CHAPTER

3

Attention Mechanisms for Counting in Stabilized and in Dynamic Displays

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Summary

Numerous studies have claimed that eye movements are a critical or even obligatory part of explicit counting whereas here we will show that counting relies on a set of attention pointers that individuate targets of interest and specify their locations independently of eye movements. We demonstrate that explicit counting can proceed to very high numbers without error in afterimages where eye movements are not possible. Previous studies with afterimages had used displays too dense to allow individuation of items by attention: the displays suffered from crowding. We also show that explicit counting is defeated for displays of more than about six items in motion because there is no mechanism available to mark already-counted items and keep that marking linked to the items as they move. In this case, only the approximate number system can operate and, interestingly, this system shows fairly accurate estimates, rather than the underestimation typically seen for denser displays.

EXPLICIT COUNTING

How do we count the number of caps in Fig. 3.1? We could quickly make a rough estimate without much effort [1] or, if there were only a few, we could "apprehend" the number in a glance (subitizing [2]). However, if there are more than, say, four of them and we want to know the exact number, we have to count explicitly [3–6]. This explicit task has a number

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FIGURE 3.1 **Counting graduation caps.**

of components: 1. select an uncounted item; 2. increment the count; 3. mark the just counted item; and, 4. stop when there are no more uncounted items [7,8]. This task offers insights into how we represent the locations of the items, select them one at a time, and discriminate the uncounted from counted items. We study this task because we are interested in how a system of attention pointers [9] might underlie these selection and marking steps.

However, before we can address the attentional processes required by explicit counting, we must deal with an extensive literature that claims that attention cannot count—at least cannot count to more than four. This literature argues that, for more than four items, accurate visual counting relies on eye movements [3,10–12]. In addition to direct recording of eye movements during counting [11,13], experimental evidence supporting this counterintuitive notion comes from studies of counting in afterimages. Because afterimages move with the eyes, it is impossible to bring individual items or subsets of items to the fovea one after the other, eliminating any role for eye movements. The first such study showed that observers could accurately count no more than four items in an afterimage despite durations of up to 60 seconds [3]. This ought to have been enough time to scrutinize many more than four items individually by moving attention from one to the next. Similar results led Simon and Vaishnavi [10] to claim that counting of more than four items "requires the use of eye movements as an individuation mechanism if perfect accuracy is to be achieved" (p. 923).

It seems unlikely that a high-level task like counting would depend on the motor responses of eye movements as an obligatory operation. It is similar to claiming that we can only count using our fingers. But that has been the claim and the data have supported it. However, in our first experiment here we show that this claim does not hold up: accurate counting of sparsely arranged items can be achieved without eye movements up to quite high numbers. The original data was an artifact, as we will show, of the stimulus display.

If eye movements are not obligatory, the alternative is simply that attention can step through the items to be counted. Klahr [7], Ullman [8], Trick and Pylyshyn [6] and others have sketched simple procedures that would enumerate items, relying on the basic ability to index targets one at a time. This indexing operation is seen as the same operator as that used to track moving targets among distractors in the Multiple Object Tracking paradigm

BOX 3.1

ATTENTION POINTERS

Physiological, fMRI, and behavioral studies have shown that the spatial allocation of attention is controlled by a map (e.g., salience map [27]; map of locations [28]) that is also the oculomotor map for eye movement planning [29,30]. Although the cortical and subcortical areas that are involved have been studied initially as saccade control areas, the activations on these maps do more than just indicate or point at a target's location for purposes of programming a saccade. Each activation also indexes the location of that target's feature information on other similarly organized retinotopic maps throughout the brain (Fig. 3.2). Overall, the link between these attention/saccade maps and spatial attention is compelling, indicating that activations on these maps provide the core function of spatial attention. In particular, attentional benefits follow causally from the effects these activations have on other levels of the visual system. The definitive evidence is given by a series of outstanding microstimulation studies. When delivering electric current to cells in saccade control areas with a movement field, for example, in the lower right quadrant, a high stimulating current triggers a saccade to that location. However, a slightly weaker stimulation that does not trigger a saccade generates either enhanced neural response for cells with receptive fields at that location (stimulating the Frontal Eye Fields and recording from cells in area V4 [31]) or lowered visual thresholds for visual tests at that location (shown for stimulation of superior colliculus [32]). These findings indicate that the attentional indexing system is realized in the activity patterns of these saccade/attention maps and the effects of their downward projections. A target to be counted needs to be individuated by an "attention pointer" in these maps. Once a new target is actively indexed, the item count can be incremented and a new target must then be selected among items not yet counted.

