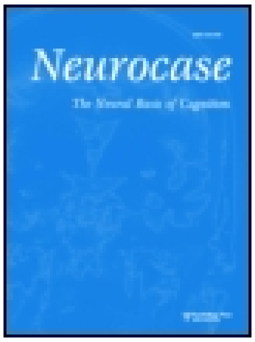

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Neuropsychological evidence for a dissociation in counting and subitizing

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There is a long and ongoing debate about whether subitizing and counting are separable processes. In the present paper we report a single case, MH, who presents with a dissociation in subitizing and counting. MH was spared in his ability to enumerate small numbers accurately along with a marked inability to count larger numbers. We show that non-visual counting was intact and visual counting improved when a motor record of counting could be maintained. Moreover, when larger numbers of items were spatially grouped into 2 subitizable units, performance dramatically improved. However, color grouping did not aid MH's performance, despite his being sensitive to color segmentation. In addition, MH made more re-visits of inspected locations than controls, and he was less aware of a re-visitation being made. The data cannot be explained in terms of general working memory problems (verbal working memory was relatively spared), or general number comprehension problems (e.g., simple sums and counting of auditory items was intact); but they can parsimoniously be accounted for in terms of impaired visuo-spatial memory. The findings support the argument that at least some processes are specific to counting and are not required for subitization – in particular spatial coding and memory for previously inspected locations.

Keywords: Neuropsychology; Enumeration; Subitizing; Counting; Visuo-spatial.

INTRODUCTION

A robust behavioral pattern underlies the enumeration of visual items: smaller numbers of items (up to 4) can be enumerated rapidly and accurately, with relatively minor increases in RT for each additional item (50–80 ms), whereas larger displays are more error prone and take longer to enumerate, with a considerable time cost per extra item (>250 ms) (e.g., Mandler & Shebo, 1982; Trick & Pylyshyn, 1993). The fast and efficient process of enumerating small numbers of items has been called *subitizing* (Kaufman, Lord, Reese, & Volkmann, 1949) while enumerating larger numbers is thought to reflect *counting*. There is a long and ongoing debate about whether subitizing and counting are separable processes.

Reaction times (RTs) to enumerate items can be thought to reflect a continuous, yet nonlinear serial process (Balakrishnan & Ashby, 1991; Gallistel & Gelman, 1992; Vanoeffelen & Vos, 1982). Subitization can then just be thought of as fast serial counting. On the other hand, the behavioral pattern can also be conceptualised in terms of two distinct underlying processes. Mandler and Shebo (1982) suggested that subitizing is a process separate from counting and it involves the recognition of simple patterns (see also Logan & Zbrodoff, 2003; Wolters, Vankempen, & Wijlhuizen, 1987). This view is supported by findings showing that larger numerosities can yield 'subitizing-like' behavior with fast enumeration slopes, provided familiar patterns are presented (Lassaline & Logan, 1993; Palmeri, 1997; Wolters et al., 1987). A further view is that subitizing

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is reliant on a parallel preattentive process which is distinct from pattern recognition but also from the serial process of counting. Trick and Pylyshyn (1993, 1994), for example, have argued that there is parallel indexing of a limited set of locations through FINSTs (Fingers of Instantiation), which, among other things, enable us to keep track of a limited number of objects in the world. This parallel indexing of a small number of items leads to the fast enumeration function for small numbers of items. However, the limitation on the number of FINSTs available (about 4) means that larger numbers require a separate counting process, where FINSTs are in turn removed from one stimulus and reassigned to another. This is slower than the parallel assignment of FINSTs and leads to slow enumeration when larger numbers of items are present.

If subitization and counting are separate processes, then it may be possible to fractionate the processes apart, following selective brain lesions. However, while there have been numerous case reports of enumeration difficulties in brain-lesioned patients (e.g., Cipolotti, Butterworth, & Denes, 1991; Holmes, 1918; Mcfie, Piercy, & Zangwill, 1950; Seron et al., 1991; Warrington & James, 1967), there has been surprisingly little neuropsychological research published on explicit distinctions between subitizing and counting. Cipolotti et al. (1991) reported a single case study on patient C.G., who suffered from damage to the left frontoparietal region. She demonstrated a preserved ability to deal with numbers below 4, while she was completely impaired at dealing with any larger numbers. The precise nature of this deficit, however, was not demonstrated. Dehaene and Cohen (1994) required 5 simultanagnosic patients to enumerate displays of 1–6 items. All 5 demonstrated accurate performance on smaller numerosities (up to 3), while their counting of larger numbers was severely impaired. Dehaene and Cohen proposed that the patients had a problem in keeping track of previously visited spatial locations. However, the study failed to specify whether this was specifically a problem related to visual memory or whether other aspects of counting were impaired (e.g., keeping a running track of items in verbal memory). Also, it may still be the case that performance in the counting range puts particular stress on processes such as keeping a running index of items, so that the dissociation between apparent subitization and counting may reflect a quantitative deficit in a more difficult process rather than a qualitative shift in visual processing mechanisms.

An argument against dissociative processes can also be mounted from the neuropsychological literature. In some patients with bilateral parietal lesions and Balint's syndrome (Balint, 1909) enumeration of even one or two elements can be error prone (Demeyere & Humphreys, 2007; Humphreys, 1998). Lemer, Dehaene, Spelke, and Cohen (2003) reported patient LEC who had a focal lesion of the left parietal lobe, Gerstmann's syndrome, and simultagnosia. LEC presented with a deficiency in subitizing as measured through enumeration times, despite good accuracy. Similar results were found by Ashkenazi, Henik, Ifergane, and Shelef (2008) with patient AD, who presented with a left IPS lesion. Similarly again, Halpern, Clark, Moore, Cross, and Grossman (2007) demonstrated impaired subitizing speed in 16 patients diagnosed with corticobasal degeneration (CBD) (although their accuracy was almost at ceiling). In a task where participants had to match dot displays to Arabic numerals, the CBD group demonstrated significantly larger RTs than a group of patients with frontotemporal dementia as well as a group of healthy age-matched controls, for numerosities lower than 4. Importantly, the CBD patients also required increasingly longer latencies to judge greater magnitudes in this subitizing range. This suggests the CBD patients adopted a 'counting' strategy in the subitizing range. Again, their counting RTs for larger numbers were also impaired. In such cases it remains possible to argue for a deficit in a single counting process, which simply becomes more difficult at larger display magnitudes.

A stronger argument for a qualitative difference between enumerating small and large numbers would come from evidence demonstrating distinct effects of contrasting factors on 'subitizing' and 'counting'. In the present paper we report a single case study of a patient who, like the others noted above, had a spared ability to enumerate small numbers accurately along with a marked inability to count larger numbers (Experiment 1). Unlike other cases, we show that non-visual counting was spared and visual counting improved when a motor record of counting could be maintained. Other experiments explored the factors influencing counting. Performance improved dramatically when larger numbers of items were spatially grouped into 2 subitizable units (Experiment 2) while similar effects did not occur with color-grouping (Experiment 3). This suggests a sensitivity to the load of stimuli on visuo-spatial memory.

Enumeration also improved when MH was forced into a serial counting mode by tapping each item in order to count (Experiment 4), The data cannot be explained in terms of general working memory problems (verbal working memory was relatively spared), or general number comprehension problems (e.g., counting of auditory items and ability to do simple sums was intact). In a final experiment (Experiment 5) we tested MH's search and assessed both whether potential target locations were re-visited and whether MH was aware when this occurred. MH made many more re-visits than controls, while also showing impaired awareness when re-visits took place. We suggest that poor spatial coding and visuo-spatial memory are responsible for the error prone counting behaviour, with these processes being specific to counting. Poor monitoring of search is insufficient to account for the pattern of deficits.

MH: CASE REPORT

MH was 53 years old at the time of testing. He suffered an anoxic incident at age 42, resulting in right side muscle weakness and raised sensory thresholds. He had no problems with walking and could still use both hands. For details of a clinical assessment, see Riddoch et al. (2004). A recent MRI scan (2006) showed disseminated lesions consistent with the anoxic aetiology (see Figure 1). Sub-cortical atrophy was apparent in bilateral lentiform nuclei and the heads of the caudate nuclei. Cortical lesions were evident in bilateral posterior parietal regions, but were more pronounced on the left side (including the occipital-parietal borders, intraparietal sulcus and superior parietal lobe). A smaller lesion was also present in the left middle frontal gyrus.

