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Distributed and Focused Attention: Neuropsychological Evidence for Separate Attentional Mechanisms When Counting and Estimating

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Evidence is presented for 2 modes of attention operating in simultanagnosia. The authors examined visual enumeration in a patient, GK, who has severe impairments in serially scanning across a scene and is unable to count the numbers of items in visual displays. However, GK's ability to judge the relative magnitude of 2 displays was consistently above chance, even when overall luminosity did not vary with the number of items present. In addition, several variables had a differential impact on GK's counting and magnitude estimation. Magnitude estimation but not counting was facilitated by using elements that grouped more easily and by presenting the elements in regular configurations. In contrast, counting was facilitated by placing the elements in different colors while magnitude estimation was disrupted. Also GK's performance on magnitude estimation tasks was disrupted by asking him to count the elements present. The data suggest that GK can process visual stimuli in either a focused or distributed attention mode. When in a focused attention mode, performance is limited by poor serial scanning of attention due to an impaired explicit representation of visual space.

Keywords: counting, estimating, numerosity, neuropsychology, distributed attention

Aspects of Enumeration

Counting is a complex action that involves a number of stages of processing, such as individuating and localizing the items, switching attention from item to item, summing the number of items, maintaining a running total of the items, and inhibiting the recounting of already counted items (inhibition of return; Tuholski, Engle, & Baylis, 2001). However, when four or fewer visual objects are present, enumeration is much faster and less error prone. When enumerating up to four items, within the normal population, there is usually only a small reaction time (RT) increase for every extra item (50–80 ms), whereas for the larger numerosities, there is a sharp and linear RT increase for every item that is enumerated (about 200 ms/item; Mandler & Shebo, 1982; Trick & Pylyshyn, 1993). This is the basis for the distinction between *subitizing* (the ability to enumerate in a fast and accurate manner a small group of four or fewer objects) and *counting* (the error-prone and slow process of serially counting more than five objects).

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The question of whether subitizing and counting are distinct processes has a long history in experimental psychology and is still a controversial issue. Some researchers strongly deny the existence of a significant change in behavior (Balakrishnan & Ashby, 1991; Van Oeffelen & Vos, 1982) and argue that the time to enumerate is a nonlinear function of the items present. Others (Gelman & Gallistel, 1978) accept the discontinuity but seek to explain enumeration as a purely serial process that acts at different rates for different target sizes. For them, subitization is just fast serial counting. Subitization is fast because it is nonverbal and counting is slower because it has an added verbal counting load. More recently, Piazza, Mechelli, Butterworth, and Price (2002) suggested that subitizing and counting are not implemented as functionally separate processes. Using positron-emission tomography to measure brain activity, they found a pattern of increased activation in bilateral middle occipital and parietal areas for both subitizing and counting (compared with the baseline task of responding to a single dot). This activation increased as the number of items increased. No separate neural system for subitizing was found.

In contrast, Trick and Pylyshyn (1993, 1994) argued against a serial determination of numerosity in the subitizing range and for a parallel preattentive process instead. They proposed that subitizing is dependent on the parallel application of a set of fingers of instantion, which index a limited set of visual locations. Because of the limited set of fingers of instantion, larger numbers of stimuli require a separate counting process. Mandler and Shebo (1982) suggested instead that subitizing involves recognition of simple patterns formed by the targets. They showed that larger numbers of items could be subitized (counted efficiently) provided they formed familiar (canonical) figures. Their data suggest that pattern recognition can at least contribute to efficient enumeration.

In a more general number apprehension theory, Feigenson, Dehaene, and Spelke (2004) suggested two separate core systems of number: one system for representing large, approximate numerical magnitudes, and a second system for the precise representation of small numbers of items. The approximate system is deemed to be sensitive to the ratio among numerosities, whereas the exact system responds to the absolute number of individual items, with a limit of about three.

Neuropsychological Studies on Enumeration

In dorsal simultanagnosia, a disorder associated with bilateral lesions of the parietal lobes, patients show a severe impairment in counting. Dehaene and Cohen (1994) suggested that simultanagnosic patients suffer from a general deficit of serial visual exploration due to an inability to use spatial tags to refer to object locations. Counting is virtually impossible because, without spatial tagging, patients are unable to assess when a stimulus has already been counted. Despite their problem in counting, however, all 5 patients reported in Dehaene and Cohen showed relatively preserved quantification of sets of one, two, or sometimes three items. These neuropsychological data show that subitizing can be preserved when counting is impaired.

Coslett and Saffran (1991) have suggested that the core deficit in simultanagnosia is "an impairment in the integration of object identity and spatial location information" (p. 1542). This would predict that differentiation of the counted items along a nonspatial dimension, for instance color, should improve counting. This was shown in Dehaene and Cohen (1994) for only 1 of the 5 patients, whose error rate dropped significantly on sets of three or four items when the stimuli were presented in different colors.

Attentional Demands

If subitization is distinct from counting, then it is likely that some of the linked attentional processes will differ too. For example, counting may depend on a form of focused attention, in which each item is selected in turn. To be successful, such a serial attentional process would need to be supported by other processes, such as spatial indexing and inhibition of return (Klein, 2000; Laeng, Kosslyn, Caviness, & Bates, 1999). In contrast, subitization would appear to depend on a more distributed spread of attention so that the multiple items present are processed in parallel (Trick & Pylyshyn, 1994).

Treisman (2006) recently has argued that there may be two modes of attending to scenes, focused and distributed attention (see also Chong & Treisman, 2005). Distributed attention provides information about the statistical properties of scenes at a glance, but it may not provide precise information about the individual stimuli present—for which focused attention is needed. It may be that simultanagnosics have an extreme limit on focused attention so that they generally only process one object at a time.

On the other hand, there are also suggestions in the literature that simultanagnosic patients can distribute their attention across a scene. For example, even though patients report seeing only one thing at a time, conjunction errors occur when there are multiple items present, suggesting that multiple features at least still are processed (Friedman-Hill, Robertson, & Treisman, 1985; Humphreys, Cinel, Wolfe, Olson, & Klempen, 2000). Similarly, simultanagnosics can attend to multiple features within objects but show deficits when asked to attend to the spatial relations between separate objects (Cooper & Humphreys, 2000; Shalev & Humphreys, 2002). The problem may not be in distributing attention, then, but in serially attending to representations of separate objects in space. Because attention may only cover multiple objects in a distributed mode, the multiple features in the different objects remain available to be bound together, leading to illusory conjunctions sometimes being formed. This may normally be prevented by attending separately to objects in turn (Treisman, 1998). If this holds, then it is possible that performance in such patients may be dissociated when they are in a focused attention mode (e.g., when counting objects) relative to when they use distributed attention (e.g., when required to report about the statistics of images—such as the relative magnitudes of two displays), with performance being particularly disturbed when in a focused attention mode.

Goal of the Present Study

The present study set out to investigate the relations between the different modes of attention mediating visual enumeration by studying a patient, GK, with a severe simultanagnosia. GK, in contrast to the patients in Dehaene and Cohen's (1994) study, has no adequate spatial orienting or serial search, and, in addition, even his subitization ability seems limited (Humphreys, 1998). This is not due to some general problem in counting per se, because GK can count numbers of auditory and tactile stimuli presented to him (Humphreys, 1998; see also the Case Report here). Given GK's limited subitization ability, it is a moot point whether he can use a distributed attentional mode in processing and whether this might influence enumeration tasks.

