

What Can Spatial Deficits Teach Us About Feature Binding and Spatial Maps?

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The “binding problem” is discussed with reference to feature integration and visual search. Neuropsychological and neurophysiological findings support the existence of multiple visual areas within the primate cortex that respond to primary features of objects and spatial locations. Evidence from studies with hemineglect and Balint's syndrome supports the role of spatial attention in feature integration and demonstrates the necessity for an intact, explicit spatial representation. Some implicit spatial maps remain intact but are not sufficient to support the perception of properly bound features. The evidence suggests strong interactions between parietal spatial representations and temporal feature representations in feature integration.

INTRODUCTION TO THE PROBLEM

The “binding problem” means different things to different people. In vision it has been discussed in various contexts including grouping, the perception of illusory contours, the coherence of lines, curvature and angles that form a shape, and the integration of features such as colour and form. There appear to be many binding problems that are linked by the common question of how we perceive a unified world that seems to be delivered to visual systems in pieces.

The answer to how different binding problems are solved both cognitively and biologically may be quite different for each type of binding. The type of binding I will address in this paper has been called feature or “property binding” (Treisman, 1996). How do different features, such as motion, shape, and

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colour, which appear to be represented more strongly in one area of visual cortex than another, become bound as a unit in perception?

Feature integration theory (FIT), derived from the study of normal subjects in cognitive psychology, proposes that this type of binding requires accurate spatial information to guide attention to the location of an object (Treisman & Gelade, 1980). Recent evidence from neuropsychology supports this proposition and extends it to suggest that the spatial information underlying our experience of bound properties is explicitly represented, which probably happens at a relatively late stage of processing (Robertson, Treisman, Friedman-Hill, & Grabowecky, 1997). Finally, the spatial information that appears critical for the type of feature binding proposed by FIT has been linked to parietal function (Friedman-Hill, Robertson, & Treisman, 1995). It appears that interactions between parietal areas and other areas that represent basic features is necessary for resolving which features belong to which shapes. A discussion of the findings that led to these conclusions and the role of spatial maps in guiding spatial attention will be the focus of the present paper.

MULTIPLE VISUAL AREAS

The evidence for multiple visual areas in cortex is compelling. There are references throughout this issue and throughout the literature to different regions of cortex that show increased activation by colour, spatial frequency, shape, brightness, location, texture, or motion (Fellman & Van Essen, 1991). Responses to these features tend to be associated with posterior cortex, although more anterior areas also respond to different features, at least when memory is involved (Wilson, O'Scalaidho, & Goldman-Rakic, 1993).

Perhaps the most discussed distinction of visual parsing has been in terms of a ventral pathway involved in object processing and a dorsal pathway involved in spatial processing. To my knowledge the first evidence to support this distinction was observed in patients with projectile war wounds. Newcombe and Russell (1969) showed that groups of patients with right parietal lobe damage had spatial deficits, whereas those with temporal lobe damage had deficits perceiving object features.

This observation was later supported in studies with non-human primates where lesion location and extent could be directly manipulated (although hemispheric differences have not been the focus of these investigations). Early studies showed that monkeys were slower to learn the location than the shape of a target after parietal lesions, whereas monkeys with temporal lesions were slower to learn the shape of the target than its location (Pohl, 1973). Ungerleider and Mishkin (1982) combined electrophysiological and lesion evidence to evaluate this distinction more fully and came to the conclusion that visual input was analysed along two major cortical pathways that were

responsive to object versus spatial information. Further sub-divisions within these pathways have designated visual areas within the temporal stream that respond to object features, such as shape or colour (Desimone, Shein, Moran, & Ungerleider, 1985).

Consistently, tasks that emphasize spatial location are associated with parietal functions while those that emphasize object identity are associated with temporal functions. Studies using various techniques have implicated the dorsal system in spatial attention (Corbetta, Miezin, Shulman, & Petersen, 1993; Mangun & Hillyard, 1990; Posner, Walker, Friedrich, & Rafal, 1984; Posner & Petersen, 1990; Robertson, Lamb, & Knight, 1988), spatial representation (Andersen, 1987, 1987; Bisiach, Capitani, Luzatti, & Perani, 1981; Colby, 1991; Duhamel, Colby, & Goldberg, 1992; Freidman-Hill et al., 1995; Goldberg & Colby, 1989), as well as spatial discrimination within and between objects (Egley, Driver, & Rafal, 1994). The temporal lobe has been associated with attention to features of objects such as colour, motion, and shape (Corbetta, Miezin, Dobmeyer, Shulman, & Petersen, 1991; Livingstone & Hubel, 1988; Luck & Hillyard, 1994), as well as object identification and memory (Miller & Desimone, 1994).