In a series of standard tests, MH scored full marks on counting tones in the Elevator subtest taken from the Test of Everyday Attention (Robertson et al., 1991). In a verbal test of simple addition, using sums totalling under 20 (e.g., 11 + 5 = ??), MH demonstrated perfect accuracy. He had a Forward digit span of 5 and a Backward digit span of 4. In a cancellation test designed to detect visual neglect, MH showed no spatial asymmetry across the page, cancelling 47/50 of the targets present. On the Corsi block tapping test (Corsi, 1972), MH presented with a very poor visuo-spatial memory span of 2. In order to measure his spatial tagging and spatial memory performance, we also administered an 'Invisible star Cancellation' test (Wojciulik, Husain, Clarke, & Driver, 2001), in which a piece of carbon paper and a blank sheet were attached to the back of the star cancellation task from the Behavioral Inattention Test (Wilson et al., 1987), and responses are made with the back of a pen (leaving no visible mark – marks are assessed on the blank paper underneath the carbon paper). MH again showed a low asymmetry neglect score (–4: omitting 4 stars on the left side of the page – ipsilesional to the main site of cortical damage), but the invisible version did result in a very high score for re-visitations (22 out of the 46 stars cancelled, asymmetry score: –6). Two age matched controls performed the same task and revisited 4 and 1 cancellation, respectively. In a span version of the moving object tracking task (Pylyshyn & Storm, 1989), MH was able to track on average about 1.5 moving objects. Five age-matched controls scored a mean of 3.5 tracked objects (*SD* = 0.25) (Hulleman & Humphreys, 2009).

EXPERIMENT 1: BASIC VISUAL ENUMERATION OF RANDOM DOT PATTERNS

In this experiment, we assessed MH's performance on visual enumeration of randomly placed dots. We also tested 8 healthy participants (average age 64.6, *SD* = 6.1) on the same task to assess normal control performance levels and two unilateral parietal patients. These patients were 72 and 52 years old. One had damage to left inferior parietal cortex and one to right inferior parietal cortex. Unlike MH, who did not present with symptoms of spatial neglect, both unilateral parietal patients had some aspects of neglect. One (right parietal) missed stimuli on the left in cancellation tasks; the other patient (patient RH; Kitadono & Humphreys, 2007) missed left side letters in reading and with shorter stimulus presentation.

Method

This experiment was programmed and run using E-prime 1.1 software (Schneider, Eschman, & Zuccolotto, 2002). The displays were presented on a black background on a 17-inch monitor with 1024 × 768 pixel screen resolution. Each participant was positioned approximately 65 cm from the screen. The stimuli consisted of 1–9 grey dots (RGB: 190,190,190), which were drawn randomly within the centre 500 × 500 pixels of the screen

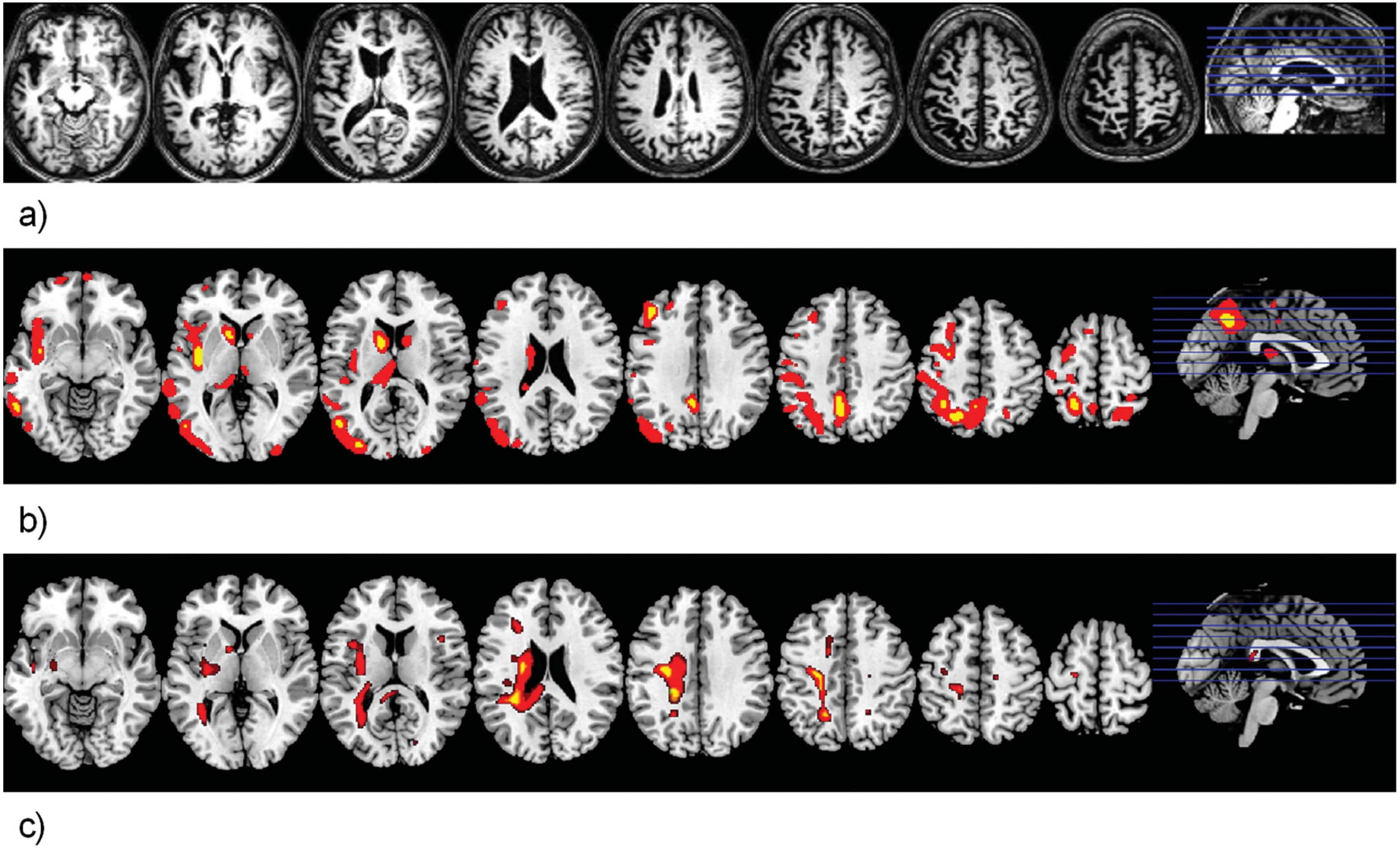

Figure 1. (a) Original normalized T1 image. (b) Grey matter lesion created in SPM5 (http://www.fil.ion.ucl.ac.uk/spm/software/SPM5) and added as an overlay on to a standard multi-slice template in MRIcron. T1-weighted images were segmented in grey matter, white matter, and cerebro-spinal fluid (CSF), and the resulting tissue classes images were normalized without modulation (i.e., to compensate for the effect of spatial normalization). Images were smoothed with a Gaussian kernel of 2 × 2 × 2 mm. SPM stats: one sample t-test with 3 covariates: healthy grey matter (201 brains aged 40+) vs. patient grey matter, age & sex. Red areas denote uncorrected significant results, yellow areas are FWE corrected with $p = .05$ and an extent threshold specifying that only significant blobs containing ≥40 voxels be included in the lesion. (c) White matter lesion created in SPM 5, using identical method, with segmented white matter instead of grey matter.

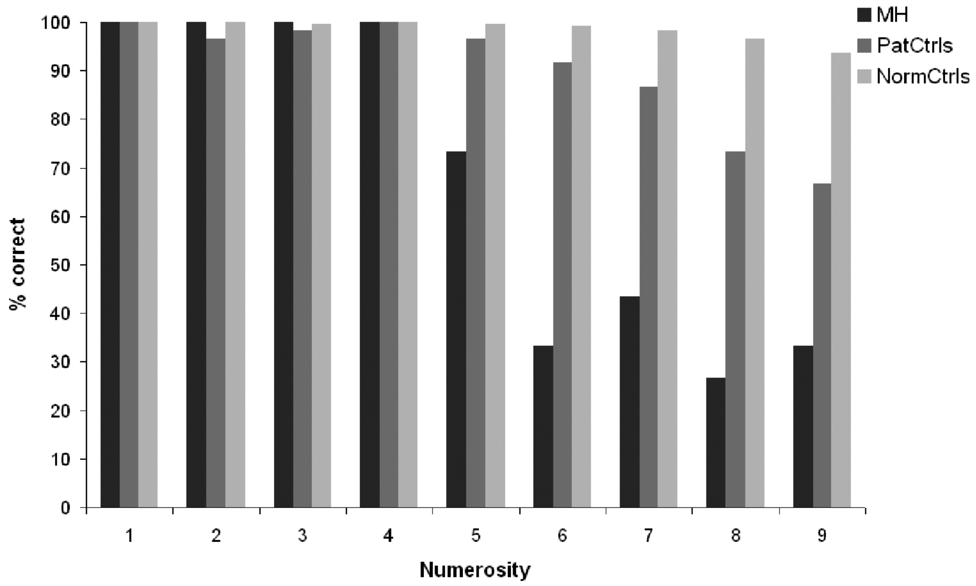

Figure 2. Performance on counting randomly positioned dots, accuracy scores for MH and the average score of 2 unilateral parietal patients and 8 healthy controls.

(14.4° visual angle). The dots had a diameter of 25 pixels (1.4° visual angle) and any two dots were separated from each other by a minimum distance of one dot diameter.