If the core deficit in simultanagnosia is a deficit in the integration of object identity and spatial location information (Coslett & Saffran, 1991), we can predict that differentiation of the counted items along a nonspatial dimension, for instance color, should improve counting. If such an effect is found on counting, the question is whether it would also occur for magnitude estimation, where performance may depend less on individual items being coded and more on a representation of groups of elements (e.g., a numerous vs. a less numerous group). Estimation may be more difficult when there are multiple colors present. In contrast to the effects of color, grouping may facilitate magnitude estimation, as it may enable all of the items to be coded and compared together. However, it may disrupt counting based on the individuation of items, because elements within a group may lose their individual identities (e.g., Rensink & Enns, 1995).

If there is evidence for variables having different (even opposite) effects on magnitude estimation and counting, then an argument can be raised for there being different modes of attention mediating performance—a serial, focused mode involved in counting (and disrupted in GK) and a distributed mode mediating magnitude estimation. Furthermore, given that subitization is impaired in this patient, the distributed mode of attention mediating magnitude estimation cannot be sufficient for accurate subitizing. If a form of distributed mode of attention is preserved in this patient, this would have implications for the interpretation of the processes required for subitizing.

We report a dissociation between counting and magnitude estimation, even when similar stimulus exposure durations and task demands were used for the two tasks. Subsequent studies then assessed effects of particular variables—such as using items with

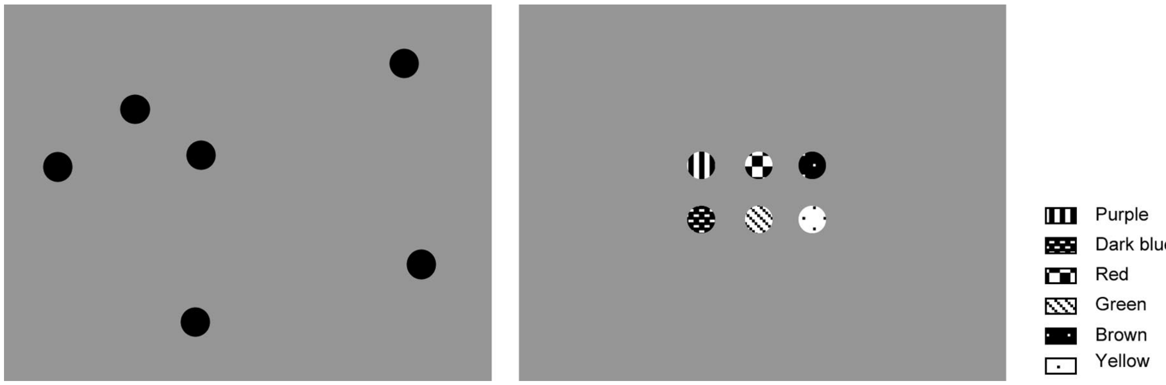

Figure 1. Example displays from Experiment 1 for random black dots (left) and canonical multicolored dots (right).

different colors and using displays in a familiar configuration with elements that grouped more easily—to evaluate whether the variables produced independent effects under the two modes of attention (on counting and on magnitude estimation). We discuss the implications of the results for understanding the normal relations between attention and different enumeration tasks.

GK: Case Report

GK was 64 years old at the time of testing. He suffered two strokes in 1986 affecting the right occipitoparietal, the right temporoparietal, and the left temporoparietal regions. GK shows symptoms characteristic of Balint's syndrome: He has psychic paralysis of fixation, and his ability to reach appropriately to visually presented items is severely impaired. Additionally, GK encounters profound difficulties when describing complex scenes containing multiple objects and, even under free vision, appears to be unable to be aware of more than one item at a time (simultanagnosia symptoms). In Humphreys, Romani, Olson, Riddoch, and Duncan's (1994) study, GK showed nonspatial extinction when items were presented above and below fixation (see also Humphreys & Riddoch, 2003).[1] When stimuli are presented simultaneously along the horizontal meridian, GK shows left-field extinction; this presumably reflects the relative severity of his right-hemisphere lesions compared with his left-hemisphere lesion. Extinction decreased when the two simultaneously presented items could be grouped (Gilchrist, Humphreys, & Riddoch, 1996; Humphreys, 1998). A magnetic resonance imaging scan is shown in Gilchrist et al. (1996).

Experiment 1: Basic Contrast of Counting and Magnitude Estimation, With Effects of Color and Configuration

In this experiment, we compared the performance of GK on counting and magnitude estimation tasks and manipulated the colors and the organization of the dots. We used displays of single-colored or multicolored dots that were either canonically or randomly organized.

Method

All of the displays were presented on a gray background on a 17-in. (43.18-cm) monitor with an 800 × 600-pixel screen resolution. GK was positioned approximately 70 cm from the screen. One dot always comprised 0.98° of visual angle across its diameter, and the dots were separated from each other by 0.98° (vertically and horizontally). There were numerosities of 1, 2, 3, 4, 5, 6, 8, and 10. In the canonical conditions, the patterns were either horizontally or vertically oriented. Numerosities up until 5 were displayed in one row or column; larger numerosities were positioned in two rows or columns. The dots were always displayed at the center of the screen. For the larger numerosities, there was a 0.5° separation between the rows–columns. In the random condition, the dots were positioned randomly within the display, with a minimum distance of 1.96° visual angle between any two dots.

In the single-colored condition, the dots were all black, whereas in the multicolored condition, no two dots were in the same color. The colors were distributed randomly over the displays so there was no bias toward certain colors only appearing in larger numerosity displays (for an example of the stimuli, see Figure 1). We used 10 different colors (green with red/green/blue [RGB]: 0, 255, 0; lilac with RGB: 255, 0, 255; yellow with RGB: 255, 255, 0; pale blue with RGB: 0, 153, 255; red with RGB: 255, 0, 0; dark blue with RGB: 0, 0, 255; brown with RGB: 102, 50, 0; black with RGB: 0, 0, 0; purple with RGB: 128, 0, 128; and orange with RGB: 255, 153, 0). The background was gray (RGB: 127, 127, 127) in all experiments.

For the counting experiments, the displays were presented on PowerPoint slides. The experimental procedure did not require precise timing, as GK is very slow and requires substantial presentation durations in order to enumerate stimuli. The displays were balanced over the test so that there was an equal number of each numerosity present, and there were as many horizontally oriented as vertically oriented displays (in the canonical conditions). Before every trial, there was a fixation screen with a black cross in the center. The fixation cross was presented for a duration of 1,000 ms; the display of dots that followed was presented for an unlimited time, until a response was made.

[1] In this study, there was no spatial bias to report one of two stimuli in either the upper or lower visual field; rather, there was bias to select just the better (and to extinguish the worse) of two stimuli. This in itself suggests that GK could operate with a spatial window of attention covering more than one shape but then was impaired at selecting more than one shape within a normal time.

GK was instructed to count the number of dots present in the display. All experiments consisted of 12 sessions, and in total there were 15 observations for each display. The order in which the displays were presented was randomized. The RTs were measured by the use of a stopwatch, and both the RTs and the responses were noted.

In the magnitude estimation experiments, GK was shown two consecutive displays. His task was to compare the two displays and to respond which one of them had more elements in it, the first or the second. The largest numerosity was always double the amount of dots in the smallest numerosity. The large numerosities consisted of 2, 4, 6, 8, or 10 dots. We used the same stimuli displays as for the counting tasks. The displays were balanced over the test; so that an equal number of each numerosity was presented, there were equal numbers of horizontally oriented and vertically oriented displays (in the canonical conditions), and the order of the two consecutive displays was balanced. Each trial consisted of a 1,000-ms presentation of a fixation cross, followed by two consecutive display presentations for 3,000 ms each. Under these conditions, no apparent motion was present, when one display changed to the next. The data were gathered in 20 sessions, resulting in 40 trials for every condition.