Again, the neuropsychological evidence is consistent with and generally preceded these observations. Cases have been reported of patients with ventral damage who lost the ability to see colour (Meadows, 1974), motion (Zihl, von Cramon, & Mai, 1983), or shape (Efron, 1968). Because of the rarity of these types of patients and nature's disinterest in our scientific criteria, the precise areas of the cortex that produce these feature agnosias is controversial. Nevertheless, ventral damage seems to be a necessary condition in producing these agnosias (Farah, 1990). The discovery of separate areas of cortex responsive to different features posed the question of how features are recombined to produce unified wholes in perception (i.e. bound). One way to address this question is to study binding errors; that is, conditions under which accurate feature binding fails.

MULTIPLE FEATURE REPRESENTATIONS

Behavioural studies of feature binding paralleled those in neuroscience that focused on separate functional visual areas. The discovery of binding errors in normal vision by Treisman and Schmidt (1982) occurred at about the same time as proposals for dorsal/spatial and ventral/object pathways in vision. However, the full connection between the behavioural and neurobiological evidence was not immediately appreciated. A large literature developed in cognitive psychology, independently from the neuroscience literature, which was concerned with how and under what conditions features were conjoined to produce the objects we perceive.

Much of the cognitive literature has been concerned with testing the tenets of Feature Integration Theory's (FIT) explanations for selection of an object in multi-item arrays. FIT proposed a means by which separate features such as shape and colour were bound together in perception (Treisman, 1988). The cognitive mechanisms involved require a relatively intact spatial map in which attention can be allocated to locations and moved across locations in a visual array. The features, according to FIT, are represented preattentively in individual feature maps and bound together through their shared location. Focused attention at a location essentially produces an area of relative excitation through inhibition of features at unattended locations. The features within the focus of attention can then be correctly combined to produce the perception of a fully integrated object.

This theory is concerned with the accurate binding of features in cluttered arrays. A single item in the display does not require such operations because each feature map can be activated by only one feature, and there would be no ambiguity that required spatial attention to bind the proper features together. In addition, a feature that is unique in the display (e.g. a red line among green and blue lines) does not require spatial attention to be detected because there is no binding confusion.

Support for FIT has been derived from several observations. First, visual detection of the presence or absence of a feature produces reaction times that are essentially independent of the number of distractors in the display— the feature “pops out”. Second, the detection of the presence or absence of a conjunction (e.g. a red horizontal line among green horizontal and red vertical lines) produces linearly increasing reaction time as the number of distractors increases. When subjects have to bind two features together in order to find a target, there is evidence for a serial spatial search (Treisman & Gelade, 1980). Subsequent studies have shown that search can be performed on groups of distractors or weighted features that can guide attentional search (Wolfe, 1994; Wolfe, Cave, & Franzel, 1989).

Third, perception of illusory conjunctions (IC) occurs when items are presented for a brief period of time and attention is divided or diverted. (Prinzmetal, Presti, & Posner, 1986; Treisman & Schmidt, 1982). If asked to report the letter that is red in a display that contains a red A and blue X, normal subjects sometimes report the X and are very confident that they saw it as red.

Although some specific aspects of FIT continue to be debated, the theory's resilience has been remarkable given the number of studies that have tested its predictions. It has received support from both behavioural and neurobiological evidence for specialized feature representations, and its main predictions have been confirmed by neuropsychological data (a topic that will be discussed later). According to FIT, attentional allocation to a location is necessary to properly bind features for accurate perception of objects. That is, spatial attention is necessary. But this brings up a critical question. What is a location?

MULTIPLE SPATIAL MAPS IN CORTEX

In neurobiological studies, spatial location is most often defined relative to the retina. The very idea of a receptive field size emerged from the response properties of a neuron to a stimulus projected to a particular area of the eye. There are many regions of the cortex that are organized topologically. Retinotopic organization in early visual areas is sustained through early primary cortical vision (Tootell, Silverman, Switkes, & De Valois, 1982). The receptive fields of neurons in these areas are relatively small. As one progresses forward in the cortex, receptive field sizes become progressively larger and vary in the extent to which they can be retinotopically defined (Gattass, Sousa, & Covey, 1985). In anterior portions of the temporal lobe and in inferior parietal regions, neurons often respond to information within large visual areas that cross the mid-line. They can be as large as the entire visual field in some cases. Although they appear to lose topography, this is not quite true. Neurons have points within their receptive fields where spike frequency to a stimulus in a given location is highest with a trailing off of the magnitude of this response as one progresses outwards towards the edges.

Given this distribution, the definition of receptive field size will vary depending on where experimentors place the threshold for increased response activity from baseline. The degree of topography is thus defined by this threshold. Receptive fields within the parietal lobe also show increased response frequency to spatial information that is more abstract than those in primary areas of the visual cortex (Andersen, Essick, & Siegel, 1985; Goldberg & Colby, 1989). That is, they need not be driven directly by a preferred stimulus. For instance, they can begin firing in anticipation of a target in a location that the neuron "prefers" (Colby, 1991).