[14,15]. Although Pylyshyn attributed this indexing to a pre-attentive operator (a FINST), others, ourselves included, demonstrate that this operation is really the central function of attention: selecting and keeping track of an item of interest [16]. Although more than one of these "attention pointers" (see Box 3.1 and Fig. 3.2) may be deployed at a time, we will focus on counting in displays where it proceeds one by one (as in Fig. 3.1). It is easy to extend the same processes to counting two or three at a time, although not much more, but this leads to the same conclusions as those that we present here.

We will argue that the major bottleneck in enumeration is in the attention system that individuates and localizes targets [9]. In particular, counting is limited by the coarseness of attentional resolution (see Box 3.2). If the display is arranged in a way that prevents the attention system from accessing individual items, then counting is severely compromised. The error of the earlier studies was exactly this point: placing the items too close to be individuated by attention. On the other hand, if the items are arranged in a way that allows the

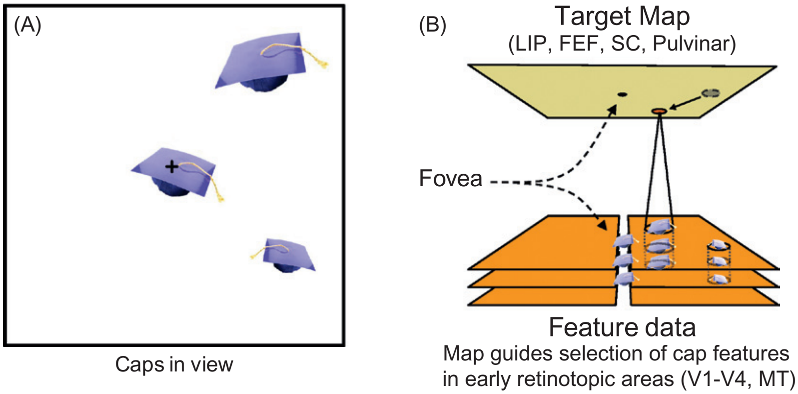


FIGURE 3.2 **Map of attention pointers.** A spatial map of attended locations directs the selection from early visual cortices (see Box 3.1). An attention pointer moves from one target to the next as one component of counting them. This map is not unlike Treisman's map of locations [28] except that it is attributed to specific anatomical structures: the sacacade control areas. Microstimulation in these areas has been shown to confer performance benefits (see [30] for a review) to corresponding retinotopic locations making these areas strong candidates for the core operations of spatial attention.

attention system to access each individual item, accurate counting can be achieved for many items without eye movements.

Our first study examines this indexing function, but counting involves both selecting the items and then, once counted, marking them as already processed. There are a number of strategies that could be considered for keeping track of already counted items. There might be a space-based strategy where counting progresses though the display from left to right, for example, always selecting the next item to the right. Or, there may be an object-based system of marking that tags counted items and where the tags stick to their items even if the items or the eyes move. Watson and Humphreys [17] claim that there are mobile markers that act to prevent the selection of a target for a second time and a similar claim is made for inhibition of return for moving items [18] or inhibitory tagging [19]. Pylyshyn [20] has demonstrated that there is indeed an inhibitory effect at the locations of moving distractors in the Multiple Object Tracking task and again this mobile inhibition might serve to mark processed items during counting. Our second study uses moving displays to test the claims of mobile object-based marking. However, we will find that explicit counting fails for moving displays. There does not appear to be any system that can tag already-processed items to prevent them from being counted again—other than attention pointers which can select and keep hold of items even as they move. However, these have a limit of about four and so are of no help for displays with more than four moving items. We conclude that explicit counting typically relies on a space-based marking of processed items.

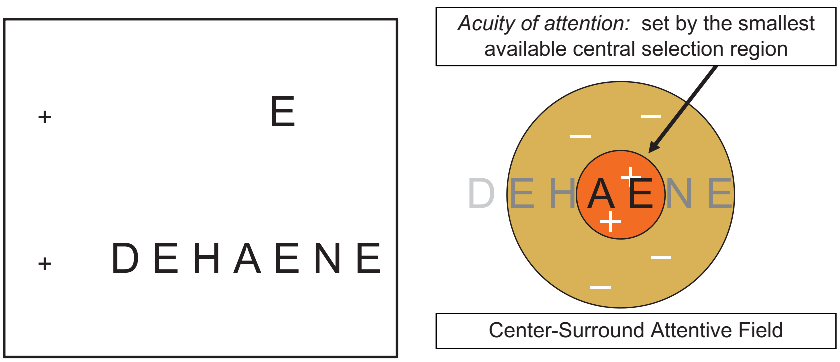
Finally, we consider the evidence that for moving displays even subitizing is degraded. In these displays, with both explicit counting and subitizing disabled, only the approximate number system [1] remains and it makes surprising overestimates for small sets of moving items.