One trial started with the presentation of a fixation cross in the centre of the screen for a duration of 1000 ms. Next, the dot display appeared and remained on the screen for an unlimited duration until a response was made. Participants were instructed to enumerate the dots in this display as accurately and quickly as possible. As soon as they felt they knew the correct response, they had to press the space bar and simultaneously spoke their response. When the spacebar was hit, the dot display disappeared and was followed by a blank screen, where the experimenter entered the reported number using the numeric key pad (for a similar method, see Atkinson, Campbell, & Francis, 1976; Watson & Humphreys, 1999; Watson & Maylor, 2006). Accuracy and reaction times (RTs) were recorded.

Both MH and the control participants completed 6 blocks in one session, with each block containing 45 randomly ordered trials (5 per numerosity). This resulted in a total of 30 trials per numerosity (1–9).

Results

Across numerosities 1–4 MH made no errors in enumeration (Figure 2). His performance fell within 2 standard deviations of the average of the healthy controls (mean control = 99.9% correct, *SD* = 0.3), and did not differ from the patient controls (p = .249, Fisher's Exact Test relative to the worst of the two unilateral patients who scored 99.2 and 98.3% correct, respectively).

In contrast, across the counting range[1] MH enumerated only 44.2% of the trials correctly. This clearly fell outside of the normal control range (mean = 98.4, *SD* = 1.3), and was also significantly worse than the poorest performance of the two patient controls (p < .001, Fisher's Exact Test – average 89.2 and 85% correct). The errors MH made ranged from overestimating by 1 cardinality to underestimating by 3. The errors were mainly underestimations (95.4% of errors), and of those the majority were underestimations of only 1 cardinality (74.7%).

In order to assess enumeration times (see Figure 3), we calculated RT slopes across the subitizing and counting ranges using linear regression, with numerosity as the independent factor. Inspection of MH's RTs suggested a discontinuation at numerosity 4, therefore we will consider the subitizing range to be numerosities 1–3 and the counting range 5–8.

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[1] The counting range was considered to involve the numbers 5–8 here, since we used a maximum 9-item display and responses to 9 items may be affected by guessing (following previous enumeration studies (e.g., Trick & Pylyshyn, 1993).

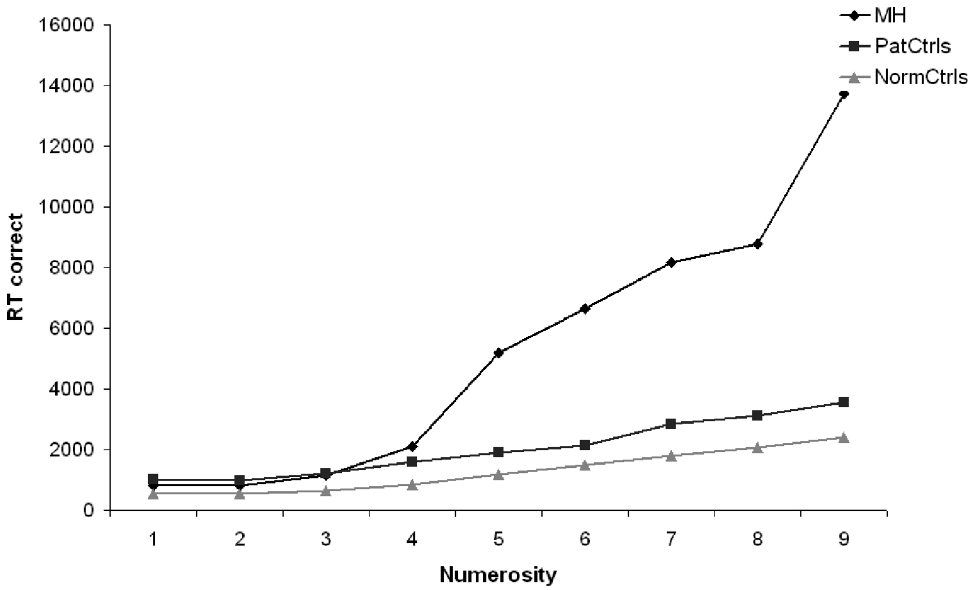

Figure 3. Correct RTs (ms) for MH and the mean of the two parietal control patients as well as the average of 8 healthy control participants as a function of the numerosity presented.

For the subitizing range, MH had an RT slope of 178.6 ms per item, which fell outside 2 standard deviations (*SD* = 32.22) of the average slope for the controls (mean = 35.20 ms per item). It was however similar to the slopes of the patient controls (150.8 and 276.25[2] ms per item). We compared MH's RTs to those of the worst control for correct responses to numerosities 2 and 3 in a univariate analysis (we treated the trials as subjects). There was no reliable difference between the two patients, $F(1, 109) = 1.139$, $p = .288$. And no interaction between the patients and the actual numerosity, $F(1, 109) = 0.748$, $p = .389$.

For the counting range (5–8), MH's RT slope (781.49 ms per item) again fell outside of the normal control range (mean = 263.64 ms per item, *SD* = 115.05), as well as being steeper than the patient control slopes (504.7 and 363.6 ms per item). We compared MH's RTs to those of the worst control for correct responses to numerosities 5,6,7,8 in a univariate analysis (we treated the trials as subjects). There was a significant difference between the two patients, $F(1, 140) = 230.950$, $p < .001$, as well as an interaction between the patients and the numerosity, $F(3, 140) = 3.623$, $p = .015$, indicating the steeper slope for MH compared to the control patient.

Although for both the subitizing and counting ranges MH showed significant RT increases per extra item enumerated, the extra cost per item on the counting range was considerably larger than on the subitizing range (178.6 vs. 781.49, respectively). This was validated by a univariate analysis (we treated the trials as subjects) on RTs with two factors: Size (small (sizes 1–3) vs. large (sizes 5–7) numbers) and Numerosity (items 1–3 vs. 5–7). We found significant main effects of Size, $F(1, 129) = 158.613$, $p < .001$ and Numerosity, $F(2, 129) = 7.753$, $p < .001$. There was also a significant interaction between size (large or small numbers) and numerosity, $F(2, 129) = 5.067$, $p = .001$, confirming the steeper slope for counting than for subitizing. The controls also showed a distinct dog leg function, in a similar analysis, with a significant interaction between numerosity and size, $F(2, 14) = 22.483$, $p < .001$.

Discussion

MH demonstrated a strikingly impaired ability to enumerate accurately in the counting range (>4), with fewer than half of the trials for these larger numerosities being enumerated correctly. In addition, when

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[2] This slope was calculated on numerosities 2 and 3 only due to this patient demonstrating unreliable RTs for numerosity 1 (*SD* = 400.29) compared to numerosities 2 (*SD* = 165.18) and 3 (*SD* = 248.52). This was corroborated by Levene's test of homogeneity of variance in a comparison of numerosities 1–3, $F(2, 82) = 4.194$, $p = .018$.

his response was correct, MH was very slow, and demonstrated considerably higher RT costs than normal as a function of each item that needed to be enumerated. In contrast, his enumeration performance on the smaller numerosities in the subitizing range was flawless. And although his RT slope in the subitizing range was somewhat steeper than that of controls, it was similar to the two unilateral parietal patient controls, in line with an overall slowing of RTs after brain damage. Importantly however, the cost per item in the subitizing range was considerably lower compared to when MH correctly enumerated in the counting range, consistent with a qualitative shift in performance for small versus large displays. For the counting performance, MH demonstrated a larger cost per item both compared to the healthy controls as compared to the patient controls, suggesting a deficit over and above general slowing of RTs after brain damage.

Since MH had no problem enumerating auditory items (see Case Report), and since he was still above chance in the counting range, his impaired counting performance cannot be explained in terms of poor number comprehension or in terms of other processes that could selectively affect counting (e.g., the keeping track of larger numbers). Rather, the data point to a problem that is specific to when MH has to assimilate larger numbers of visual elements. One critical factor here might be an impairment in visuo-spatial short-term memory. MH's performance on the Corsi block task was poor, as was his ability to track moving items, and both of these may reflect a limitation in visuo-spatial short-term memory. In Experiment 2, we manipulated the locations of the random dots in order to lower the load on visuo-spatial memory. Would this facilitate counting?

EXPERIMENT 2: VISUAL ENUMERATION OF ITEMS IN 2 SPATIALLY DEFINED SUB-UNITS

In this experiment, the displays were split up in a lower an upper visual field, each containing subitizable numbers of dots.

Method

The experimental set-up and procedure was identical to Experiment 1, except for the lay-out of the random dots on the display. Rather than randomly positioned across the entire display, the display contained 2 invisible rectangles (size 512 × 200 pixel – 14.5 × 5.7° visual angle). These were separated along the vertical axis by 4.8° (168 pixel), with equal distances from the top and bottom of the screen, and centered horizontally, with equal distances to the sides of the screen. This subdivision allowed for a manipulation of spatial grouping: the dots were drawn in the upper and/or lower visual field. A further manipulation to ensure that no more than 2 spatial groups would occur by chance, was to draw the dots (within a group) equidistant from each other. This was done by starting from a centre location, and then selecting a random location on a 85-pixel (2.5°) radius. The next location was subsequently determined on a random angle from the last one (again fixed distance of 2.5°), and so on until all dot locations were determined. There were imposed constraints to ensure dots would not overlap or fall within 75 pixel (2.2°) distance from any of the previously chosen locations, and all locations stayed within the predetermined area (upper or lower field).