Other studies have shown that areas within the frontal lobe respond to preferred locations across target retention intervals (Goldman-Rakic, 1987). Neurons within the principal sulcus in monkeys continue to fire when a location is held in working memory. Other spatial maps in other areas of cortex have been found that respond to the spatial parameters of the head, arm, hand, leg, etc. (Graziano & Gross, 1994). There appear to be multiple body reference frames within the brain as well as multiple areas that respond to extrapersonal locations.

In sum, there seem to be multiple spatial maps in visual systems that can have different functions. The relationship between each spatial map and feature integration is not known. In addition, the relationship of neurons in these areas to the perceptual awareness of locations is not yet articulated. Some neuronal responses are equally strong whether the animal is anaesthetized or not. However, neurons within areas of the inferior parietal lobe have been shown to respond to more abstract properties of space in the awake behaving animal, and the neuropsychological data from humans has implicated this area in spatial

awareness, spatial attention, and in feature binding, as discussed in a later section.

MULTIPLE SPATIAL REPRESENTATIONS (COGNITIVE LEVEL)

Retinotopic, object-based, scene-based,
environmental-based maps

We often discuss “location” as if its definition is known. The world is three dimensional; every object exists in a location in space; no two objects can inhabit the same space at the same time. Yet, the space, or really spaces, we refer to in perception are those that are constructed through neural computations. In this internal world, there appear to be many spatial maps or reference frames that can govern what we see, where we look, and how our attention is allocated.

The concept that different frames of reference influence perception has had a relatively long and interesting history in psychology. At the beginning of this century, the Gestalt psychologists demonstrated the inadequacy of limiting the definition of space to retinal coordinates in the perception of objects (Koffka, 1935; Robertson, 1986). A square tipped onto one of its angles is perceived as a diamond. But if a rectangle is placed around the diamond at the same tilt, the perception of the enclosed shape becomes a square (Figure 1). The retinal or environmental frame seems to dominate in the first instance, but a frame centred on the tilted rectangle seems to dominate in the second. The form is perceived in object-centred or scene-based coordinates (Marr, 1982).

Some representational system such as spatial reference frame seems necessary to account for the perception of one object or a part of an object as “next to”, “above”, or “within” another object (Hinton, 1981; Rock, 1973). The perception of other spatial relations such as perceived size, orientation, position, and reflection would also seem to require some type of spatial coordinate representation (Palmer, 1990).

Several studies have shown that these different spatial frames do influence perception of objects. Studies using body or head tilt (where retinal and environmental spaces are dissociated) have demonstrated that people can adopt different frames when encouraged to do so (Attneave & Olson, 1967; Attneave & Reid, 1968). Other studies have shown that tilted subjects automatically adopt different frames under different stimulus conditions (Corballis, Anuza, & Blake, 1978; Corballis, Nagourney, Shetzer, & Stefanatos, 1978; Corballis, Zbrodoff, & Roldan, 1976). Further observations have demonstrated the influence of object-based frames that can be dissociated from both environmental and retinal coordinates in perceptual processing (Attneave & Reid, 1968;

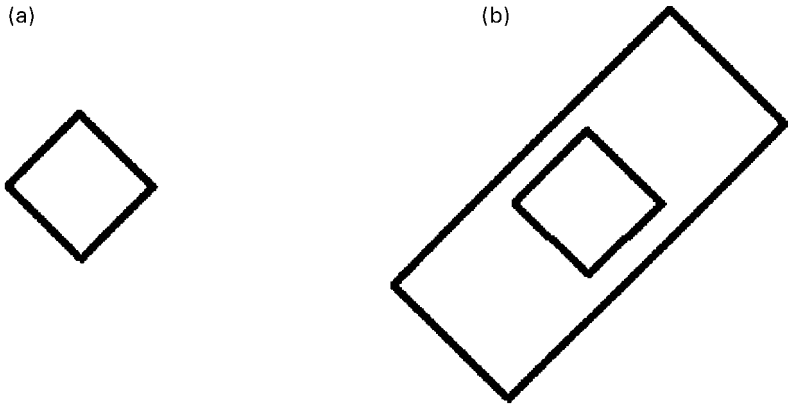


FIG. 1. Item (a) appears as a diamond; item (b) appears as a square. (Adapted from Koffka, 1935.)

Humphreys, 1983; Humphreys & Quinlan, 1988; Jolicoeur & Kosslyn, 1983; Palmer, 1980, 1990; Robertson, Palmer, & Gomez, 1987).

As the discussion in the foregoing paragraphs indicates, the question of how reference frames influence perceived shape is a familiar one. Investigations into their role in guiding spatial attention emerged more recently (Logan, 1995; Robertson, 1995; Robertson & Lamb, 1988, 1989).