BOX 3.2

ATTENTIONAL RESOLUTION

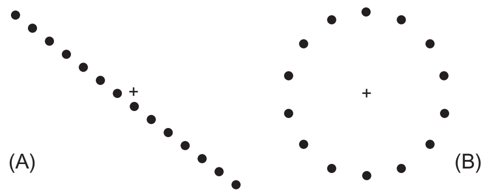
An attentional focus (the downward projection from an attention pointer) selects a spatial region for processing benefits and engages surround suppression [33,34] to prevent nearby distractors from arriving at object recognition areas. However, if two objects are too close to be isolated in a single attentional selection region, the result is the loss of individuation of the two and an irretrievable mixing of both their features (Box 3.2 Fig. 1). This feature mixing and loss of access to individual items is the hallmark of crowding. We have proposed that the cause of crowding is this resolution limit of attention—the minimum possible size of the attentional selection region at a given eccentricity [15,35,36]. So when items are too close to be individuated—when they cannot be resolved by attention—they can no longer be counted either. This is easily noted in the linear arrays of Box 3.2 Fig. 2A when keeping your eye fixed at the central + sign. The first few items near fixation can be selected and counted but then next few seem inaccessible. Interestingly, the outermost item can be picked out, perhaps by a large selection region centered further out that only reaches in to the outer item.

Attentional resolution is finest at the fovea and coarser in the periphery, like visual resolution, but 10 times or so worse so that there are many textures where we can see the items, they are above visual resolution, but we cannot individuate or count them (as in Box 3.2 Fig. 2A). Our attentional resolution is so poor that if our visual resolution were that bad, we would be legally blind. In addition to being finer in the fovea, attention resolution is also better for items arrayed tangentially, around a circle



BOX 3.2 FIGURE 1 **Attentional resolution and crowding.** When fixating the + on the left, the "E" is easy to read on top, but hard on the bottom even though it is at the same eccentricity. This crowding effect has been attributed to the resolution of attention [35], the smallest selection region available at the eccentricity of the target (see Box 3.2). If more than one item is present in the selection region, they cannot be accessed individually, their features are mixed and it is no longer possible to tell how many there are [15].

BOX 3.2 *(cont'd)*



BOX 3.2 FIGURE 2 **Examples of linear and circular dot arrays.** While fixating on the +, try to move your attentional focus to select each dot in turn in A and then B, as you would if you were explicitly counting the dots. You may find this easier in B than in A, especially for the outer dots in A where the crowding effect becomes significant. Accurate counting without eye movements is possible for more items in configurations similar to B as compared to A.

centered at fixation, like a clock face, than radially, along lines passing through fixation [15,37]. This is part of the reason why the circular array in Box 3.2 Fig. 2B is easier to count than the linear array. The other reason is that the critical spacing at which crowding becomes significant is about ⅓ of the eccentricity [38] so the items around the circle can maintain a constant spacing, always greater than the critical spacing for their eccentricity. In the linear array, however, the fixed spacing between items will always at some point become closer than ⅓ their eccentricity. The linear, radial array guarantees crowding and failure of explicit counting when fixated in the center.

EXPERIMENT 1: WHAT IS THE LIMIT FOR EXPLICIT COUNTING IN AFTERIMAGES?

Many of the early studies on enumeration without eye movements were done with the stimuli arranged linearly, centered at the fovea like that in Box 3.2 Fig. 2a [3,10]. This leads to crowding of the outer items as the critical spacing for crowding is about ⅓ eccentricity and the fixed spacing of the previously used arrays will get too close quite rapidly. In this study, we again use an afterimage to stabilize the display on the retina, eliminating the effects of eye movements. We then demonstrate that with a circular arrangement counting in afterimages can be accurate for at least up to 16 items. This number is not the real upper limit of counting performance with afterimages as we did not explore arrays with more than 16 items. The performance is limited by the quality of afterimages, the duration they remain visible, but most importantly by attentional resolution itself (Box 3.2).