There were 7 numerosities (2–8) × 2 grouping conditions. The dots could either all fall within the upper or lower visual field, or they could be split in subitizable units (≤4) over the two areas. For examples of the displays used, see Figure 4. The instructions and procedure were the same as in Experiment 1. Only MH completed this experiment across 2 sessions (with a 1-week interval). There were 4 blocks in one session, with each block containing 56 randomly ordered trials. This entailed 4 trials per numerosity in the split-field condition and 2 trials per numerosity where all dots were in the lower half and 2 trials in the upper half condition (4 per numerosity). This resulted in

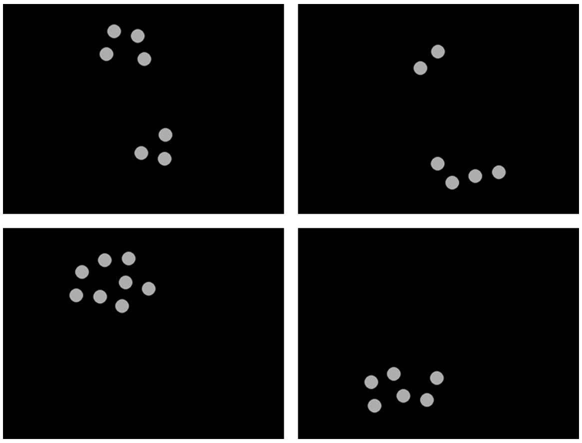

Figure 4. Examples of the stimuli used in Experiment 2, where the numerosities were presented either divided over 2 visual fields (top), or all within one visual field (bottom).

a total of 32 trials per numerosity (2–8) per condition (split-field or grouped).

Results

As in Experiment 1, MH's accuracy was perfect for enumerating numerosities up to 4, both in the split-field and grouped conditions (see Figure 5). However, when there were more than 4 dots present, and all of the items were presented together in either the top or bottom visual field, we replicated the results from Experiment 1, with MH responding correctly on fewer than half the trials (mean % correct = 46.9), there was no reliable difference between his performance here compared to in Experiment 1, when all the dots were spaced out over the visual field (p = .468, Fisher's exact test). However, when the dots were presented in two subitizable units in two separate visual fields, his accuracy dramatically increased (mean % correct = 75), this difference was significant (p < .001, Fisher's exact test). Even though MH's accuracy was not perfect in this split-field condition, it is important to note that all the trials where MH made an incorrect response contained a subgroup of 4 items in one of the fields. The data on enumeration times in Experiment 1 indicated that MH's subitizing limit was nearer to 3 than 4 (see Figure 3, Experiment 1). In the trials which contained fewer than 4 items in the subgroups, MH's accuracy was 100%.

The errors MH made ranged from overestimating by 2 items to underestimating by 2. For the grouped condition, 58.8% of errors were underestimations, while for the split-field condition underestimations comprised 84.4% of errors made.

RTs for MH's correct responses are presented in Figure 6. RT slopes for the subitizing range (2–3) were 171 and 233 ms per item for the one field and split-field conditions; slopes for the counting range (5–8) were 1712 and 859 ms per item for the one field and split-field conditions, respectively. A between-subjects analysis was conducted on the raw RTs for correct responses, with the factors being Spatial grouping (1 vs. 2 visual fields), Size (Small vs. Large) and Numerosities (2,3–5,6). There were overall significant effects of Spatial grouping, $F(1, 213) = 19.914$, $p < .001$, with faster response times in the split-field condition, effects of Size, $F(1, 213) = 191.214$, $p < .001$, with responses to small magnitudes faster than to larger magnitudes and effects of Numerosity, $F(1, 213) = 9.875$, $p = .002$. In addition, the interaction between Spatial grouping condition and Size, $F(1, 213) = 24.515$, $p < .001$, was significant. There were no other reliable interactions.

When we considered numerosities up to 4, where MH demonstrated perfect accuracy, we also found faster RTs for split-field numerosities than for grouped dot displays, $F(1, 186) = 5.967$, $p = .016$, as well as an effect of numerosity, $F(2, 186) = 45.447$, $p < .001$. There was also a significant

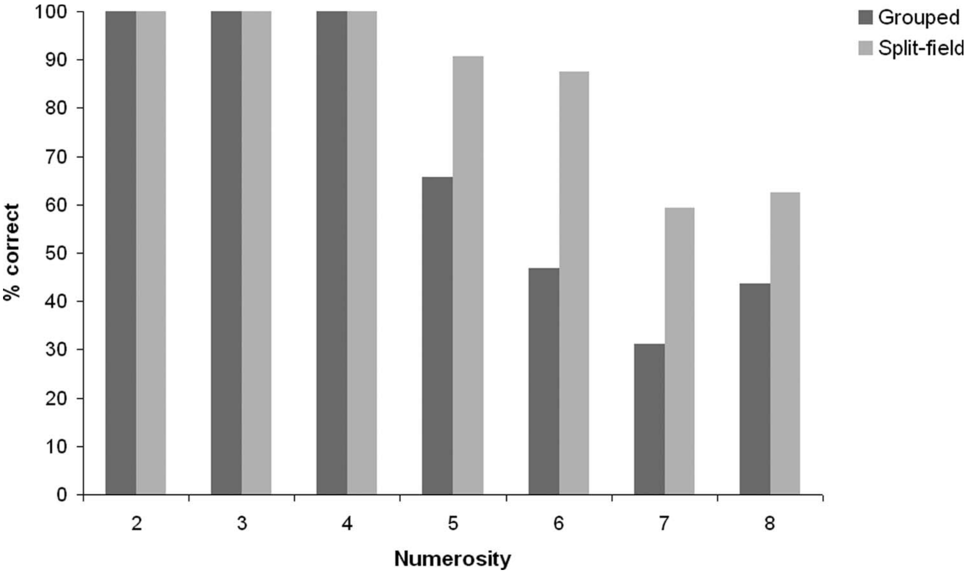

Figure 5. MH's performance when enumerating randomly positioned dots, placed either together in one visual field, or split over two visual fields in subitizable units.

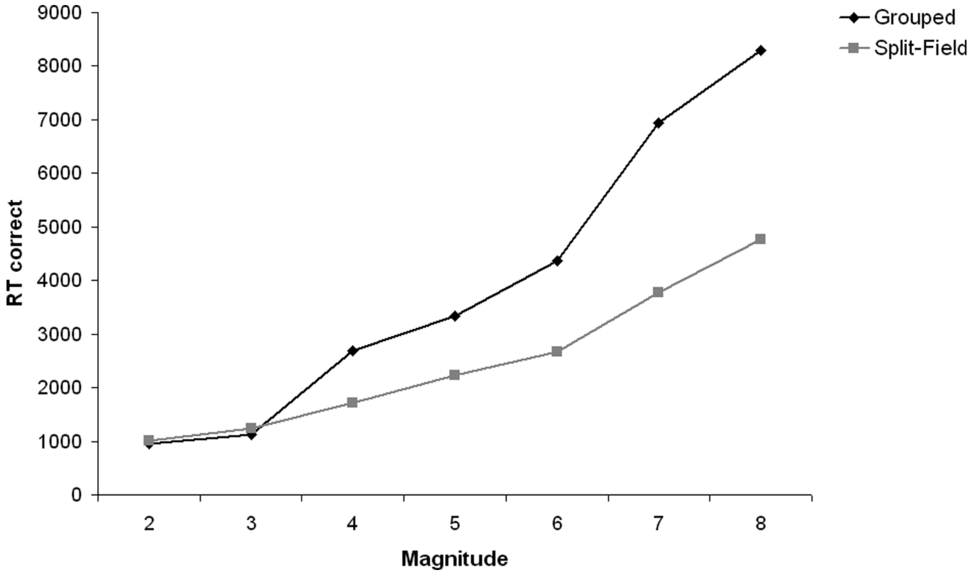

Figure 6. Correct RTs (ms) for MH, when correctly enumerating dots, either in 2 visual fields or grouped in the top or bottom part of the screen.

interaction between the condition and the numerosity, *F*(2, 186) = 9.6, $p < .001$. However, with numerosities 2 and 3, we found only a significant effect of the numerosity, *F*(1, 124) = 6.546, $p = .012$, but no significant effect of the spatial grouping, *F*(1, 124) = .851, $p = .358$, and no interaction, *F*(1, 124) = .152, $p = .697$. This demonstrates that grouping into two spatially distinctive units makes no difference in the speed to enumerate small numbers up to 3, but does help deliver a faster performance on displays of 4 dots and over. In other words, enumerating 4 dots in one visual field was harder for MH than enumerating 2 groups of 2 dots or a group of 3 dots with an extra separately placed dot. This confirms our initial analysis where we considered the limit of MH's subitizing range to be 3 rather than 4 items.

A final comparison was made between the grouped (one field) condition and the original first experiment (where items covered both fields, as in the split field condition here). This revealed no reliable difference in RTs, *F*(1, 259) = 1.033, $p = .310$, demonstrating that the beneficial effect of splitting the display into subitizable groups cannot be accounted for by the wider spacing of the items.