Logan (1995) showed that attentional effects could be predicted by the frame the subject was cued to adopt. In one study (Exp. 8) he presented a central fixation dot surrounded by eight dots organized in a diamond-shaped matrix (Figure 2). This configuration can be conceived as 4 different diamonds defined by a subset of 4 dots; one where the central dot is located at 12 o'clock (the lower diamond), another where it is located at 6 o'clock (the upper diamond), and two others where it is either located at 3 or 9 o'clock (the left and right diamonds, respectively). Logan cued the subjects about which diamond to adopt as their frame while still fixating the central location. He then had them report the colour of a dot either to the right or left or towards the top or bottom within the cued diamond. Previous experiments demonstrated that it was more difficult to make judgements when the target location was to the left or right in a stimulus display (horizontal axis) than when it was towards the top or bottom of the display (vertical axis). Since the same dot (e.g. the central one) could be along the horizontal axis in one frame (e.g. the central dot is right in the frame of the left diamond) but along the vertical axis in another (e.g. the central dot is up in the frame of the bottom diamond), the effects of adopting a reference frame could be evaluated.

Logan found a difference in performance depending on whether the target was part of the vertical or horizontal axis of the adopted frame. For instance, the mean reaction time to respond to the central dot when it was on the horizontal

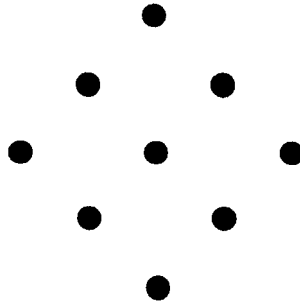


FIG. 2. The dot in the centre can be thought of as the top item in the 4 dots forming a diamond at the bottom; the bottom item in the 4 dots forming a diamond at the top; the left item in the 4 dots forming the diamond to the right; and the right item in the 4 dots forming the diamond to the left. (Adapted from Logan, 1995.)

axis of the frame was 1010 ms (left or right diamond cued), while the mean reaction time to respond to the same dot when it was on the vertical axis was 884 ms (upper or lower diamond cued).

In studies using quite a different approach, we exploited a right visual field advantage in perceiving a letter's reflection and varied the orientation of the reference frame (Robertson, 1995; Robertson & Lamb, 1988; 1989). Letters were presented briefly in either the right or left visual field, and reaction time to determine the reflection of the letters was measured. When letters are upright, the influence of retinotopic-, environmental-, object-, and scene-based frames are aligned. Thus, the frame in which the bias occurs cannot be known. Rotating the stimulus display around fixation dissociates retinal and environmental frames from scene- and object-based frames. The question was whether the rightward bias found in the upright display would follow the frame, and it did. That is, the advantage was found within the space defined by the frame independent of its orientation.

In two conditions the stimuli were presented as if rotated 90 degrees around the central fixation point from upright (i.e. appearing in the subject's upper or lower visual field but with the top of the letters pointing either to the left or right of the screen). In these cases the bias shifted with the frame. There was a rightward bias relative to the orientation of the letters in the scene-based frame (i.e. upper visual field when the frame's top was rotated leftward and lower field when the frame's top was rotated rightward).

Dell Rhodes and I (Rhodes & Robertson, 1996) have gone on to show that when the scene rotates during viewing, attention is guided by the orientation of the scene-based frame depending on the task. In the first set of experiments two columns of letters several degrees apart defined an upright frame centred on the computer screen. A small upright stick-man was centred at fixation. The frame and stick-man either remained upright or rotated 90 degrees to the right or left

around fixation. One arm of the stick-man then changed by adding an arrow to one extended arm designating the side of the frame where a target would most likely appear (endogenous orienting in a Posner cueing paradigm). Across all frame rotations subjects were faster to respond to the target when it was in the cued location than when it was in the opposite uncued location. More importantly, there were directional advantages that were predicted by the orientation of each frame (i.e. in scene-based coordinates). Attentional shifts favoured the right location in the upright frame when it was validly cued, and this advantage shifted with the frame (i.e. better for upper visual field targets when the frame rotated counter-clockwise and better for lower visual field targets when the frame rotated clockwise).

The conclusion that subjects adopt a spatial reference frame to perform a task seems to depend on subjects being aware of the different frames by which to define space. It is unlikely that subjects lose awareness of their upright position or the upright position of the room when evaluating stimuli within a rotated frame on a computer screen. But this assumed awareness begs the question of what spatial information contributes to spatial awareness, a awareness that presumably is necessary to control visual attention to a spatial location. This question has been only vaguely addressed in the literature on spatial attention, and yet it would seem fundamental in understanding how we select a location in anticipation of an upcoming target, how we search for a target in a cluttered array, how we consciously know where an object is located, and what spatial maps are required for feature integration. Because we live in a three-dimensional world, we need to be aware of a three-dimensional space. If we lived in a two-, four-, or five-dimensional world, we would need to be aware of a different space. In addition, because we live in a hierarchically structured space (with local objects embedded within more global objects) we need to be aware of spatial relationships within and between these spaces. Even if computations below the level of awareness were best formulated in other spaces (perhaps non-Euclidean), the one that is critical in getting around the world is the three-dimensional, hierarchical one in which we live. It seems reasonable that these spatial representations would be necessary in controlling endogenous spatial attention.

