Research Article

NATURE AND DYNAMICS OF REFERENCE FRAMES IN VISUAL SEARCH FOR ORIENTATION: Implications for Early Visual Processing

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Abstract—*Visual detection of a line target differing in orientation from a background of lines is assumed to occur early in vision and to involve filter mechanisms acting in parallel over the visual field in retinotopic maps (Foster & Ward, 1991; Treisman, 1985; Wolfe, 1994). But retinotopicality does not imply that early vision takes place in a retinal reference frame. This article briefly reviews experiments on this issue and analyzes their implications regarding early visual processing. The review shows that the spatial frame of reference used in visual search for orientation is dynamically determined by various sensory cues to orientation (Marendaz, Stivalet, Barraclough, & Walkowiac, 1993; Stivalet, Marendaz, Barraclough, & Mourareau, 1995). These findings suggest that intersensory integration and perceptual organization are involved at a processing level preceding visual search. This functional viewpoint is discussed in relation to data from neuroscience and psychology (visual search, microgravity).*

Most theories of vision postulate the existence of early visual processes in which local operations covering the whole visual field code in parallel basic visual features such as luminance, color, orientation, length, line termination, and curvature (e.g., Julesz, 1991; Marr, 1982; Treisman & Gormican, 1988; Zeki, 1993). Neurophysiological data and psychological models have suggested that these low-level processes encode visual input in retinotopic maps (Cavanagh, 1989; Tanaka, 1996; Treisman, 1993; Van Essen & DeYoe, 1994). Although the concept of retinotopic maps suggests that the spatial organization of feature detectors respects the topology of the retina, it does not imply that the detectors estimate the values of spatial features (e.g., orientation, size) solely within a retinally defined reference frame (vs. a gravitational frame, e.g.). In what spatial reference frame does early vision operate? When vision is involved in action, there is evidence that the reference frame is essentially determined by retinal cues. For example, Aglioti, DeSouza, and Goodale (1995) have shown that reaching and grasping is insensitive to the Tichener circles illusion even if visuomotor programming occurs after the operation of the identification processes that are sensitive to the illusion. So, it is important to distinguish the nature of early visual processes as a function of whether the goal of the perception is action or identification, as these two types of perception do not involve the same visual system (e.g., Van Essen & DeYoe, 1994). This article concerns the nature of the spatial reference frame used by early vision involved in identification. To answer this question, my colleagues and I have manipulated, in various experiments, orientation information stemming from various sensory modalities (visual, vestibular, proprioceptive, somatosensory) while subjects were performing a visual search task involving a search for a target line segment differing from distractor lines by its orientation. In this article, I briefly review these experiments and discuss their implications for early visual processing in relation to data from neuroscience and psychology (visual search, microgravity).

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VISUAL SEARCH FOR ORIENTED LINES: ANISOTROPY AND PSYCHOPHYSICAL MODELING

When the target differs widely in orientation from the distractors, visual search for oriented lines shows a classical anisotropy (or oblique effect; Essock, 1980). For example, when targets and distractors differ by 90°, a vertical or a horizontal target is detected immediately and faster than an oblique target (Marendaz, Stivalet, & Genon, 1991). However, when targets and distractors differ in orientation by about 18°, a dramatic reverse anisotropy appears. For example, when the target is tilted at 18° from the vertical, with the distractors vertical, the target pops out (i.e., search times are fast and independent of the number of distractors). When the target is vertical and the distractors are at 18° from the vertical, the target does not pop out, and search times increase with the number of distractors, suggesting spatially serial and attentional processing (Treisman, 1985; Treisman & Gormican, 1988). A similar asymmetry in search times has been observed for the horizontal (Marendaz et al., 1991).