Results

Counting. In the single-colored condition, GK showed a severe impairment in counting the dots, both in canonical and in random displays (see Figure 2). The error rates showed a linear increase from small to large displays. A linear regression analysis (for the single-colored dots) indicated that 71.4% of the variation in errors can be predicted from the presented numerosity. The linear relationship between these variables was highly significant, $F(1, 238) = 596.78$, $p < .001$. Remarkably, GK did not report all of the one-dot displays correctly, and he made mistakes for all numerosities. There was no evidence for preserved subitizing. The rise in performance for Numerosity 4 in the canonical condition could partly be explained by guessing: When we regard the overall prevalence of answers, GK responded *4* on 38 occasions, although each display was only shown 15 times. Average RTs of the correct responses for each condition separately as well as an overall average are presented in Figure 3. These data show a significant linear relationship with the presented numerosities, $F(1, 209) = 111.49$, $p < .001$, with 34.8% of the variation in the average RT accounted for by the variation in the presented numerosities (departures from linearity occurred only at the largest display sizes too, and there was no evidence for departures from linearity around the normal numbers for subitization). The RTs are consistent with a serial counting process, and there was no evidence for a fast parallel processing of the smaller numerosities.

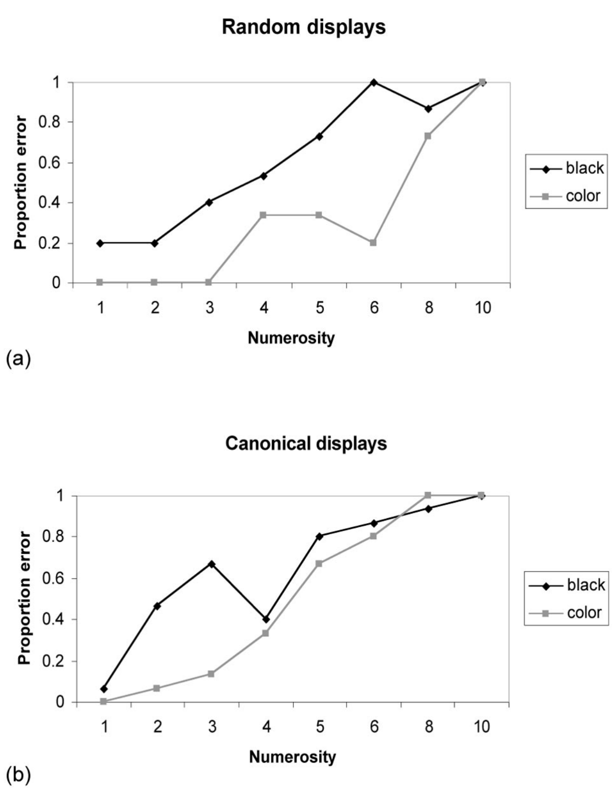

Figure 2. The proportion of errors made by GK when counting in Experiment 1 for random displays (a) and for canonical displays (b).

The data in all conditions show a significant effect of numerosity, overall $\chi^2(1, N = 480) = 149.8$, $p < .001$. This finding shows that although GK made errors on the low numerosities, they were still easier than the higher numerosities (76.3% correct for Displays 1–4 vs. 20.4% for Displays 5–10). GK found it increasingly difficult to keep track of the number of items as the numerosity increased. Also, there was a significant overall effect of color, $\chi^2(1, N = 480) = 27.113$, $p < .001$ (36.7% correct for single-colored displays vs. 60% for multicolored displays). GK's performance in the single-colored dots condition differed significantly from the multicolored dots condition, both in canonically organized displays, $\chi^2(1, N = 240) = 7.467$, $p = .006$, and in randomly organized displays, $\chi^2(1, N = 240) = 21.654$, $p < .001$. The color manipulation reliably improved counting (see Figures 2a and 2b). Finally, GK's performance in counting multicolored dots was improved by a random distribution of the dots across the display, compared with the canonically organized displays, $\chi^2(1, N = 240) = 5.625$, $p = .018$. There was no improvement in counting randomly—as opposed to canonically—organized single-color displays, $\chi^2(1, N = 240) = 0.162$, $p = .687$. This might be because GK's ability to count single-colored items was at floor level.

In order to assess the types of errors, we first correlated the responses with the presented numbers. This resulted in significant correlations for the multicolored displays in both canonical ($r = .858$, $p < .01$) and random ($r = .956$, $p < .01$) displays. The single-colored displays also showed significant correlations between the presented numbers and the responses, again in both canonical ($r = .669$, $p < .01$) and random ($r = .660$, $p < .01$) organizations. Next, we compared the range of errors. In order to assess whether there were more close errors (defined as responses that differed by 1 or 2 from the actual number presented) than far errors (responses that differed by more than 2), we compared the frequencies of these ranges of errors for each condition separately. We found no significant differences in the number of close to far errors in the single-colored condition, both for the canonical, $\chi^2(1, N = 156) = 2.105$, $p = .147$, and the random, $\chi^2(1, N = 150) = 1.952$, $p = .162$, displays. For the multicolored displays, there

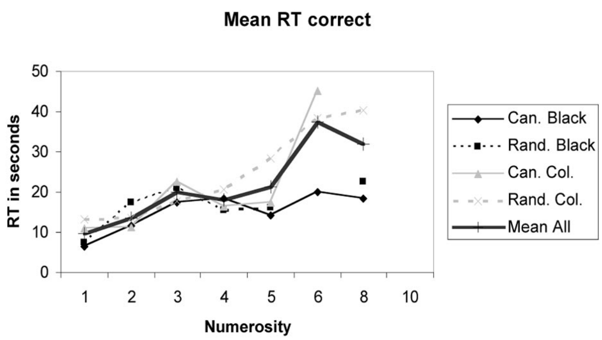

Figure 3. Reaction times (RTs) for correct responses in all four conditions (black and multicolored [Col.] items, in random [Rand.] or canonical [Can.] positions) plus the average RT over the four conditions.

again was no significant difference in the range of errors in the canonical condition, $\chi^2(1, N = 114) = 1.071$, $p = .301$, but there were significantly more close than far errors in the random condition, $\chi^2(1, N = 78) = 12.512$, $p < .001$.

Estimating. For both the canonical and the random displays, GK's performance was significantly above chance (see Figure 4), over all numerosities: black canonical, $\chi^2(1, N = 400) = 23.38$, $p < .001$, multicolored canonical, $\chi^2(1, N = 400) = 20.35$, $p < .001$, black random, $\chi^2(1, N = 400) = 17.55$, $p < .001$, and multicolored random, $\chi^2(1, N = 400) = 4.46$, $p = .035$, showing that he was able to compare numerosities.

There was an overall effect of numerosity size, $\chi^2(1, N = 640) = 4.723$, $p = .030$. GK made fewer errors when comparing the larger displays as opposed to the smaller displays (62.2% correct for trials with largest numerosities, 2 and 4, vs. 70.3% for largest numerosities, 8 and 10). When we divided the data, there was a marginally significant difference in accuracy between larger and smaller numerosities for canonical displays, $\chi^2(1, N = 320) = 3.905$, $p = .048$, but no difference for randomly organized displays, $\chi^2(1, N = 320) = 1.317$, $p = .251$. Overall, GK also was significantly better at comparing canonical than random displays, $\chi^2(1, N = 800) = 4.926$, $p = .026$. Although there was no overall effect of the color manipulation, $\chi^2(1, N = 800) = 3.098$, $p = .078$, for the random displays only, GK made significantly fewer errors with single-colored compared with multicolored displays, $\chi^2(1, N = 400) = 4.425$, $p = .035$.