As the discussion in this and the previous sections suggests, there may not be just one space that guides attention. There appear to be different spaces that are useful under different conditions. As suggested earlier, it may be the case that part of attentional control involves or requires selecting the proper reference frame in which to perform a task and then directing attention to a location in this frame. If one is looking for an object across the expanse of a city view, an environmental or scene-based frame may be selected to guide attentional search. If a target is more likely to be part of an object (e.g. a pip in a lemon), then it might be more useful to use an object-based frame. If survival depends on looking at an abruptly moving object appearing in peripheral vision, then a retinotopic or

head-centred reference frame may be more important. The coordination and availability of these frames may be a necessary condition in order to perceive a unified spatial world in which unified objects are perceived.

There may well be a series of reference frames, with subordinate frames describing local object coordinates existing in superordinate frames that describe the relationship of one object to another. As will be discussed later, neuropsychological evidence has supported the hypothesis that attention within object-centred frames can be disassociated from attention within scene-based and environmental-based frames.

THE LOSS OF EXPLICIT SPATIAL INFORMATION

Unilateral visual neglect

Unilateral neglect typically occurs with damage in the distribution of the middle cerebral artery of the right hemisphere. The hallmark of unilateral neglect is inattention to and unawareness of the side of space contralateral to the lesion (Heilman, Watson, & Valenstein, 1985; Rafal & Robertson, 1995; Rizzolatti & Camada, 1987; Robertson, 1994). Since neglect is more likely to be detected with right hemisphere damage than left, this means that in patients with unilateral lesions, overall the left side of space is more likely to be ignored than the right. For discursive purposes we will discuss unilateral neglect as if it only occurs in patients with right hemisphere damage because the syndrome is more common under such conditions, but it is important to note that cases of right neglect after left hemisphere damage also occur (Ogden, 1987). The importance of visual neglect for the present purpose is that the performance deficits have been linked to attentional search, and feature-binding errors have been observed in two patients with right parietal damage resulting in extinction (Arguin, Cavanagh, & Joanne, 1994; Cohen & Rafal, 1941).

Studies by Bisiach and his colleagues (Bisiach, Capitoni, Luzzatti, & Perani, 1981; Bisiach & Luzzatti, 1978; Bisiach et al., 1979) suggested that neglect of the left side of space could occur in abstract spatial representations such as a visual image of a scene or pattern. In one study they presented pairs of cloud-like forms vertically arranged and drifting behind a barrier with only a slit in the centre where subjects could see parts of the clouds as they slowly moved rightwards or leftwards. Patients were asked to report whether the clouds in a pair were the same or different shapes. When the clouds were different shapes, and the difference was on the right side, subjects with left neglect were quite accurate in their judgements. When the difference was only on the left side, subjects judged the shapes as the same. Despite seeing the left side of the clouds only in central vision through the central slit, the left side of the representation of the cloud forms was neglected.

Partly as a result of such findings, Ladavas (1987) proposed that left neglect would be found even when all stimuli were presented to the “intact” hemisphere (i.e. all input on one side of fixation). In one condition she presented two horizontally placed objects to the ipsilesional side of fixation (i.e. both projected directly to the intact hemisphere) in a group of patients with right hemisphere damage and left visual extinction. In this case the left-most object was left of the centre of the display but both objects were to the right of fixation. Despite the fact that the left object in the display was closer to the fovea than the right object, performance was worse for the left object. This finding is consistent with a mechanism that represents the two objects within a reference frame centred on the display and then fails to attend to the object on the left side of the frame.

A different study using a conjunction search task with a group of patients (Treisman & Gelade, 1980) directly demonstrated that the magnitude of neglect varied with the extent of the display (Grabowecky, Robertson, & Treisman, 1993). When patients with left neglect were instructed to search for a conjunction target in a central area of each display, irrelevant flanker distractors presented to the right of this area (on their good side) increased mean response time to find the target in the central target area (i.e. increased their neglect). However, when the same stimulus displays with their right-sided flankers was balanced by adding left-sided flankers to the left of the central target area, reaction time to find the target then returned to near baseline (when no flankers were present). When the flankers were presented only on the neglect side, there was a small but not significant decrease in reaction time to find the target. These results are consistent with a shift in the centre of the reference frame to the centre of mass of the display. This shift was more pronounced on the right than the left suggesting that the source or centre of coordinates defining the scene-based frame was more accurately computed for spatial shifts to the right than to the left in patients with left neglect. This spatial shift may be related to an increase in binding errors found on the left side of spatial displays (Arguin et al., 1994; Cohen & Rafal, 1991). When the centre of the reference frame shifts right, the left-most side of the field outside the frame may become spatially distorted or more coarsely represented.