Discussion

We replicated the results from Experiment 1, with MH demonstrating perfect performance across the subitizing range in contrast to him being seriously impaired at counting. This experiment also demonstrated that when the numerosities were spatially grouped into two subitizable units, MH's performance improved dramatically in the counting range. Even though MH's accuracy was not perfect in this split-field condition, he was both significantly more accurate and faster when the display consisted of two subitizable patterns compared to when all the dots were presented grouped closely together in one part of the display. Furthermore, when only considering displays containing subgroups of fewer than 4 elements, MH's counting performance was error-free. We found no differences in performance (accuracy or RT) between the closely grouped condition in one visual field and the performance in Experiment 1, demonstrating that this is not just an effect of average spacing of the elements.

EXPERIMENT 3A: VISUAL ENUMERATION OF ITEMS IN 2 COLOR-DEFINED SUB-UNITS

In Experiment 3a we assessed whether the advantage of grouping the display into subitizable units (Experiment 2) depended specifically on spatial grouping, or whether grouping by another feature (i.e., color) resulted in the same improvement.

Method

The experimental set-up and procedure was identical to Experiment 1, except for the coloring of the dots in the display. There were 2 conditions: a heterogeneous condition, where there were two groups of dots: green (RGB: 0, 128, 0) and red (RGB: 255, 0, 0), and a homogeneous condition, where the dots were all colored in the same color (red or green). In the heterogeneous condition, the numbers of red and green dots were always subitizable units, e.g., 4 and 2 to make 6. The colors were assigned at random, so that the items did not form spatial groups of separate colors. Examples of the displays used can be found in Figure 7.

The instructions and procedure were the same as in Experiment 1. MH completed this experiment across 2 sessions (with a 1-week interval). There were 4 blocks in one session, with each block containing 56 randomly ordered trials. This entailed 4 trials per numerosity in the heterogeneous condition and 2 trials per numerosity where all dots were green and 2 trials where they were red. This resulted in a total of 32 trials per numerosity (2–8) per condition (heterogeneous or homogeneous).

Results

As in Experiment 1 and 2, MH's accuracy was near perfect for enumerating numerosities up to 4, both with heterogeneous colors (only 1 error on a display of 4 elements) and in the homogeneous color condition (see Figure 8). When there were more than 4 dots present, and the dots were all in one color (either red or green), MH responded correctly on just over half of the trials (mean % correct = 54.9). When the dots were presented in two subitizable units in two different colors, he responded correctly on 58.6% of the trials. The difference between the heterogeneous and homogeneous displays was not statistically significant (p = .529, Fisher's Exact test).

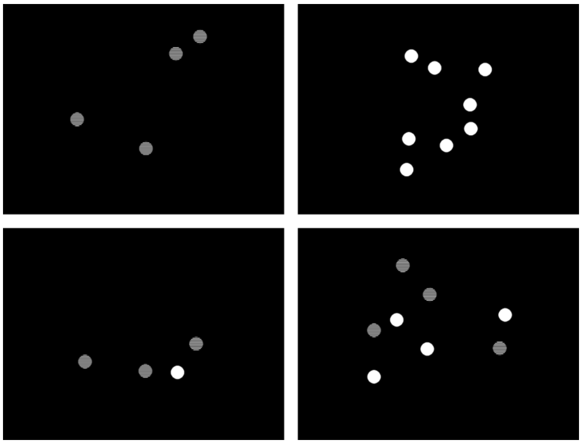

Figure 7. Examples of the stimuli used in Experiment 3a, where the numerosities were presented in 2 subitizable units (defined by color), or in homogeneous displays of 1 color.

The errors MH made ranged from overestimating by 2 items to underestimating by 2. For the homogeneous color condition, 71.7% of errors were underestimations, while for the 2 color condition this was 83% of the errors made.

The mean RTs for MH's correct responses are presented in Figure 9. RT slopes for the subitizing range (2–3) were 354 and 388 ms per item for the homogenous and heterogenous conditions, respectively; slopes for the counting range (5–8) were 1496 and 1485 ms per item for the homogenous and heterogenous conditions, respectively. The raw RTs for correct trials were entered into a between-subjects ANOVA with the factors being Color grouping (1 vs. 2 colors), Size (small vs. large) and Numerosity (2,3–5,6). There was no reliable effect of color grouping, $F(1, 205) = 2.480$, $p = .117$. There was only an overall significant effect of size, $F(1, 205) = 178.079$, $p < .001$.

Discussion

We found no advantage for splitting the numerosities into subitizable units defined by color. This indicates that MH was unable to use color segmentation as a means to group the elements into subitizable units. In contrast to this result, Riddoch et al. (2004) reported that MH had a good ability to detect a target defined by a local color difference relative to the background. Hence, MH does not have a problem in color segmentation per se, but he does when he has to use color to guide enumeration. The data suggest that spatial grouping still dominates, and overrides any color effects. This is consistent with the argument that subitizing and counting are inherently spatial processes, operating on a map of stimulus locations (Watson & Maylor, 2006).

EXPERIMENT 3B: EFFECTS OF COLOR AND SPATIAL GROUPING ON VISUAL ENUMERATION

Experiment 3b tested whether there were beneficial effects of color segmentation on counting, but

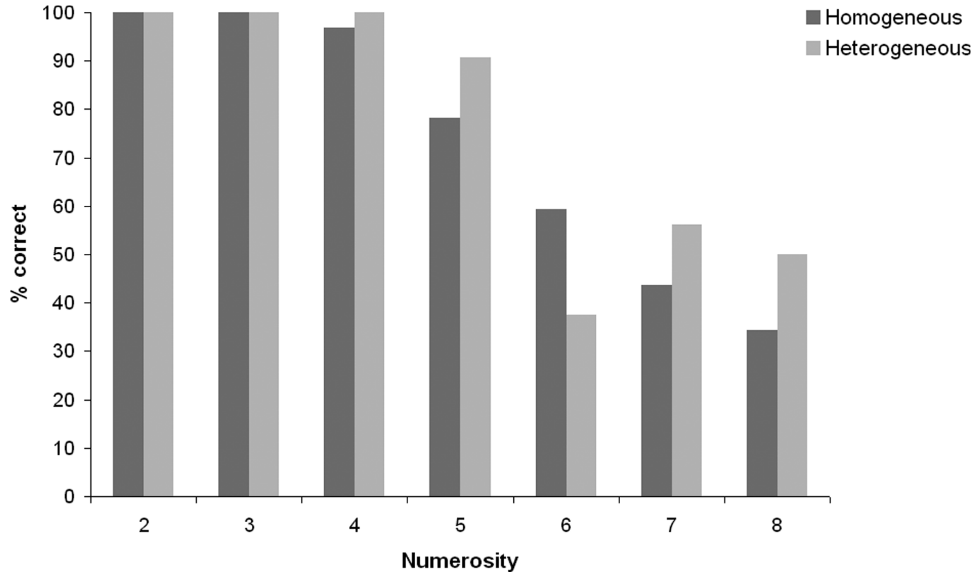

Figure 8. Accuracy when enumerating displays made up of randomly positioned green or red dots, versus randomly positioned mixed green and red dots.

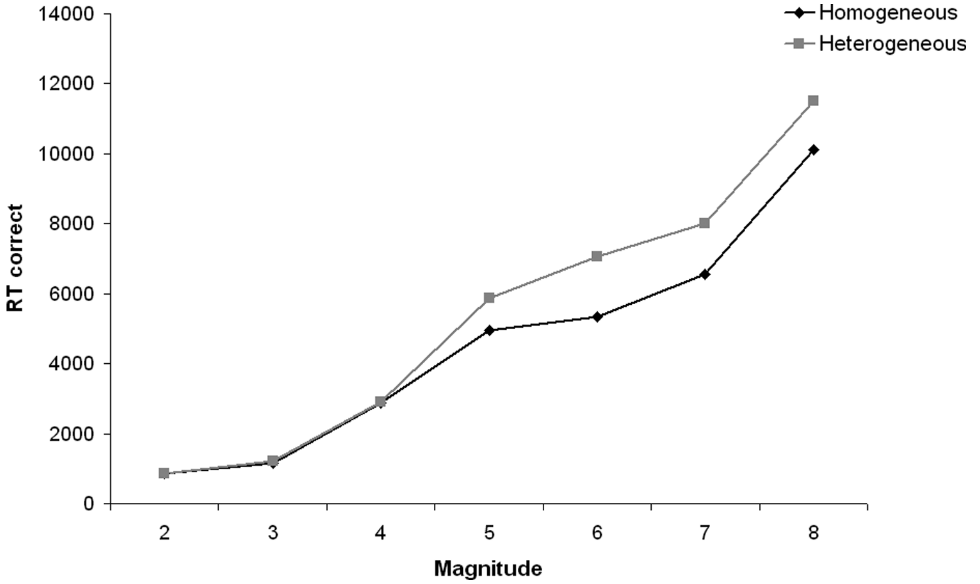

Figure 9. Correct RTs (ms) when MH enumerated displays of green or red dots, versus mixed green and red dots.

when the colors were spatially segregated so that different spatial groups could be formed.