Foster and his colleagues have shown that these search asymmetries can be accounted for by a psychophysical model containing two types of anisotropic orientation-sensitive filters (whose major axes are near the vertical and the horizontal) and a decision mechanism based on the signal-to-noise ratio observed at the outputs of these two filters (Foster & Ward, 1991; Foster & Westland, 1995; see also Wolfe, 1994). According to this model, the classical anisotropy is due to the fact that an oblique line is encoded by both vertical and horizontal filters (whereas a vertical or horizontal line is encoded directly by one type of filter). The reverse anisotropy is due to the fact that the 18° (or 108°) distractors activate the vertical (or horizontal) filters with a magnitude similar to that of the vertical (or horizontal) target. So, in this situation, no specific activation signals the presence of the target. In contrast, a target tilted at 18° (or 108°) among vertical (or horizontal) distractors pops out, because only the oblique target activates the 90° (or 0°) filters (for details, see Foster & Westland, 1995).

NATURE AND DYNAMICS OF REFERENCE FRAMES

What kind of reference frame may affect the coding of orientation? In order to examine this question, my colleagues and I used two experimental paradigms in the context of visual search for line segments whose orientation differed from the orientation of distractors by 18°. In the first, the postural-gravitational reference frame was manipulated by modifying the subject's posture. In a second paradigm, we manipulated the visual context by circumscribing the displays with a square frame at various orientations. If the processing of orientation in visual search operates in a purely visual (i.e., retinocentric) reference frame, the same reverse anisotropy should be obtained whatever the orientation cues stemming from the visual context or other sensory modalities. In each experimental condition, the subjects were given an additional alphanumeric visual search task: finding a *Q* among *O*s (parallel search) or an *O* among *Q*s (serial search). The purpose of the second task was to ensure that any variation in response patterns obtained with line segments was due to a change in the reference frame and not to noise associated with the experimental conditions. The results showed that posture or visual context did not influence performance in the alphanumeric search task.

Postural-Gravitational Reference Frame

Figure 1 summarizes the data my colleagues and I (Marendaz, Stivalet, Barraclough, & Walkowiac, 1993; Stivalet, Marendaz, Barraclough, & Mourareau, 1995) obtained in experiments manipulating the weighting of vestibular, proprioceptive, and somatosensory inputs. Subjects were presented with item configurations while standing upright, lying supine, sitting immobilized, or sitting under centrifugal acceleration. (A cone whose diameter subtended a visual angle of 10° occluded everything except the central portion of the screen.)

The results showed that the amplitude and direction of the anisotropy varied as a function of postural-gravitational cues. First, when the subjects were standing upright, the vertical and horizontal axes were sensorily "overenforced" because of the convergence of various cues provided by the vestibular system (which codes the direction of balance, Stoffregen & Riccio, 1988; and gravitational acceleration), the muscular and articulatory endocaptors (which regulate the balance of muscular tonicity), and the cutaneous exocaptors (which record the relative pressure