Other evidence showing that neglect occurs within reference frames other than retinotopic was first reported by Calvanio, Petrone, and Levine (1987). They tilted subjects 90 degrees clockwise or counter-clockwise from upright and then presented upright patterns in one of the four quadrants of the visual field. The question was whether neglect would be relative to retinal or environmental coordinates. They found that neglect was relative to both environmental and retinal coordinates. The left side of the retinally based frame suffered as did the left side of the environmentally-based one. Further studies by others extended these findings (Farah, 1990; Farah, Brum, Wong, Wallace, &

Carpenter 1990; Ladavas, 1987), and a report by Driver and Halligen (1991) showed neglect in object-centred frames as well.

A recent elegant demonstration of the role of reference frames in neglect was reported by Tipper and Behrmann (1996). In one study they showed two differently coloured circles to patients with left neglect and then asked them to detect a small dot that either appeared in the circle on the left or the right of the display. Half the time the circles were connected by a line producing a barbell type object with two differently coloured circles as ends, and half the time the two circles were unconnected (Figure 3). A critical manipulation, was that the circles could either rotate 180° or remain stationary before the dot appeared. When the display was stationary, the right dot was detected faster than the left in both the connected and unconnected stimuli. When the display rotated, the left dot (still the right side of the barbell in object-centred coordinates) was detected faster, whereas the dot in the right circle was detected faster than the left for the unconnected stimuli.

A follow-up study (Behrmann, in press) pitted object-centred and scene-centred frames against one another in a group of subjects with neglect. The barbell with its different-coloured ends was present on each trial in this study and was tilted 45° . This tilt was introduced so that two squares could be added to the display at 3 and 9 o'clock and located just below or above the ends of the barbell (Figure 4). These squares were unattached to the barbell and to each other, and they never moved. On half the trials the barbell rotated 90° so that the right side of the bar moved leftwards and the left side moved rightwards, placing each end the same distance from a square as before but in the opposite visual field. After the rotation, the location of the right side of the barbell in object-centred coordinates was closer to the left square in scene-based coordinates. A dot then appeared either in one circle of the barbell

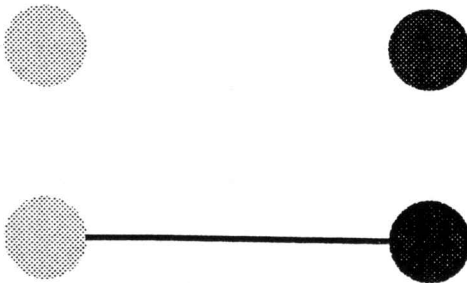


FIG. 3. The top two circles were unconnected coloured circles in the original study. The bottom two circles contained the same coloured circles but were connected by a line to form a single object (a barbell). On each trial the circles remained stationary or rotated through 180° so that the right (darker) circle remained on the right in object-centred coordinates in all cases but moved to the left in scene-based coordinates when rotation occurred. (Adapted from Behrmann, in press).

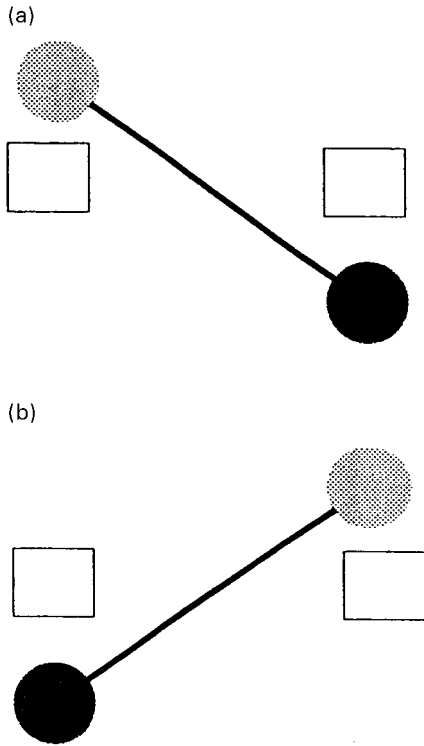


FIG. 4. The two coloured circles were connected to form a barbell as in Fig. 3 but were now placed on the screen with two squares (grey in the original study). On each trial the barbell (a) remained stationary (e.g. the darker circle remained on the right in scene-based coordinates close to the right square) or (b) rotated to produce the second stimulus (the darker circle moved to the left becoming close to the left square). In all cases the two squares remained stationary. (Adapted from Behrman, in press.)

or in one of the squares, and subjects were instructed to respond when they detected the dot.

As before, detection of the dot was better on the right side of the barbell in an object-centred frame (i.e. in the circle that was now on the *left* side of the display). However, the most remarkable result was that detection of the dot in one of the squares (which did not move) was not affected by the rotation of the barbell. The performance advantage still favoured the *right* square in the scene-based or retinotopic coordinates (the square on the subjects right) even when the barbell rotated.