Discussion

The results confirm that GK was extremely poor at counting random dots and that he showed no sign of subitization. This finding replicates prior data (Humphreys, 1998). There was a reliable effect of whether the items were spatially random or in a familiar configuration, and GK's counting of displays with multicolored tokens was better than his counting of black items. Indeed, with multicolored dots, GK's counting of random displays was better than his counting of configural displays, particularly for the larger numerosities. This may be because the spacing between the items was on average larger in the random relative to the configural stimuli. It is possible that, with small spacings, some colors merged as a function of GK's poor location coding (Humphreys et al., 2000) so that the counting of multiple colors was disrupted. The advantage for counting multicolored over black items is consistent with GK having impaired location codes, which should support the indexing and serial scanning of attention, and it matches prior data from patients with parietal lesions (Dehaene & Cohen, 1994). The fact that GK could not count as few as three items without making 40% errors also indicates the severity of his problems with spatial indexing, if indexing processes are important for subitization (cf. Trick & Pylyshyn, 1994).

Although GK's counting of visual stimuli was poor, he was above chance at the estimating task, over all numerosities. His performance did improve at the larger numerosities, which might be because the magnitude of the differences between the comparison patterns then increased. It might be argued that the above-chance performance on the estimation task was because there were large disparities between the stimuli that had to be compared. Note, however, that GK's errors on counting were often considerably different from the number of items presented, and on 42% of the trials his counting responses were wrong by a factor of two or more. Thus, the above-chance performance on estimating was unlikely to be due to the magnitudes of the differences used. In this respect, it is interesting to note that GK was better at estimating with configural than with random displays, which is the opposite of the pattern we observed with counting. In addition, GK showed an advantage for estimating black dots compared with multicolored dots—which again dissociates from the data on counting. These qualitatively different patterns of performance suggest that contrasting information may contribute to GK's counting and

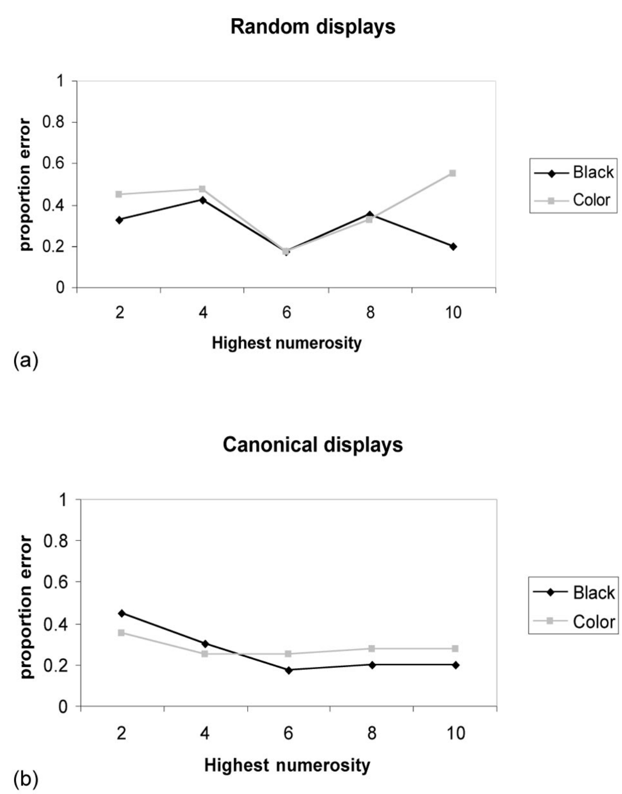

Figure 4. Proportion of errors in the estimation task in Experiment 1 for random displays (a) and for canonical displays (b).

estimating performance. With counting, factors that individuate items (multiple colors, on average wider spacing) facilitate performance. With estimating, factors that contribute to grouping the elements (same colors, smaller spacing, and/or regular configuration) may benefit performance. This would be consistent with GK being able to encode groups of items but primarily when he adopts a distributed mode of attention in order to estimate the number of items present. This argument was confirmed in an experiment comparing performance with single-colored collinear squares with dots in canonical organizations. Although there was no difference in accuracy when counting canonically organized squares (50/120 correct) versus dots (42/120 correct), $\chi^2(1, N = 240) = 1.12$, $p = .28$, estimating was significantly better for the displays containing collinear squares (174/200 correct) than canonical dots (147/200 correct), $\chi^2(1, N = 400) = 11.499$, $p < .001$. This shows converging evidence for the importance of grouping when estimating.

Overall, this pattern of dissociation is consistent with there being two modes of attention: focused and distributed attention. Focused attention is used by GK in counting. In this mode of attention, performance is helped by individuating the items (assigning one color to each item, using random rather than grouped displays). In contrast, distributed attention is used in estimating, perhaps because statistical information can be inferred (Chong & Treisman, 2005) when displays are grouped under distributed attention conditions. Under distributed attention conditions, the statistical information available from displays may be stronger when elements group than when they do not group.

Experiment 2: The Effect of Short Display Durations on Counting

One difference between the counting and estimating tasks in Experiment 1 was that (relatively) short durations were used for estimating, whereas unlimited durations were used for counting. It may be that GK can derive relatively global representations of displays under short duration conditions (making him sensitive to grouping by proximity–configuration and common color) but that this information is lost when he starts to scan attention (e.g., for counting). To test this possibility, in Experiment 2, we had GK count stimuli that were presented for the same duration as the displays in the estimating task in Experiment 1, namely 3 s.

Method

The method was the same as that for the counting task in Experiment 1, except that the displays were presented for a fixed interval of 3 s. There were 15 trials per numerosity. Only displays with black dots were used, in both canonical and random organizations.

Results

The accuracy when counting under these short presentations was not significantly different from a chance performance (one in eight) for both canonical, $\chi^2(1, N = 240) = 1.566$, $p = .211$, and random, $\chi^2(1, N = 240) = 2.480$, $p = .115$, organizations (see Figure 5). It was significantly lower than when there was an unlimited amount of time available both for canonical, $\chi^2(1, N = 240) = 8.52$, $p = .0035$, and random, $\chi^2(1, N = 240) = 9.76$, $p = .0018$, displays. Performance was poor across all numerosities, and unlike in Experiment 1, it made no difference whether the configuration was random or a canonical pattern.

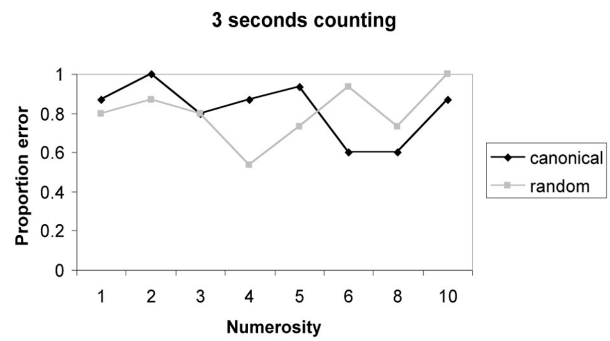

Figure 5. Proportion of errors in the counting task in Experiment 2.

In addition, when analyzing the responses (see Figure 6), 50.8% of the responses for the random displays were wrong by two or more elements. For the canonical displays, this percentage was 64.2.