Method

In this experiment, we manipulated spatial grouping between the color groups. There were always 2 subitizable color groups, and this time the spacing between the elements was held constant, so as to control for the accidental spatial grouping that could have occurred in Experiment 3a. The dots were positioned equidistant (see Method Experiment 2) in the centre of the screen (500 × 500 pixel area – 14.4° visual angle). The total number of dots in a display always consisted of 2 subitizable color sub-groups (red and green – see Experiment 3a). This time either the color groups also

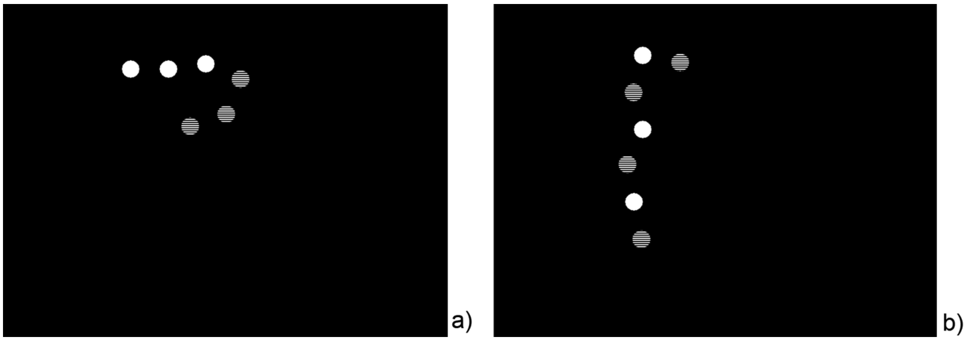

Figure 10. Examples of displays in Experiment 3b.

formed spatial groups (Figure 10a), or the colors were interleaved, therefore disrupting spatial grouping of the two color groups (Figure 10b).

Results

As before, MH's accuracy was near perfect for enumerating numerosities up to 4, in both conditions (1 error on numerosity 4) (see Figure 11). When there were more than 4 dots present, and the color groups formed spatial groups, MH responded correctly on 89.6% of the trials. However, when the colors were interleaved and did not form spatially defined subgroups, performance dropped to 65.6% correct. This difference proved statistically significant ($p < .001$, Fisher's Exact test). There was no difference in accuracy between MHs performance in the interleaved and hetereogeneous conditions in Experiment 3a (where there was no equal spacing between the elements) ($p = .332$, Fisher's Exact test).

The errors MH made in this experiment ranged from overestimating by 1 item to underestimating by 2. In the color grouped condition, 70% of errors were underestimations, while for the color interleaved condition underestimations comprised 82.4% of the errors made.

RTs when MH responded correctly are presented in Figure 12. RT slopes for the subitizing range (2–3) were 296 and 274 ms per item for the spatially and color grouped vs. color grouped only

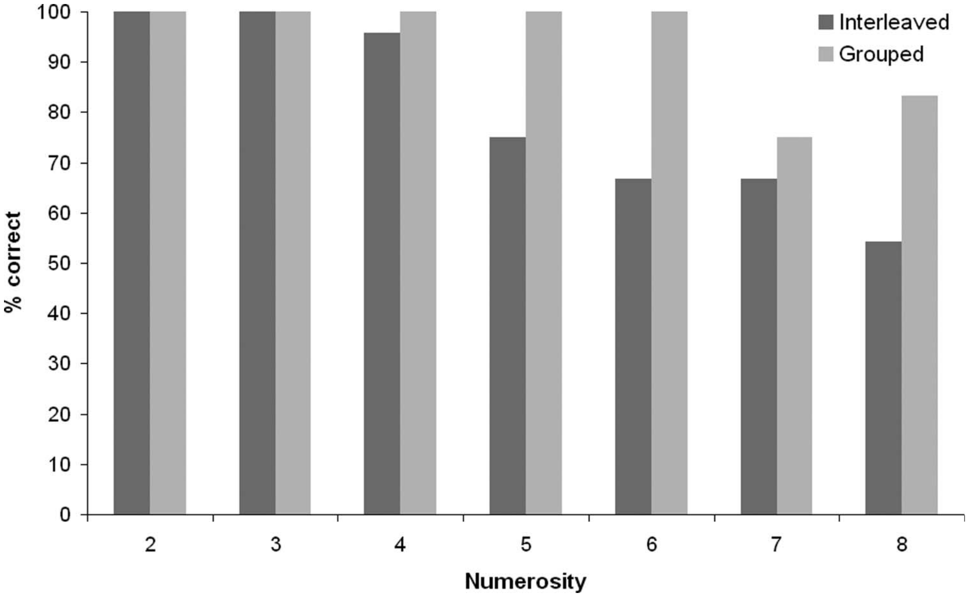

Figure 11. Accuracy when enumerating displays made up of mixed green and red dots where the color groups were also spatially defined, or not.

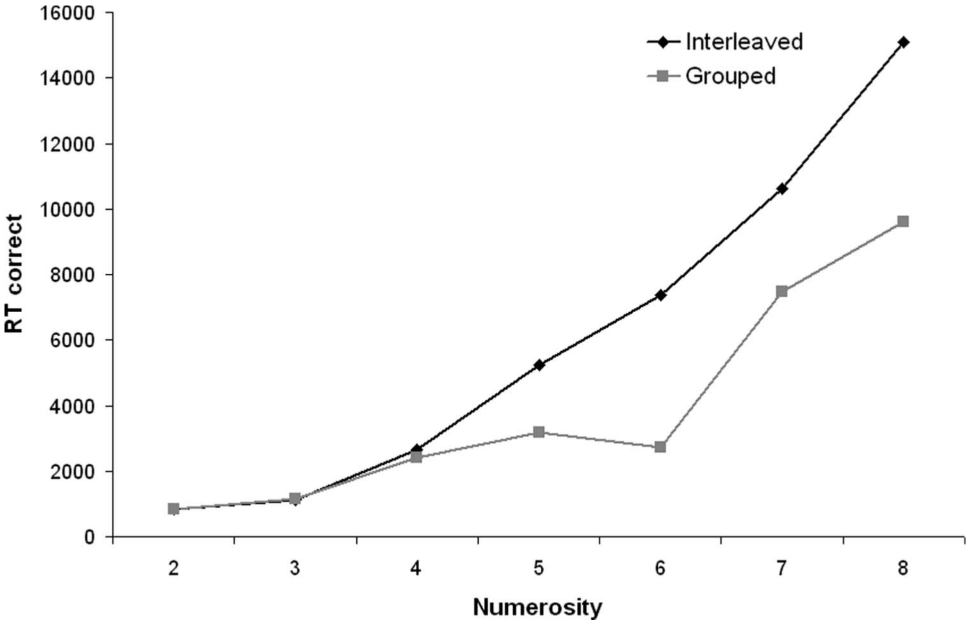

Figure 12. Correct RTs (ms) when MH enumerated displays of green and red dots, which additionally formed spatial subunits or not.

conditions, respectively; slopes for the counting range (5–8) were 961 and 1351 ms per item for the spatially and color grouped vs. color grouped only conditions, respectively.

The raw RTs for correct trials were entered into a between-subjects ANOVA with the factors being spatial Color grouping (grouped vs. interleaved), Size (Small vs. Large) and the Numerosity (2,3–5,6). There was a significant effect of Spatial color grouping, $F(1, 164) = 65.646$, $p < .001$, as well as Size, $F(1, 164) = 15.747$, $p < .001$, and Numerosity, $F(1, 164) = 7.668$, $p = .006$. There were also reliable interactions between spatial Spatial grouping and Size, $F(1, 164) = 66.526$, $p < .001$, and between Spatial grouping and Numerosity, $F(1, 164) = 9.818$, $p = .002$. The three-way interaction was also reliable, $F(1, 164) = 10.159$, $p = .002$.

Taking performance in the subitizing range only (2–3), there was no reliable difference between the two grouping conditions, $F(1, 90) = 0.049$, $p = .825$. For the counting range (5–6), MH was significantly slower for displays that could only be grouped by color, in contrast to the when there was both spatial and color grouping, $F(1, 74) = 54.970$, $p < .001$.

Discussion

Experiment 3 demonstrated that, although MH was not helped by color grouping in itself (Experiment 3a), he did benefit when the colors formed spatially separate subitizable units. This indicates that, although MH can use color segmentation (Riddoch et al., 2004), spatial grouping rather than color grouping is used for counting. (Watson & Maylor, 2006). With spatially grouped colors, MH's performance improved in the counting range but there was no effect within the subitizing range.

EXPERIMENT 4: FORCED SERIAL COUNTING

One interpretation of the data from Experiments 2 and 3 is that MH relies on subdividing the display into subitizable units in order to count. However, when the display does not group into smaller (subitizablke) units, MH loses track of where he has been and which parts he has already counted. If this is the case, then performance might be improved if MH is able to use another form of stimulus coding to keep track of the items. This was tested here by requiring MH to gently tap each dot in order to count the total number of dots in a serial manner. If MH can use a motor representation of where he has explored, then the tendency to re-trace counted items may reduce and MH may be more accurate at enumerating large display sizes.