These data demonstrate quite convincingly that neglect can follow movement of one frame (object-based) without affecting another (scene-based). There is not just one space directing attention, but many. One question for future research is whether this independence is asymmetrical. Would a rotation

of a global scene-based frame determine the orientation of a local object-based frame, but not vice versa? There remain empirical questions about whether different frames of reference that normally influence one another become unbound in patients with neglect or whether instead the reference frames are normally independent. In either case, how these different frames influence feature binding is unknown.

Balint's syndrome

Object-centred neglect has been observed in patients with right hemisphere damage, but somewhat paradoxically, patients with bilateral parietal damage resulting in Balint's syndrome and more severe spatial problems do not show object-centred neglect. If anything, these patients appear to attend to nothing but objects. In fact, a defining characteristic of Balint's syndrome is the perception of no more than one object at a time. However, the definition of an object can change depending on stimulus properties (e.g. closure, connectedness, common fate, etc.). Balint's patients have been shown to be sensitive to these properties.

For instance, Humphreys and Riddoch (1993) showed that when two coloured circles were attached by a line to form a barbell, their patient perceived both ends of the barbell, but when the circles were unattached by removal of the connecting line, only one circle was perceived (Humphreys & Riddoch, 1993). This example also demonstrates that the problem is not one of "tunnel vision". A larger object was perceived when the stimulus grouped into a single object, and a smaller one was perceived when it did not. These patients also see a familiar object such as an elephant whether it is drawn large or small. (Some patients with simultanagnosia do show signs of tunnel vision, but this is more common with patients having diffuse damage, see Thaiss & DeBleser, 1992. These patients can typically locate objects, unlike patients with classic Balint's syndrome).

When symptoms are severe, these patients only perceive one object at a time (simultanagnosia) even when two objects are within the line of sight (Balint, 1909; Holmes, 1918; Rafal, 1996). They also show a pseudoparalysis of gaze (optic apraxia): Although eye fixation appears frozen, if the eyes are fixated on the examiner's face, they will move freely in the socket if the head is turned for them (i.e. there is no primary motor paralysis). Finally, these patients have difficulty with visually guided reaching (optic ataxia). When reaching for the one object they do perceive, they may reach in front of them or randomly through space until their hand or arm bumps up against the object. Again, this cannot be attributed to motor deficits. Reaching for a part of their own body is unaffected and they are able to follow instructions related to spatial locations of their body

as well (e.g. raise their right or left hand on command). Egocentric space appears quite normal.

Robertson et al. (1997) have argued that simultanagnosia in Balint's patients is due to the lack of adequate explicit representations of space. If space collapses onto the object that is perceived, then it will be nearly impossible to locate that object or to know where to move attention in order to find another object. If there is no representation of space outside the perceived shape, its location cannot be calculated, and the direction of reaching will be inaccurate.

Balint's patients lose awareness of objects other than the one they perceive at the moment. When symptoms are severe they may see only local parts of an object or their attention may be drawn to items such as a watermark on a piece of paper (Rafal, 1996). On the other hand, they can report large objects in their visual field as well such as a door or blackboard if it happens to be the object of their attention. However, whether the objects are large or small, they have severe difficulty reporting where the item they perceive is located even when they are looking directly at it.

In a systematic study of a patient (RM) with these problems, Friedman-Hill et al. (1995) found that performance was at chance in judging whether an X was to the right or left or above or below an O in free viewing conditions with unlimited exposure time. His ability to judge whether the X was in the upper or lower part of a screen was slightly above chance but still very poor. Despite his difficulty in perceiving more than one object in a room, he accurately detected simple features in cluttered "pop-out" displays. Consistent with his spatial deficits upon clinical observation, however, he could not report the location of the feature he easily detected.

On the surface, this loss of spatial awareness seems similar to that observed in patients with unilateral visual neglect on their neglected side (Eglin, Robertson, & Knight 1989; Grabowecky et al., 1993), except that Balint's affects both sides of space. Some people have suggested that Balint's syndrome is a type of double neglect where both sides of space are neglected (Farah, 1990), but there remains a puzzling question as to why these patients do not lose both sides of objects as well. Neglect can occur in object-based frames (one side of the object is neglected), so it is puzzling that damage to both parietal lobes seems to reinstate perception of an object, albeit only one. However, if spatial attention is allocated within spatial frames, then damage that affects the representation of spatial coordinates could result in attention being left to attend to only objects or parts of objects; perhaps through object-based systems of the temporal lobes. If spatial information within reference frames (even object-based frames) is affected then the perceived orientation of the object may be effected as well, a prediction that was confirmed in RM (Robertson et al., 1997). Without a system of spatial reference frames the relative location and orientation of items in a display are difficult if not impossible to calculate.