Discussion

GK performed very poorly when he had to count dot displays presented for just 3 s, and his accuracy was close to the floor. This suggests that his estimation performance is much less affected by exposure duration than his counting, consistent with him adopting different strategies. This fits with the suggestion that GK is using a distributed attention mode to respond to the statistical properties of the displays in the estimation task and with Chong and Treisman's (2003) finding that the exposure duration of the display did not affect statistical processing. In addition, there was little evidence for a systematic relationship between the number of items and GK's response (see Figure 6). Finally, there was no overall difference between counting with random and canonical figures, whereas with estimation there was an advantage for canonical displays (Experiment 1). However, any effect of the pattern could have been obscured by the low level of performance here. Overall, the data provide no grounds to argue that the differences between counting and estimating in the first study were due to the contrasting durations for the tasks.

Experiment 3: Removing Effects of Luminosity and Equating for Chance

In Experiment 3, we addressed two issues. One is the question of luminosity. Can the contrasting results for estimating and counting be accounted for in terms of GK responding to the overall luminosity of the displays in the estimation task, whereas he attempts to individuate items when counting? Note that, in Experiment 1, there was a direct correlation between the number of elements present and the overall luminosity of the display. With the use of single-colored black dots on gray backgrounds, overall luminosity diminished with the number of dots being displayed. In Experiment 3, we used displays that were made up of black and white dots, shown on a gray background. There were random proportions of black and white dots in each display so that the

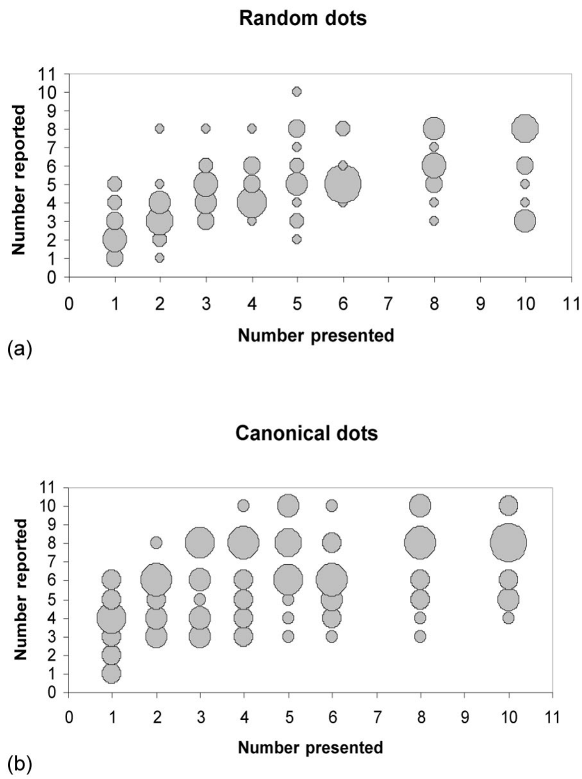

Figure 6. The number reported relative to the items present in Experiment 2 for random displays (a) and for canonical displays (b).

overall luminosity of the display did not correlate with the number of items present. Any use of overall luminosity will not benefit performance under these conditions. Experiment 3 also assessed whether differences in guessing could have contributed to the contrast between counting and estimating. In Experiment 1, there was a 1/8 probability of responding correctly on the counting task, whereas there was a much higher 1/2 probability of a correct response in the estimation task. In this experiment, we contrasted counting and estimating using a two-alternative forced-choice design for both tasks.

Method

This experiment was made using E-prime 1.1 (Schneider, Eschman, & Zuccolotto, 2002). Dots of the same size as in Experiment 1 (0.98°) were drawn on random locations on a gray background (RGB: 127, 127, 127), with the constraint of a minimum distance of a one-dot diameter between any two dots. A random proportion of the dot display was made up of white dots; the other dots remained black. Because the proportion was chosen randomly (from zero to the total number of dots in that display), there was no correlation between the overall luminosity of a display and the numerosity present. In the counting task, GK was instructed to count the total number of dots present, and, as soon as he knew the number, he was asked to hit the space bar and then make a choice between two numbers that were read out loud to him. These numbers were the same as the ones used in the estimation task in Experiment 1 (1–2, 2–4, 3–6, 4–8, and 5–10). In the estimation task, the display was presented for a fixed duration of 3 s, and GK was asked to estimate the number of dots present and was then again given the choice between two numbers. There were 16 trials per numerosity alternative, resulting in a total of 160 trials in both the counting and the estimating task.

Results

The overall level of performance was above chance both when GK used the counting strategy (62% correct), $\chi^2(1, N = 320) = 4.636$, $p = .031$, and when he used an estimation strategy (77% correct), $\chi^2(1, N = 320) = 22.967$, $p < .01$. However, GK performed significantly better when using an estimation strategy (compared with when trying to count the number of dots present), $\chi^2(1, N = 320) = 7.733$, $p < .01$. The data are depicted in Figure 7 as a function of the largest number given in the forced-choice decision. Because there was no relation between the overall amount of luminance in the displays and the numerosity, the difference between counting and estimating cannot be attributed to GK using a luminance-based strategy.

Discussion

GK was above chance at both counting and estimating, when given two-alternative forced choices to respond to, but he remained reliably better at estimating than counting. This again provides grounds for the argument that GK is able to use more visual information when he estimates the number of items in a display than he can use when in a counting mode. The fact that the advantage for estimating remained here, even when we used random numbers of black and white dots, also indicates that the advantage is not simply due to GK responding to the overall luminosity of the display in this condition (note that there was no relationship between luminosity and the number of items present in this experiment).

Experiment 4: The Intentional Control Over Attention Modes

Experiment 3 suggests that GK has some control over which mode of attention is adopted, because estimation remained better than counting even when similar choice responses were involved

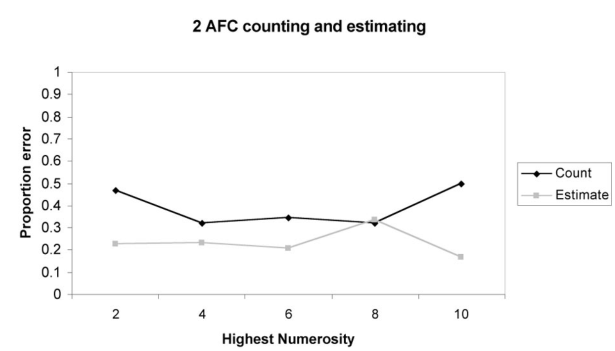

Figure 7. Proportions of errors made in the two-alternative forced-choice (2 AFC) versions of the counting and estimating tasks, performed with black and white dots. The data are shown as a function of the highest number in the forced-choice decision.

in both tasks. GK's control over his visual attention was examined further in Experiment 4. In this study, we asked GK to try to count the number of dots present when carrying out a magnitude estimation task. For this task, we used canonical multicolored dot displays. We contrasted these results with when he was asked to try and look at the mass in order to estimate which display had more elements (using distributed attention). There were 40 observations per pair of numerosities, in each of the two conditions.

Note that the estimation task continued to use a two-alternative forced-choice procedure, with GK being asked only to vary his strategy, not to give a different answer, or guess the number of items present. Hence, if the crucial difference between GK's performance on the counting and magnitude estimations tasks was because the latter used a two-alternative forced-choice procedure (and with displays differing by an order of two when the numbers of items present differed), then we should again observe good (above-chance) performance in estimation (though it should now be based on counting).

Results

Performance was above chance both for estimating when using a counting strategy, $\chi^2(1, N = 400) = 4.90, p = .027$, and for estimating while trying to capture the entire display in a glance, $\chi^2(1, N = 400) = 20.35, p < .001$. There was, however, a reliable difference between the two strategies (see Figure 8): When using the "mass estimation" strategy, GK's accuracy was significantly higher, $\chi^2(1, N = 400) = 5.43, p = .019$.