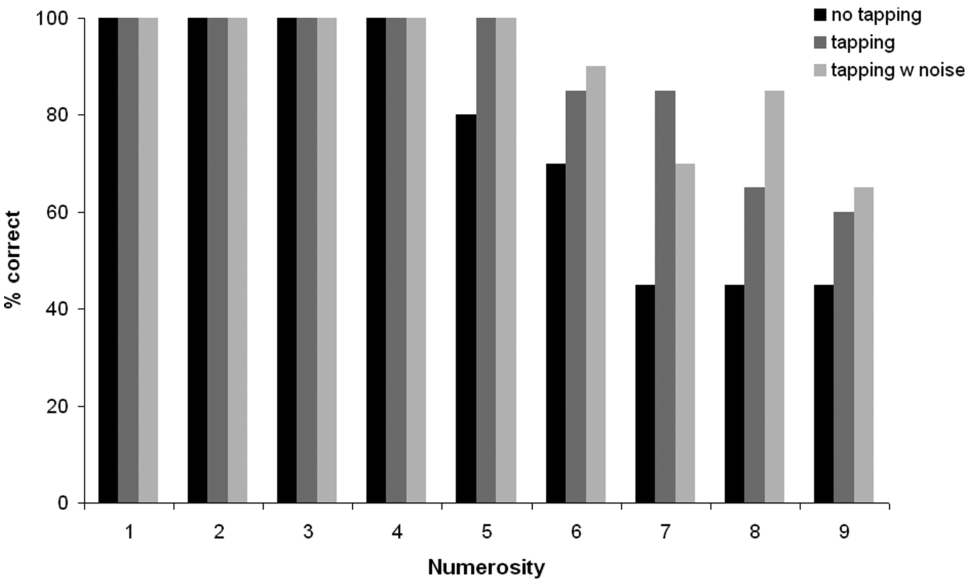

Figure 13. Accuracy when enumerating random dot displays, with MH not touching the stimuli, compared to when he tapped each dot successively in order to count (either while listening to nothing or white noise to mask the tapping sounds)

Method

Rather than using a computer task, we used a paper task; this enabled MH to tap each dot in succession with the back of a pen as he counted the total number of dots present. The stimuli were shown on A5 pieces of paper. The dots were drawn with the same algorithm as in Experiment 2, creating equidistant random dot patterns (see the Method for Experiment 2). This was done to eliminate any spatial grouping that can occur by chance in a completely random display. MH's task was to count the total number of dots present on the paper. Responses were noted and RTs were recorded by stopwatch. There were 3 conditions, which were administered sequentially over 6 sessions (with a 1-week interval). In the first condition, MH was instructed to tap each dot with the back of a pen in order to count the total number of dots present. In the second condition, MH was instructed just to count, without touching (as in Experiments 1–3). In the final condition, MH again was instructed to count the dots while tapping each dot sequentially, but this time was wearing headphones delivering white noise in order to mask any sounds of the tapping. This was done to ensure that MH was not counting the sound of the taps, but instead was using the tapping as a visuo-motor aid. MH performed a total of 20 trials per numerosity, per condition.

Results

In all three conditions MH made no errors when enumerating displays of up to 4 dots (see Figure 13). In contrast there was a relatively high error rate in all conditions across the counting range (5–8), with an average of 60% correct in the no tapping condition, 83.75% correct when tapping each dot and 86.25% correct when tapping each dot while listening to white noise. The difference between the no-tapping and tapping conditions was statistically reliable, both for standard tapping (p = .001, Fisher's Exact test) and for tapping in white noise (p < .001, Fisher's Exact test). There was no difference between the two tapping conditions (p = .825, Fisher's Exact test).

The errors MH made in this experiment ranged from overestimating by 2 items to underestimating by 2. In the 'no tapping' condition, 86% of errors were underestimations, in the 'tapping' condition, 76% were underestimations and in the 'tapping with noise' condition, this was 50% of the errors made.

RTs when MH responded correctly are presented in Figure 14. RT slopes for the subitizing range (1–3) were 0.143s per item[3] in the 'No tapping' condition, 0.345 s per item in the 'Tapping'

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[3] The slopes here are expressed in order of sec given that RTs were recorded by stopwatch.

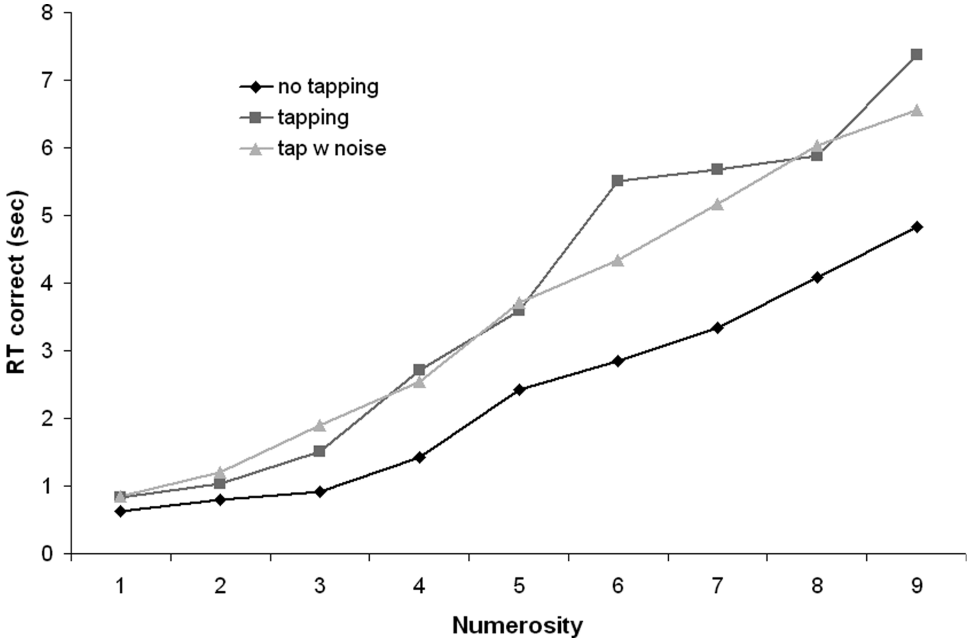

Figure 14. MH's mean correct RTs (s) when correctly enumerating displays of random dots (i) without any tapping, (ii) with tapping each dot and (iii) with tapping each dot while listening to white noise.

condition and 0.523 s per item in the 'Tapping with noise' condition. For the counting range (5–8), RT slopes were 0.536 s per item in the 'No tapping' condition, 0.755 s per item in the 'Tapping' condition and 0.776 s per item in the 'Tapping with noise' condition.

A between-subjects analysis was conducted with the factors being Tapping condition (no tapping, tapping, tapping with noise), Size (Small vs. Large) and Numerosity (1,2,3–5,6,7) on the raw RTs for correct trials. We found a reliable effect of the Tapping condition, $F(2, 307) = 36.401$, $p < .001$, with MH being slower when he was tapping the dots compared to when he was not. There were also reliable effects of Size, $F(1, 307) = 613.864$, $p < .001$, and Numerosity, $F(2, 307) = 26.581$, $p < .001$. There were also significant interactions between Tapping condition and Size, $F(2, 307) = 16.332$, $p < .001$, as well as between Size and Numerosity, $F(2, 307) = 4.785$, $p = .009$. *Post-hoc* LSD tests showed a significant difference between the 'No-tapping' and 'Tapping' conditions ($p < .001$ for both tapping with and without noise). There was no difference between the two 'Tapping' conditions ($p = .215$).

When we considered the subitizing range (≤3) only, we found a significant effect of the Tapping condition on RTs, $F(1, 171) = 21.288$, $p < .001$. There was also an effect of Numerosity, $F(2, 171) = 33.405$, $p < .001$, and a reliable interaction between Numerosity and Tapping condition, $F(4, 171) = 3.758$, $p = .006$. *Post-hoc* LSD tests showed a significant difference between the 'No-tapping' and 'Tapping' conditions ($p < .001$ for both tapping with and without noise). The interaction was due to the effect of numerosity being stronger in the tapping conditions (see Figure 14).

For the larger numerosities (5–8), we found a reliable effect of Tapping condition, $F(2, 172) = 24.243$, $p < .001$. There was a significant effect of Numerosity, $F(3, 172) = 15.099$, $p < .001$, but no interaction. *Post-hoc* LSD tests showed a significant difference between the 'No-tapping' and 'Tapping' conditions ($p < .001$ for both tapping with and without noise). There was no difference between the two 'Tapping' conditions ($p = .247$). RTs were slowed in the tapping conditions, but this did not affect the slope of the function.

Discussion

This experiment again replicates the findings from the previous experiments, where MH demonstrated normal subitizing performance in terms of accuracy (<3 items), in contrast to an impaired counting performance. We further demonstrated that counting accuracy could be helped by forcing

MH to count serially, though the rate of counting remained similar irrespective of whether MH was required to tap. This suggests that MH counted serially in each case, but that having to tap the items helped him keep track of how many items he had found. The generally slower counting, when tapping was required, may simply be due to the extra time needed to make an explicit motor response. On top of this, though, MH showed a larger slope on his subitizing function when he had to tap relative to when he did not. This is consistent with him being able to assimilate subitizable numbers of items in a more parallel manner, faster then serial counting.