Methods

Observers

Four observers, three males and one female, aged between 21 and 34, participated in this experiment. All had normal or corrected to normal vision. Three of the four observers were naïve to the purpose of the experiment, one of the authors (SH) was the fourth observer.

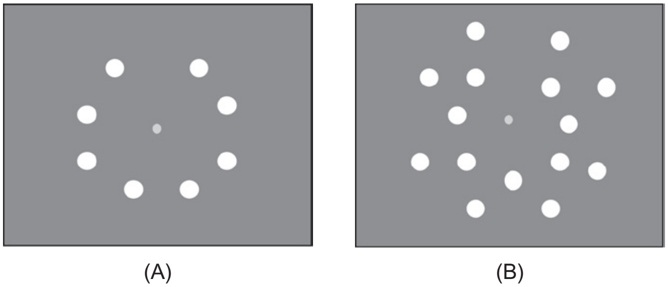


FIGURE 3.3 **Arrangements of bright discs used to generate afterimages.** (A) In the main experiment six to nine bright spots were used, placed around a circular ring with some jitter to avoid spacing cues. (B) In a second test, 14, 15, or 16 bright spots were arranged in two rings.

Apparatus and Stimuli

A large, thick, black cardboard screen was placed in front of a chin rest that could be switched between two positions to place the cardboard screen at 23 cm or 30 cm viewing distance. In the middle of the screen, an aperture was cut to expose a circular area (radius = 12.5 or 9.6 degrees, depending on the chin-rest position), where a ground glass diffuser was placed. Test cards were placed into a thin slot between the diffuser and the heavy black cardboard. The test cards were made of thin black cardboard with six, seven, eight, or nine holes punched in them using an ordinary paper hole puncher. The holes were arranged in a circular formation around the fixation. To make the configuration less regular, the spatial position of each hole was randomly perturbed from the imagined circle in a random direction (see Fig. 3.3A). This arrangement was used to prevent observers from making enumeration estimations based on regular inter-hole distances. To prevent possible familiarity from repeated exposures, four different cards were created for each number of holes yielding a total of 16 cards. The diffuser was illuminated very briefly (1 ms) by a camera flash unit (UNOMAT BC 32T) from behind so that the light was visible only through the holes, generating afterimages corresponding to the holes of the card. Figure 3.2 shows an example of the stimulus used.

Procedure

Observers were dark adapted for about 10 min before the start of the experiment. The experiment was run in a dark room. Test cards were randomly ordered and placed, one at a time, in the slot in front of the glass diffuser. When the observer was ready to begin a trial, he/she would place his/her chin on the chin rest, and fixate the small, photoluminescent dot in the center of the card. The discs on average were about 6 (or 8) degrees away from the fixation point when the chin rest was in the distant (or closer) position. After a verbal warning, the experimenter would trigger the camera flash. Following this exposure, observers were asked to count the number of discs in the resultant afterimage. To prolong their afterimage while they inspected it, they looked directly at a large, flickering uniform square that alternated between light (35 cd/m^2) and dark every 500 ms (1 Hz). Placing their afterimage on flickering background has been shown to significantly lengthen the visibility of the afterimage [21,22]. On average it usually took about 5 s for subjects to report the number of discs. There was a 2-min break before the next trial to allow the afterimage to dissipate. Each observer was tested on 16 trials, or four repetitions for each number of items. The position of the chin rest was changed between each trial (23 or 30 cm). This manipulation made the residual afterimage of the previous trial different both in size and in retinal position, hence minimized the possibility that any weak afterimage from the previous trial would be mistakenly counted in the present trial.

Results and Discussion

The results were clear. Three of the four subjects made no mistakes at all in any condition. The fourth subject made one mistake out of the 16 trials. In other words, in the combined performance of the four subjects (64 trials), only one mistake was made. The observers in our experiment could accurately count up to at least nine items when targets were presented as afterimages and eye movements were not a factor. This is twice the previously claimed limit.

Although the main purpose of this experiment was not to find the upper limit of counting without eye movements, all observers felt that they would be able to count more than nine discs. Consequently, we ran two of the four subjects (one author and one naïve subject) with 14, 15, and 16 discs. In this condition, the discs were arranged in two concentric rings (7 + 7, 7 + 8, or 8 + 8, see Fig. 3.3B). Each disc position was again randomly perturbed to avoid regularity. Each subject was tested four times for each condition. Together there were 24 trials, and both observers achieved 100% accuracy.