Discussion

The results of both Experiments 3 and 4 are consistent with GK having some intentional control over his processing of visual displays, with counting being worse than estimating even with exactly the same presentation conditions. We suggest that, when asked to count the elements, GK adopts a more focused attention mode, and in this mode he is impaired at deriving statistical information from the whole display. He also has difficulty in conducting an accurate serial search of the items present; consequently, his accuracy decreases. This result is also methodologically important because it indicates that the reason for GK's relatively good estimation performance was not a result of the forced-choice procedure or the display pairing used.

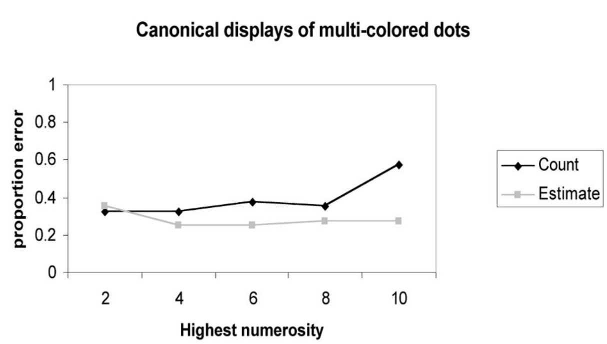

Figure 8. The proportion of errors in Experiment 5 when "counting" in an estimation task. Data are shown as a function of the highest number in the forced-choice decision.

Experiment 5: Counting Colors. A Specific Deficit in Spatial Tagging?

If the core deficit in counting in simultanagnosia is a problem in spatial tagging (Laeng, Kosslyn, Caviness, & Bates, 1999), then GK may be better at counting nonspatial features than he is at counting spatial elements. For example, counting the number of different colors in a display may be somewhat easier than counting the number of exemplars of a particular color (see Dehaene & Cohen, 1994). To investigate this possibility, we used displays of a constant number of dots so that there was no longer a correlation between the number of dots and the number of colors (similar to the displays used in Watson, Maylor, & Bruce, 2005). GK was asked to count the number of different colors present in the display.

Method

We created displays of 48 dots, which were positioned in the middle of a 100 × 100-pixel square cell. The screen resolution remained at 800 × 600, and there was an imaginary grid, in which the 48 dots, with a 50-pixel diameter (0.98° of visual angle), were positioned. There were displays with one, two, three, four, five, six, and eight different colors (green with RGB: 0, 255, 0; lilac with RGB: 255, 0, 255; yellow with RGB: 255, 255, 0; pale blue with RGB: 0, 153, 255; red with RGB: 255, 0, 0; dark blue with RGB: 0, 0, 255; brown with RGB: 102, 50, 0; and orange with RGB: 255, 153, 0). The colors were randomly sampled per display. There were two configurational conditions. In the mixed-colors condition, all colors were mixed randomly over the imaginary grid. In the grouped-colors condition, the colors were grouped by proximity and formed clusters. In both conditions, the 48 dots were equally divided over the available colors (see Figure 9). For each numerosity, there were 20 observations. GK was asked to count the number of different colors present.

Results

We investigated the effect of the spatial organization, comparing GK's performance in the mixed-colors condition with his performance when counting colors that formed clusters. We also compared GK's performance when counting the number of colors relative to his performance when he counted random and canonical displays of multicolored dots (Experiment 1). The results show no significant difference between counting colors in clusters to counting randomly mixed colors, $\chi^2(1, N = 280) = 1.511, p = .22$. When relating GK's performance here to the findings in Experiment 1, the results show that counting the number of different colors in both the mixed- and the grouped-color configurations was better than counting the number of multicolored shapes (see Figure 10), in both canonical displays, $\chi^2(1, N = 260) = 35.18$, $p < .001$, and $\chi^2(1, N = 260) = 23.305, p < .001$ (mixed and grouped, respectively) and in random configurations, $\chi^2(1, N = 260) = 10.14, p = .002$, and, $\chi^2(1, N = 260) = 4.063, p = .043$ (mixed and grouped, respectively). When we regard the RTs of the correct responses, a linear regression provided a significant fit for the data, $F(1, 226) = 189.025, p < .001$, and the variance in numerosity accounted for 45.3% of the variance in the RTs. Any departure from linearity occurred with the highest numbers, and

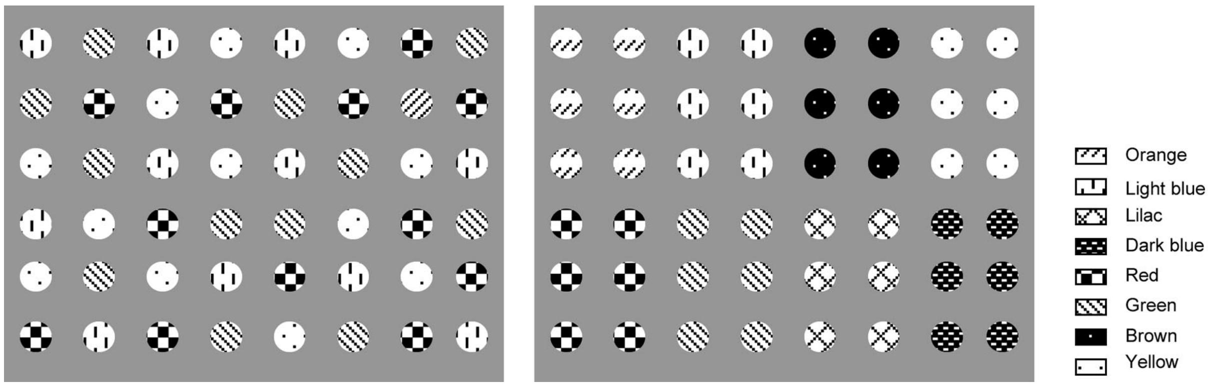

Figure 9. Example displays from Experiment 6 (counting colors task) in the mixed-colors condition (left) and in the grouped-colors condition (right).

there was no evidence for departures from linearity around the numbers characteristic of subitization.

Discussion

In contrast to GK's performance when he had to count the number of colored shapes in a display, enumeration improved when he had to count the number of different colors present. Indeed, the contrast between the experiments (counting token shapes vs. counting color features) was remarked on by GK, who noted that he really liked these displays and this task. The results support those reported by Dehaene and Cohen (1994) but in an even more dramatic fashion given that GK is unable to count even small numbers of individual shapes. One reason for this contrast is that, unlike counting individual shapes, counting colors does not depend on encoding an accurate spatial representation of the stimuli (e.g., in order to prevent tokens being recounted). Prior work has shown that GK is very poor at spatial coding, for example failing to discriminate whether shapes presented as far as 3° above or below fixation fall in the upper or lower visual field (Humphreys et al., 1994). Moreover, GK's performance was not helped by spatially grouping the colors together in separate clusters; if anything, counting mixed colors seemed to be easier. This finding suggests that counting colors was not necessarily based on the same information that determined estimation performance (where performance improved with grouping). The data also suggest that GK was unable to use the spatial information provided by each cluster of same-colored items to facilitate search. This again fits with the idea that GK is impaired at using spatial information (here even from multicolored displays) to guide counting. The data suggest that color counting does not depend on accurate spatial coding nor does it depend on gaining an overall estimation of the statistics of the visual scene; instead, colors may be counted serially within an internal color space even when location codes are damaged.

