilled. Note that the group mean patterns shown here for Neglect are not necessarily representative of individual level patterns of performance (see Figure 3).

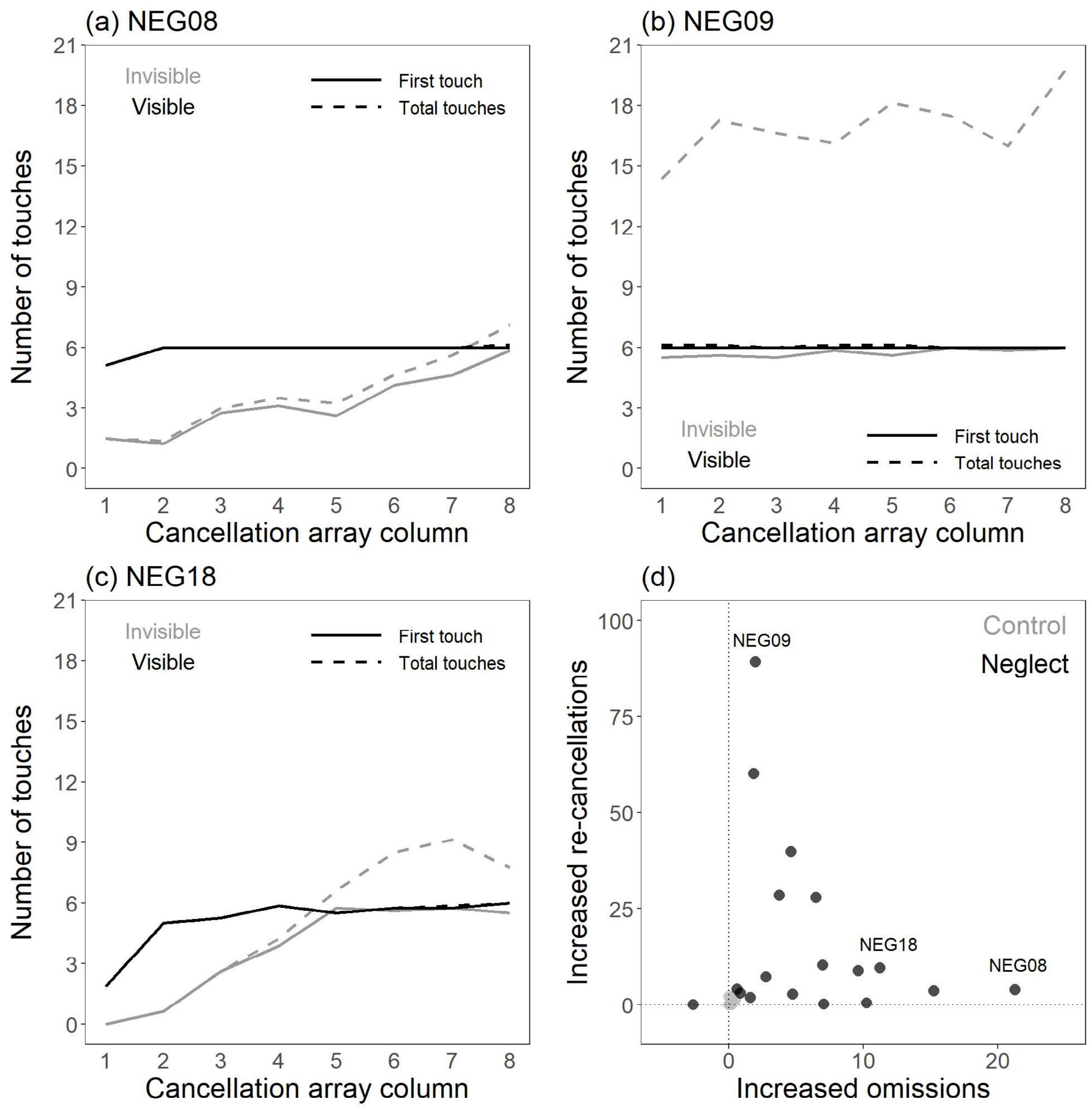
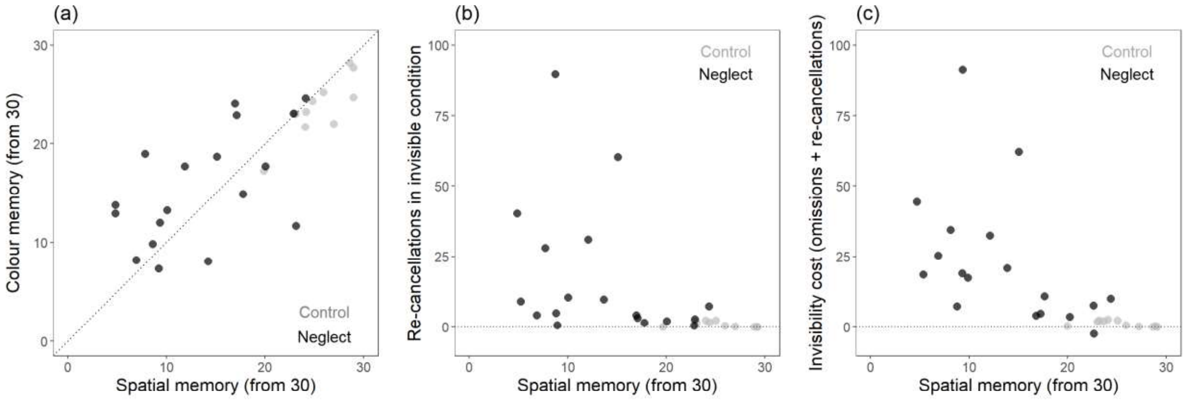


Figure 3. (a) Individual profile for participant NEG08, exemplifying an increase of omission errors in the invisible cancellation condition. **(b)** Individual profile for participant NEG09, exemplifying an increase of re-cancellation errors in the invisible cancellation condition. **(c)** Individual profile for participant NEG18, exemplifying an increase of omission and re-cancellation errors in the invisible cancellation condition. In this instance, the pattern is lateralised so that more re-cancellations on the right are accompanied by more omissions on the left. **(d)** The relationship between increased omissions and increased re-cancellations in the invisible condition. The individual participants from panels (a)-(c) are labelled on this plot for clarity. Neglect data follow a rough L-shaped distribution: individual participants show primarily an increase in omissions (rightward on the x-axis) or re-cancellations (high on the y-axis), with a few moderate intermediate cases. This suggests a trade-off between the two types of error in the invisible condition, which different participants resolve differently (see main text). Any overall measure of the impact of the invisible cancellation manipulation should therefore consider omissions as well as -cancellations.



(a) Working memory score per participant for the spatial memory and colour memory tasks. Neglect participants perform generally worse than Control participants, especially for the spatial task, and the two groups show different patterns of relative performance between the tasks. Most Control participants (10/11) lie below the dotted diagonal, indicating that the colour task is more difficult for them. Neglect participants do not show this pattern, with the majority (13/18) above the diagonal, indicating that the spatial task is the more difficult. **(b)** Neglect participants with lower spatial memory scores tend to make more re-cancellation errors in the invisible condition (Spearman's ρ -.48; Kendall's τ -.34). **(c)** The relationship with spatial memory is stronger if we use the total Invisibility Cost, which is the summed increase of re-cancellations and omissions in the invisible condition (Spearman's ρ -.63; Kendall's τ -.45). See also Table 2.