Although this experiment demonstrated that observers can count many items without eye movements when objects are presented as afterimages, the results were not entirely surprising to us. Earlier experiments have shown that the attention system is capable of indexing individual objects in visual space without eye movements [15,23] using only fixation instructions to control eye movements. Our current data support our belief that there is no fundamental difference between the fixating condition of our earlier attention experiments and the afterimage condition tested here. During the current experiment, observers had the sense of moving their focus of attention from one disc to the next, serving the purpose of indexing each item [6–8]. When the items were arranged in a way that minimized crowding, attentional indexing was not difficult for displays with many more items than the previously claimed limit of four [3].

Attentional resolution is not uniform across visual space being, like visual resolution, much finer in the fovea [15]. For this reason, eye movements are often required to bring fine details to the foveal area in dense displays in order for them to be selected and counted. However, we emphasize that the nature of these eye movements in facilitating counting is completely different from the claim of an obligatory role of eye movements in counting [10]. When all the display items are spaced so as to be resolvable without eye movements, counting can proceed based on movements of attention alone and the upper limit of counting performance is set by the resolution limits of attention. This attention limit is much coarser than the limits of visual resolution [15]. The scaling of attentional resolution with eccentricity predicts that the maximum number of individually accessible locations is in the range of 40 to 80 [15], an upper bound to counting which would require very long lasting afterimage or a stabilized but non-disappearing display to verify.

WHAT IS THE LIMIT FOR EXPLICIT COUNTING IN MOVING DISPLAYS?

Once an item in the display has been selected and counted, it needs to be marked so that it is not recounted. Certainly when counting using eye movements, the common experience is to use a space-based strategy, proceeding in an orderly fashion across the display, say, from left to right or from top to bottom so that the current location specifies the items remaining to be counted. In this way, counted items do not have to be actively marked as each item's status is given by the current position and the direction of progress across the display. Nevertheless, some authors propose object-based mechanisms where each previously attended item is marked "old" once attention moves away and this marking prevents attention from returning to the same location again. This object-based marking might be considered a purely local tag but Watson and Humphreys [17] claim that the mark can move with the object. Similar claims of mobile marking have been made for inhibition of return [18], inhibitory tagging [19], and distractor inhibition [20]. If this object-based tagging could really keep track of moving, already-processed items, explicit counting should be possible with arrays of moving items. If marking the already-counted items is purely space-based, however, it should fail with moving items and explicit counting should not be possible. Trick, Audet, and Dales [24] looked at counting in randomly changing displays and found that random motion did not preclude subitizing in the range of one to four items, whereas the motion did slow number discrimination above that range. In their study, however, subjects were unable to accurately discriminate numbers in the range from 6 to 9 even when they did not move and their accuracy did not get worse when the items were moving. So it remains to be seen if accurate enumeration is possible for moving displays under conditions where enumeration would be exact if the displays were static.

Methods

Observers

Ten observers, seven males and three females, aged between 24 and 45 participated in this experiment. All had normal or corrected to normal vision. The observers were naïve to the purpose of the experiment.

Apparatus and Stimuli

Between six and 18 high-contrast dots moved on a computer screen with a refresh rate of 60 Hz. The dots subtended about 0.5° and the screen 27.5° × 22.5°. Each dot followed a different circular path (7° radius), keeping all dots on the screen throughout the trial, with random centers, directions, and speeds (between 7.5° and 30° per second).

Procedure

After reading the task instruction, observers triggered each of 28 trials (four trials at each of seven numerosities: 6, 8, 10, 12, 14, 16, and 18) by clicking the computer mouse. The dots appeared in motion and continued for 10 s before disappearing. At the end of the trial subjects recorded their number judgment and clicked to proceed to the next trial.

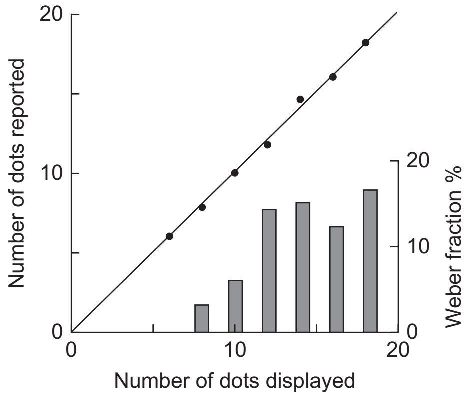


FIGURE 3.4 **Number estimation for moving dots.** With 10 observers, the average number estimated was quite close to the actual number. No errors were made in any of the 40 estimates for six items but for displays with more items, the Weber fraction of estimates steadily increased to about 15% of the number presented.