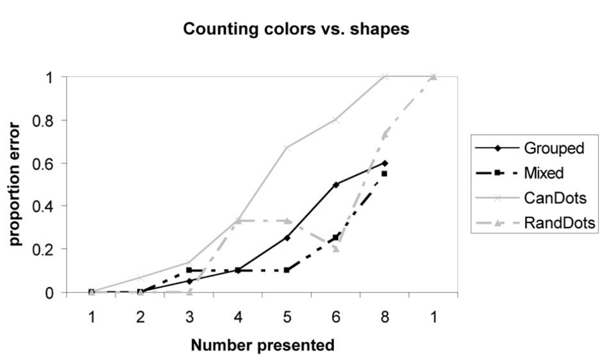

Figure 10. Proportions of errors in Experiment 6 for GK counting colors in mixed and in grouped displays and for counting multicolored dots in random (Rand) and in canonical (Can) displays.

Experiment 6: Limiting Normal Vision

One account of the spatial deficit in patients with Balint's syndrome is that they are constricted in using an abnormally narrowed attentional window so that they "see" only one part of space at a time (Thaiss & De Bleser, 1992). The data we have presented on GK's counting and estimating do not fit with this proposal because the results on estimating suggest he can adopt a broader attentional window under some circumstances. In the final experiment presented here, we sought to provide converging evidence from normal participants that GK's performance cannot solely be explained by having a restricted attentional field. In this study, we set out to investigate how neurologically normal participants perform on a counting task when their perceptional window is limited to (about) one object at a time. We varied whether the displays were made up of colored or black dots and whether the dots fell in canonical or random configurations. Do the beneficial effects of using same-colored dots and canonical configurations, which we found for GK in an enumeration task, emerge when normal participants operate with a limited spatial window? More specifically, would the data mimic the findings with GK in a counting or an estimation mode?

Method

Stimuli. The enumeration stimuli were dot patterns on a gray background (RGB: 140, 140, 140), with each display area being 800 pixels wide × 600 pixels high. There were between one and nine dots per display. The display could be partitioned by the use of an imaginary grid with cells of 100 × 100 pixels. The location of each dot was always in the middle of a cell. The dots had a diameter of 50 pixels (0.98° visual angle). All stimuli were presented on a 17-in. (43.18-cm) screen with a resolution of 800 × 600 pixels and a refresh rate of 70 Hz. The experiment was programmed in Java 1.2.2 and was run on a Windows XP platform.

There were four conditions in total. Two color conditions in which either the dots were colored, with no two dots in the same color (same colors as in Experiment 1, without the black), or the dots were all black. Aside from this distinction, there were also two configuration conditions, one in which the dots were displayed canonically and the other in which the dots were displayed at random positions.

In the canonical condition, the dots were placed in adjoining cells, with no cell in between. In the random condition, the dots were placed in randomly sampled cells of the display. The conditions were crossed, resulting in black and multicolored canonical displays and black and multicolored random displays.

Procedure. A gray mask (slightly lighter than the background of the stimuli; RGB: 200, 200, 200) hid the stimulus, while a square of 100 × 100 pixels opened randomly, showing a part of the display before the square was closed again. All 48 cells were opened at least once so that in the end, the entire display was seen. If every cell were to be opened only once, in order to count the dots, a participant would not have to retain the location of the dot but he or she could simply count the opened squares with dots in them. Therefore, the cells were split up in two groups, the marked cells (the cells that have a dot in them) and the unmarked cells (the cells that do not). Because the ratio of these two groups varied with the number of stimuli present (1–9 dots), we showed a fixed number of extra marked and unmarked cells. For 50% of the trials, 3 of the marked cells were shown a second time as well as 4 of the unmarked cells. In the other half of the trials, 4 of the marked and 3 of the unmarked cells were shown a second time. Because of this method, 55 windows were always opened on a trial. The timing used in this experiment approximately reflects the total duration needed by GK in order to try to count the items present.

All trials were randomized within the color and configuration conditions. We also controlled for order effects by mixing up the order in which participants received the four conditions.

Each trial consisted of the presentation of a focus screen for 1,000 ms, followed by 55 randomly opening windows showing parts of the display, each for 300 ms. At the end, an answer screen was presented in which the participant filled in how many dots there were behind the mask. Each participant was given a practice session of six displays so that he or she understood the task.

Participants

Six male controls, age matched to GK, participated in the study, which took place across four sessions. The participants had an average age of 63 (56, 58, 62, 65, 68, and 69, respectively). Each participant received £18 ($33.32) for his time.

Results

A repeated-measures analysis of variance revealed a significant effect of numerosity, $F(8, 40) = 44.374$, $p < .001$, partial $\eta^2 = .899$, with participants making more errors as more dots were presented. There was a reliable effect of color, $F(1, 5) = 26.237$, $p = .004$, partial $\eta^2 = .840$, with multicolored dots yielding significantly fewer errors than single-colored dots (see Figure 11). There was, however, no reliable effect of organization (random vs. canonical). None of the interactions achieved significance, though there were marginal interactions between color and number, $F(8, 40) = 2.128$, $p = .055$, and among color, number, and organization, $F(8, 40) = 1.9836$, $p = .074$.

When only the higher numerosities were considered (six, seven, eight, and nine), we again found a significant effect of numerosity, $F(3, 15) = 6.150$, $p = .006$, and a marginally significant effect of organization, $F(1, 5) = 4.655$, $p = .083$, with canonical organizations yielding more errors than randomly organized displays. It is possible that the high performance in all conditions on the smaller numerosities masked this effect of canonicality in the overall analysis.

We also compared GK's performance to this simulation of his performance with control participants. There was no reliable difference between GK's performance and that of the control group. GK's improvement in accuracy with multicolored relative to black stimuli fell within two standard deviations of the mean improvement of the control group (control: $M = 0.142$, $SD = 0.067$; GK: $M = 0.237$), as did his improvement with randomly organized over canonical displays (control: $M = 0.005$, $SD = 0.110$; GK: $M = 0.086$).

Discussion

These results largely replicate the performance of GK in the counting task. When counting, GK showed an advantage for multicolored over single-colored displays and for random over canonical configurations. When controls were given a limited visual field, they, like GK, benefited from the presence of multiple colors. Although there was no general effect of configuration with the control group, there was a trend toward improvement with randomly organized displays compared with canonical displays when performance on the larger numerosities was considered. Furthermore, GK's improvements due to the color and configuration manipulations fell within the range of the control sample. We suggest that displays with items in different colors, and displays with randomly placed items, benefit serial search with a limited spatial window, because (a) the individual colors lessen any load on spatial memory, and (b) the locations of the items can be

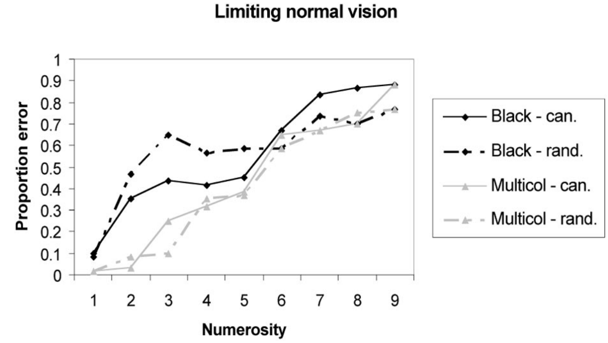

Figure 11. Proportion of errors made by control participants when counting with a limited spatial window (Experiment 7). Can. = canonical; rand. = random; Multicol = multicolored.

individuated more easily when the items are randomly positioned. This pattern held for both GK and the controls.