Reduced ability to bind features

Patients with Balint's syndrome can identify a perceived object. That is, they are able to perceive a defining shape. Because of this ability, it was assumed that they saw the object with all its features intact, but this turns out not to be the case. The assumption also led to the proposition that spatial attention was reduced in these patients to cover only the spatial extent of the object perceived. However, this does not capture the full dimensions of the problem either. We have shown that such patients have abnormal feature binding as well. They miscombine a feature such as colour, size, or motion in the scene with the shape they perceive.

When RM was required to search for a conjunction among varying numbers of distractors, he was very poor at it. Furthermore, when he did make an error it was more likely to be a false alarm (reporting a target as present on target-absent trials) than a miss (reporting a target as absent on target-present trials). He made few errors when searching for a feature, and these errors were equally distributed across false alarms and misses. These observations are consistent with his high illusory conjunction rate. These illusory conjunctions occurred with displays of only two letters that remained on the screen in full view for up to 10 seconds. For instance, if shown a red X and blue O, he often and confidently reported that he saw the X as blue or the O as red. We later showed that this effect was independent of the distance between the two letters, further supporting the view that spatial information was not available to affect binding (Robertson et al., 1997). Other explorations of his feature-binding problems demonstrated that they extended to shape and size (Friedman-Hill et al., 1995) and to shape and motion (when the motion was linked to one of the objects in the display (Bernstein & Robertson, 1996, 1998).

If RM's attentional focus were reduced to cover only the space of the object he saw, these illusory conjunctions would not be expected. Instead, RM's visual system miscombined features that were spatially separate. The data are consistent with FIT's predictions that accurate feature binding requires spatial attention, which in turn requires an intact explicit representation of spatial coordinates. When this spatial information is lost, attentional allocation within reference frames seems lost as well. An object's shape, colour, motion, etc. may be visible, but these lack the coherence that occurs when these features can be co-located in a common location.

Implicit versus explicit spatial information

Not all spatial information about locations was affected in RM. He was perfectly able to lift his right or left hand on command and move his eyes right or left when instructed to do so. When touched by the experimenter on his back, he was able to say whether he was touched on the right or left side or at an upper or lower location. His body space was intact.

Other evidence suggested the possibility of spatial information below the threshold of awareness (Robertson et al., 1997). We presented the word “up” or “down” centred either in the upper or lower half of a large vertical rectangle. Over several sessions, RM was asked to verbally report the location of the word (taking as much time as he needed). In the first session he was at chance and had to be prodded to guess; on each trial he would shake his head and say he did not know. Yet, he was able to name the word on each trial accurately and rapidly, and his naming reaction times showed Stroop-like spatial interference. He named the word faster when its meaning was consistent with its spatial location than when it was inconsistent. Over the course of time, RM’s ability to locate the word improved, but the magnitude of the spatial interference remained the same. Thus, across changes in his ability to explicitly access spatial information, there was little change in spatial interference. These results are consistent with multiple spatial representations, but also suggest that some may be represented below the level of awareness. It should also be noted that as RM’s explicit spatial abilities improved, his ability to search for conjunctions also improved, as did his ability to bind features correctly in a two-item display.

WHICH SPATIAL MAPS ARE CRITICAL FOR FEATURE INTEGRATION?

The data as a whole are consistent with the fundamental tenets of Feature Integration Theory, but they suggest that the integration relies on an explicit map of space. Spatial attention that requires a serial search seems to require spatial awareness, as does properly combining features such as colour, motion, size, and shape. This conclusion does not necessarily exclude the possibility that spatial correlations between features can happen earlier in the visual system below some threshold for spatial awareness (perhaps as early as V1 or V2), but it does propose that the explicit ability to locate perceived items in space is fundamental to the perception of correctly bound features in cluttered arrays.

The explicit spatial experience associated with parietal function must be more abstract than spaces defined in purely retinal coordinates, and the extra computational requirements that are assumed to be involved in representing such a map could delay spatial processing and spatial awareness. If this is correct, then the findings discussed in this paper suggest that the explicit perception of bound features happens rather late in the processing stream.

I also discussed evidence that some spatial maps remain relatively intact even in a patient with severe spatial problems due to bilateral parietal lesions. RM had intact explicit knowledge of visual spatial information about his own body, and there was evidence that spatial information of a stimulus location existed below the level of awareness. Perhaps another function of the parietal lobe is to integrate different spatial maps, resulting in the experience of a unified world.

In an elegant overview of the spatial functions of the parietal lobes, Stein (1992) made a similar argument but concluded that the parietal lobes act to convert signals from one reference frame to another by accessing a set of distributed information processing rules. In his language, no “real” map of space exists in the parietal lobes. Although this is surely true, just as no real yellow exists in the brain, the question becomes how visual systems interact to represent the perception of a unified space. Just as the experience of bound features suggests an integration between such features as colour and shape, so too the experience of a unified space suggests an integration as well. This integration of spatial maps in turn appears fundamental for proper feature binding. An explicit spatial map related to parietal function has more to do than simply direct movement or action (although this is clearly one of its critical jobs). It also appears to be the basis for proper feature integration, a perceptual process.

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