Results and Discussion

The results were straightforward (see Fig. 3.4). When the moving display had only six items, there were no errors. In this case, some subjects reported that they could track three of the items simultaneously and then rapidly "tell" that there were just three others. For more than six items, however, subjects' estimates became increasingly variable. They reported giving up on explicit counting and simply guessed. The estimates showed a Weber fraction that increased from eight to 12 items and then remained steady at about 15% (0.15, the mean absolute deviation divided by the mean estimate).

This experiment provided no evidence that there is any marking system that tags already-selected and counted items to prevent their recounting. We suggest that attentive tracking was able to individuate and facilitate groups of up to six and occasionally eight items by keeping track of three or four items and then quickly recognizing how many others there were in a glance. Beyond that number there was no obvious strategy that could track already-counted items and, as a consequence, counting depended on estimates. Note that unusually, the estimates here are quite accurate (although not precise). The mean reported number does not differ much from the actual number presented (slope = 1.07, intercept = −0.6, $r^2 = 0.997$). In contrast, numerical estimates are typically below the real value for randomly distributed static patterns [25].

CONCLUSIONS

We explored two components of explicit counting—selecting new items and marking old. The strategies used by our subjects draw on fundamental visual routines of spatial attention and help us understand the limits of these functions and how these limits constrain counting. We showed that eye movements are not obligatory for accurate counting

BOX 3.3

MOTION INDUCED OVERCOUNTING. MOTION DEFEATS SUBITIZING

In a recent paper, Afraz, Kiani, Varizi-Pashkam, and Esteky [26] report a breakdown of exact counting in displays with small numbers, three to six, of moving items. The items were equally spaced around a circular path and presented long enough for exact counting of these small numbers. Nevertheless, at higher rates of motion, the reports were reliably higher than the actual count, typically by one item even when there were only four items. Why would this happening?

We suggest two reasons. First, at the high speeds used by Afraz *et al*. [26], it is difficult or impossible to track more than a single item [39] making it hard to track a few targets and subitize the rest, a strategy we saw in our second experiment. Second, we suggest that in some conditions, rapid, accurate estimation like subitizing depends on perceiving the geometry of the dot array at a single glance [40]. Triangles and quadrilaterals can be recognized all-of-a-piece and the shape then defines the number without having to sequentially enumerate each vertex. We suggest that when a rigid dot array is rotating, the perception of its geometry breaks down and is no longer available to indicate the number of dots. Rather than triangles or squares, we just see dots moving along a circular motion path.

In the absence of the geometrical cue to number and the inability to track even three or four items at this speed, the only process available for enumerating is the approximate number system. These already-published data therefore suggest that the approximate number system overestimates for small numbers. This is an interesting observation as previously it has not been possible to evaluate the approximate number system for small number sets as other more accurate counting processes invariably intervene.

although, of course, they are useful for densely packed arrays of items where the extra resolution of central vision may be necessary. In our displays, accurate counting of up to 16 was possible in afterimages where eye movements are not possible. The actual limit with larger displays is undoubtedly much higher. The selection and individuation of items relies on a set of attention pointers [9] that are limited only by their spatial resolution. When inter-item spacing is closer than the size of the attentional selection regions, crowding prohibits access to individual items. We also found that there was no object-based marking operation that tagged items already attended and counted and that could then move if the objects were moving. Counting in moving displays even with long exposures cannot make use of a space-based strategy to keep track of counted items either. Judgments above six to eight items were likely based on guessing, calling on the approximate number system [1]. An earlier study [26] has shown that, at even higher speeds than we used in Experiment 2, exact counting is not even possible for small number sets (three to six). We argue that, at these speeds, the geometric cues to number are lost (see Box 3.3), so that even for small sets of items, only approximate judgments could be made. This is a range of numbers that has not been explored in adults with the approximate number system, and the results of Afraz *et al*. [26] show that judgments in this low range are overestimated as opposed to the classic underestimates seen for higher ranges.

Overall, the core component of explicit counting of items is the individuation of each item (or small groups of two or three) in turn, a process that is a central function of spatial attention (attention pointers [9]) matched with a space-based strategy for keeping track of counted items.

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