Our main conclusion from this experiment is that GK's performance can largely be explained in terms of his having a limited attentional window when counting. It seems that when neurologically normal participants' vision is limited to one object at a time, similar problems in counting arise to those found in GK. On the other hand, GK's estimation performance cannot be attributed to the operation of a limited spatial window of attention.

General Discussion

GK was very poor at counting, but his counting was facilitated when cues were added to individuate the stimuli in the displays—with multicolored rather than single-colored items and with random patterns rather than configural displays. His errors on counting were also at best loosely related to the numbers of items present. On the other hand, GK was above chance at estimating the numbers of items present, and his estimation performance benefited when the items were grouped—with single-colored rather than multicolored items, with configural rather than random displays, and with collinear rather than circular elements.

Exact Versus Approximate Number

At a first glance, our findings of severely impaired counting but relatively preserved estimation fit with the idea of an impaired exact number system and a preserved approximate number system, following the distinction proposed by Feigenson et al. (2004). This account stresses that the exact number is abstract, being accessible from different modalities. However, GK remains able to count when stimuli are presented in modalities other than vision (e.g., the elevator counting task in the Test of Everyday Attention; Robertson, Ward, Ridgeway, & Nimmo-Smith, 1991). This finding indicates that there is no impairment of the exact number system per se; rather, there is a deficit specifically in the visual coding of number. GK has highly impaired visual counting and there is no evidence even of accurate visual counting within the subitization range. As elaborated below, we attribute this visual counting problem to GK's impairment in visual attention and spatial representation following his bilateral parietal lesion.

Focused Versus Distributed Attention

The differences between GK's counting and his estimating can be accounted for in terms of there being contrasting modes of visual attention. Focused attention, using a narrow attentional window, is adopted for counting; a more distributed attention mode, covering a wider spatial area, is adopted for estimating. Consistent with this proposal, we found that GK's performance when he was asked to count the items present worsened with the same displays as those used for estimating. He also performed worse at counting than at estimating when the two tasks were controlled for chance levels of responding, and his counting was very poor when the display durations were limited to the exposures used for estimating. These last results further indicate that when in a focused attention mode, GK cannot explicitly use the information potentially available when a distributed mode of attention is used.

Estimating and Distributed Attention

The results when estimating indicate that patients with Balint's syndrome cannot be characterized as simply having an abnormally narrowed spatial window of attention (cf. Thaiss & De Bleser, 1992). The data also indicate that such patients are able to attend to more than one element in a display, when a distributed mode of attention is adopted. This last conclusion is also supported by evidence on the perception of hierarchical stimuli in Balint's patients. Typically, such patients are biased to identify the local elements in such displays and they can be abnormally poor at identifying global forms (Karnath, Ferber, Rorden, & Driver, 2000; Shalev, Humphreys, & Mevorach, 2005). Nevertheless, there is evidence for implicit processing of the global forms because RTs to local elements can be speeded when the global forms are consistent rather than inconsistent with the local letter identities (Karnath et al., 2000; Shalev et al. 2005). Shalev et al. (2005) further showed that such patients could be cued to a hierarchical global form if they had identified a solid large figure before the hierarchical stimulus is presented. Of note, this cuing effect dissipated rapidly as the interval between the cue and the hierarchical form increased. This finding suggests that although Balint's patients can adopt a distributed mode of attention, they find this state difficult to sustain and can quickly collapse back into using a narrow attentional window. We speculate that this bias toward a narrow attentional mode is because of damage to neurons in the posterior parietal cortex with relatively large receptive fields that help to sustain a distributed mode of attention (cf. Intriligator & Cavanagh, 2001).[2] Because of their parietal damage, Balint's patients find this mode of attention difficult. Nevertheless, our data reveal that it is possible, and when distributed attention occurs, the patients can be sensitive to effects of multiple-item grouping and interitem similarity in visual perception.

Our results also indicate that GK was more sensitive to grouping between the items when he used a distributed mode of attention (when estimating rather than counting). Thus, in the estimation task only, performance was improved with square patterns, when the elements could group by collinearity when in canonical patterns. This result is consistent with grouping by collinearity being modulated by attention (see also Freeman, Driver, Sagi, & Zhaoping, 2003); grouping by collinearity is stronger when the elements fall in an attended spatial region. This is not to say that same degree of grouping does not operate without attention (indeed GK's worse counting of items in configurations relative to randomly located stimuli suggests some degree of preattentive grouping; see Gilchrist et al., 1996, for prior evidence), but it appears that grouping interactions are stronger when the elements are attended. This finding fits with an interactive view of visual processing in which top-down attentional activation combines with bottom-up activity from stimuli to facilitate visual processing (Cinel & Humphreys, 2006; Hochstein & Ahissar, 2002).

[2] This is not to say that visually responsive neurons in other cortical regions do not also have large receptive fields; there is, for example, strong evidence for this in infero-temporal cortex (Desimone & Ungerleider, 1989). However, to the extent that parietal neurons control the focus of visual attention, then loss of parietal neurons with large receptive fields will disrupt a distributed mode of visual attention.

Counting and Focused Attention

The advantage GK showed for counting multicolored over single-colored items was also mimicked in normal observers, when they were presented with a limited spatial window over the display. This result provides converging evidence for GK having a narrow attentional window when he adopts a counting strategy, and, by contrast, when he adopts a wider window in the estimation task. Also, we note that GK's counting of color types was better than his counting of individual item tokens (see also Dehaene & Cohen, 1994).

This finding is consistent with GK having impaired location coding, with the result that he finds it difficult to tell if he has counted individual stimuli before (at least in a focused attention mode). Individual color types, however, may be identified even with poor location codes so that color counting is advantaged. For example, color types may be detected by activation in separate color maps, within a color space, that GK remains sensitive to, though he has difficulty recovering the location of any activity within each map. It appears that the parietal lobe is critical for the explicit recovery of such location codes for separate objects (see Humphreys, 1998). This disruption to GK's explicit representation of the spatial locations of separate objects can help explain his very poor counting (when operating in a focused attention mode). For example, with poor spatial coding, it may be difficult to fix attention accurately on individual object tokens, and it may be difficult to construct a spatial representation of those locations already attended. It can also help explain the rather puzzling finding that although GK can operate in a distributed attention mode, he still shows no sign of subitization. This finding is puzzling because subitization itself likely depends on a mode of distributed attention. However, subitization may, in addition, require accurate coding of object locations so that objects can be individuated (cf. Trick & Pylyshyn, 1993, 1994). Without individuation through accurate location coding, subitization is disrupted, despite GK being able to adopt a distributed as well as a focused mode of attention. An outline of the proposed relations between the mode of attention and the need for accurate spatial coding is provided in Table 1. This outline suggests that GK's performance is relatively preserved when accurate spatial coding is not required, whereas he can adopt either a focused or a distributed mode of attention for counting and estimation tasks, respectively. When in a distributed attention mode, GK shows enhanced sensitivity to grouping as well as sensitivity to statistics about the numbers of items present, but he may not have explicit information about the individual items in the group, including explicit information about their locations. We suggest that this finding characterizes the form of object coding that operates when attention is distributed across space (see also Shalev & Humphreys, 2002).

Table 1
Proposed Relations Among the Task, the Mode of Attention, the Requirement for Accurate Spatial Encoding, and GK's Performance

Task	Performance	Mode of attention	Spatial encoding
Subitizing	Severe impairment	Distributed	Required
Counting items	Severe impairment	Focused	Required
Estimating	Mild impairment	Distributed	Not required
Counting Features	Preserved	Focused	Not required

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