Although tapping helped the accuracy of MH's counting of larger diplays, there was no effect of whether tapping was done with or without white noise. Apparently he did not rely on counting the auditory taps he made. As an alternative we suggest that tapping functioned as a visuo-motor aid, helping MH remember the locations he already visited. Forti and Humphreys (2004) reported a quite similar result in a patient with unilateral visual neglect, where making a pointing response to items significantly improved memory for inspected locations. It appears that the visuo-motor response can provide a substitute spatial representation, when visuo-spatial memory is impaired.

EXPERIMENT 5: TESTS OF MONITORING

In the final experiment, we examined whether MH's problems in counting reflected an inability to monitor which items had been checked, rather than an impaired ability to maintain locations that had been visited. We note that MH's lesion extended into the middle frontal gyrus, and an impairment in controlling selection and in monitoring where attention is allocated may reflect this more anterior damage (e.g., Anderson et al., 2007). To test whether the problem was one of control and monitoring alone, we had MH perform a search task where he was rewarded (assigned points) for finding successive targets but 'punished' (points were removed) if he re-visited a previously selected location which could contain a target. When each potential target location was selected, he was also asked whether he thought he had visited there before (see Mannan et al., 2005). If there is a problem only in monitoring where search has been carried out, then MH's re-visits of target locations should be no greater than those of controls, but he should be impaired at judging that the locations were re-visited (revealed by a proportional increase in the number of re-visited sites that MH believed he inspected for the first time). On the other hand, an increase in re-visitations, especially re-visitations which occur some time after the initial visit, may reflect impaired visuo-spatial memory (Mannan et al., 2005).

Method

MH was tested along with 6 age-matched control participants (average age was 64.5). Each participant was given a sheet of paper 60 × 60 cm in size, centred at midline. The sheet was marked with 400 dots (each 3 × 3 cm apart), and a small thimble was placed over 64 of the locations. Twenty-two targets (small markers) were placed randomly, each under one thimble. The task was to explore all the thimbles to find the targets. For each target found, participants were given a reward of 1 point. For each thimble location re-visited, the participants lost 2 points. Participants were told the rules and instructed not to re-visit a location if they could help it. As each thimble was selected, the target was asked to say whether they were visiting it for the first time or whether they thought they had made an error and were re-visiting it. There were no time limits. We recorded the number of targets detected, the number and temporal order of re-visits, and the responses on re-visits. Each participant took part in 10 trials.

Results

The controls all detected all the targets. They made on average 5.2 re-visits per search ($SD = 2.3$) and detected that an error had occurred on an average 1.75 ($SD = 0.8$) of these re-visits (detection rate of 33.7%). When new locations were visited, the controls thought that they were re-visiting the location on an average 4.3% of trials. MH detected an average of 91% of the targets. He made an average of 26 re-visits per search task, which was more than 9 *SD*s from the control mean. All of the re-visits occurred after he had searched at least 3 other potential target locations, suggesting that the re-visits were not due to motor perseveration (see Mannan et al., 2005). On average he reported that he was wrong on 6.5 of the re-visits (detection rate = 29.5%). This falls within 2 *SD*s of the control rate of detecting when a re-visitation occurred incorrectly. When new locations were inspected, MH falsely claimed that a re-visitation was made on 5.4% of the trials.

Discussion

The data from the search task confirm our initial clinical results when MH was asked to perform an invisible star cancellation task – he made frequent re-visits of previously inspected locations. These re-visits typically followed after at least 3 other locations had been inspected, suggesting that re-visits reflected the loss of information about which locations had been searched and not motor perseverations. Despite the abnormal numbers of re-visits, MH made around the same proportions of detection responses as controls (deciding that he had made an error by re-visiting the location). This last result suggests that there was not a marked problem in monitoring, post-selection, when asked to assess whether a location was re-inspected, but there was a problem due to losing information that would otherwise guide him away from inspected locations. MH's ability to detect re-inspections may be due to residual memories which are too weak to guide search but can raise forced-choice responses to approximately the normal level.

GENERAL DISCUSSION

We have presented evidence from a patient, MH, who has impaired spatial memory and who makes abnormally large numbers of re-visitations of inspected locations when visual feedback is minimised in cancellation tasks (see Case Report). We demonstrated that accuracy in the subitizing portion of the enumeration function was normal while there was dramatic impairment for counting more than 4 elements. MH's performance was greatly improved when the elements were presented in two spatially defined groups, with each group representing a subitizable number. However, color grouping did not aid MH's performance, despite his being sensitive to color segmentation (as shown by his improved performance when the two color groups also form spatial groups; see also Riddoch et al., 2004). We showed also that MH's counting performance improved when he was forced into a serial mode for enumeration by tapping each dot in sequence. Finally, we demonstrated that MH made many re-visitations of inspected locations during search, consistent with him having an impaired visuo-spatial memory. However, relative to controls, he did not differ in his ability to detect when re-inspections occurred.

These data support the argument that at least some processes are specific to counting and are not required for subitization – in particular counting but not subitization is dependent on memory for previously inspected locations. Due to MH's impaired visuo-spatial memory, we suggest that he failed to maintain which items had already been inspected and he was unable to count in an efficient serial manner. Counting was aided when the items segmented into two spatial groups because he then had only to maintain the general locations of the groups, and not the locations of the multiple independent stimuli.

One difficulty for the argument that MH had simply lost visuo-spatial memories for stimuli is that his counting performance did improve when he was forced to count serially, by tapping (Experiment 4). This can be explained if tapping meant that MH used a separate motor-based memory system, distinct from his impaired visuo-spatial memory, and if his motor memory system is relatively preserved.

An alternative proposal is that there exist different forms of visuo-spatial representation. Some authors (see Lecerf & de Ribaupierre, 2005; Mammarella et al., 2006) distinguish between two kinds of visuo-spatial memory tasks, each of which requires a memory for patterns of spatial locations, but which differ in the type of spatial process involved: simultaneous in one case (e.g., as measured in pattern memory tests) and sequential in the other (i.e., in the Corsi blocks task). In this framework, MH was impaired at using simultaneously available visuo-spatial memories, but he was able to use sequential visuo-spatial memories – and hence tended to be more accurate when serial processing was encouraged by tapping.

An argument related to this last proposal is that MH is oversensitive to pattern information (there is a form of 'over-grouping'; see Riddoch et al., 2004). Riddoch et al. had MH search for an orientation-defined target that could sometimes group into a larger visual pattern. MH was markedly impaired when grouping took place. Riddoch et al. (2004) suggested that MH has an over-reliance on visual coding in the ventral stream, and fails to utilise more dorsal visual information in search. When dorsal representations are not used, items tend not to be individuated but are treated instead as an undifferentiated mass, disrupting exact counting (see Humphreys, 1998). With small groups, however, a pattern recognition process could be used, enabling him to 'subitize' displays with small numbers of items or displays where the items segment into two small spatial groups. This would fit with the argument that subitizing relies on pattern recognition processes (Logan & Zbrodoff, 2003; Mandler & Shebo, 1982). It would also mesh with the argument that MH is poor at using simultaneously available visuo-spatial memories. According to this account, forcing MH to tap may mean that he 'weights' dorsal representations more strongly, leading to better counting.

The impaired visuo-spatial memory and 'over-grouping' accounts can make different predictions about the types of counting error that might arise. According to the memory proposal, MH ought to make over-estimations because he should re-visit items/locations that have already been inspected. This would mimic his performance on the hidden cancellation task. In contrast, according to the 'over-grouping' account, under-estimations may occur because MH treats items as a group rather than individuating each item. The data here demonstrate a majority of underestimations occurred in each experiment, consistent with predictions of the over-grouping account. It should be noted, however, that the two accounts are not mutually exclusive. MH may tend to group items inappropriately and he may have poor spatial memory for locations he has visited. The fact that MH did make some over-estimations fits with this.

Whichever account is put forward, the data from Experiment 5 indicated that the problem was not simply due to poor monitoring of search. When search was measured MH made abnormal numbers of re-visits of inspected locations, but, on forced-choice testing, he could quite often detect that a re-visit occurred. If monitoring was selectively impaired then we would not expect increased numbers of re-visits while MH should have been impaired at detecting when a re-visitation took place. The results contradict these predictions.

The present results indicate a strong contrast between MH's performance in the subitization range and with larger magnitudes. At least for displays of up to 3 items, MH showed a normal enumerating function in terms of accuracy and relatively fast RTS, but both RTs and accuracy deteriorated rapidly for larger magnitudes. There were also differential effects of particular variables on the two parts of the enumeration function. For example, subitization was not affected by grouping or by segmenting the stimuli into color groups, whereas counting was. In addition, counting was aided by making MH tap items that he counted, whereas subitization slopes tended to increase. The differential effects of these variables is at least consistent with the argument that there is a particular visual process subserving subitization that is spared here, along with an impaired counting function. The data do not differentiate, however, whether subitization is spared due to MH maintaining a preserved number of FINSTs (Trick & Pylyshyn, 1993) or due to him using a pattern recognition process. Further work is required to distinguish these possibilities.

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