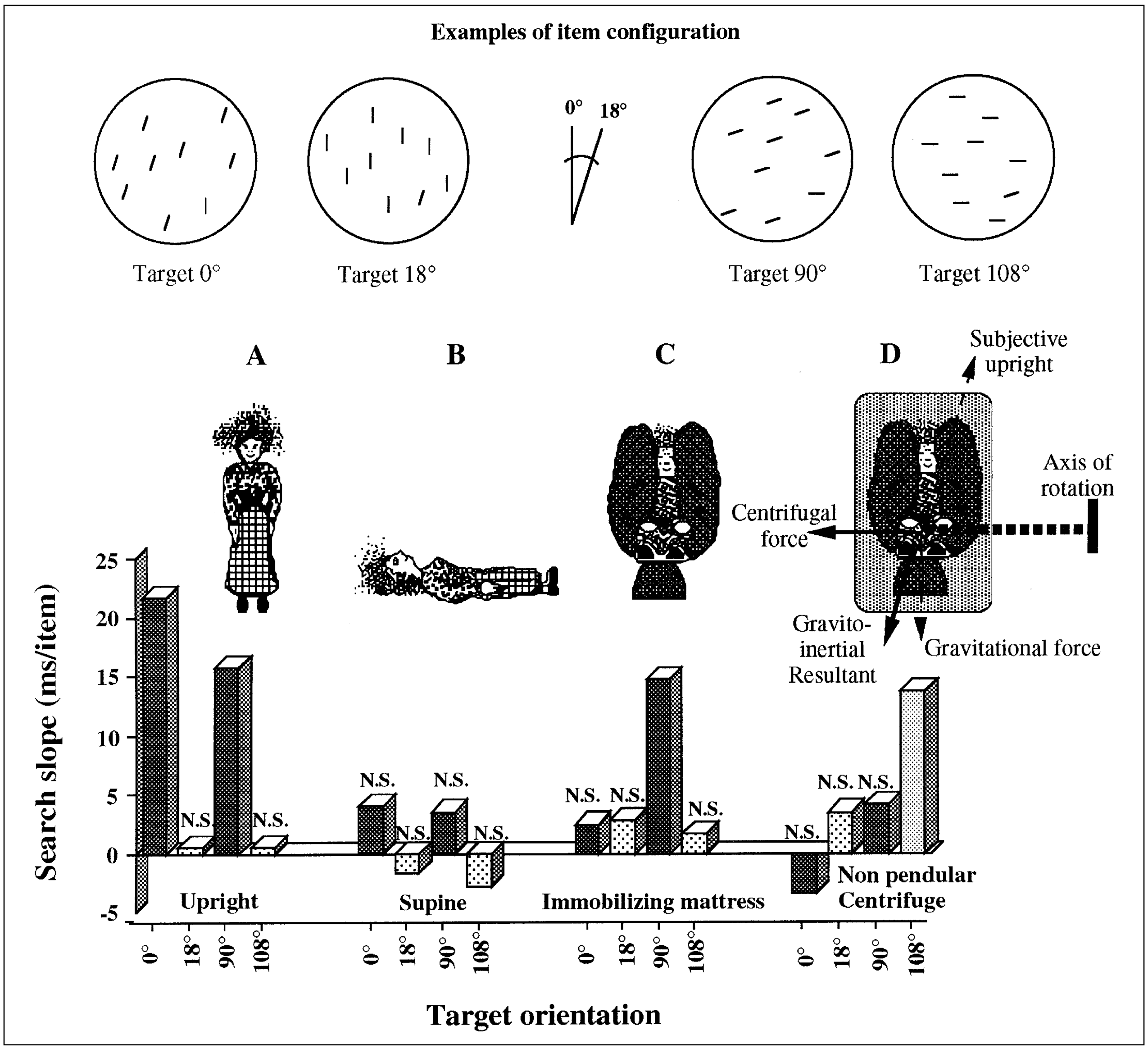

Fig. 1. Examples of item configurations and search slopes as a function of target orientation and subjects' posture. Subjects were presented with item configurations while (a) standing upright, (b) lying supine, (c) sitting immobilized, or (d) sitting under centrifugal acceleration (adapted from Marendaz, Stivalet, Barraclough, & Walkowiac, 1993, and Stivalet, Marendaz, Barraclough, & Mourareau, 1995).

across the soles of the feet). In the visual search task, a serial-attentional search for vertical and horizontal targets was observed (Fig. 1a).

Second, when subjects were supine, most sensory cues relevant to the definition of the egocentric vertical and horizontal reference axes were suppressed or largely diminished. These cues were diminished because in this condition the display plane is orthogonal to the gravitational vertical, the subjects do not have to maintain their posture, and the stimulated mechanoreceptors are nonspecific pressure receptors. In the visual task, a rapid and spatially parallel search for vertical and horizontal targets was observed (Fig. 1b).

Third, when subjects were sitting immobilized, most cues that participate in establishing the vertical reference axis were suppressed. In particular, these cues include vestibular information associated with the direction of balance and proprioceptive information from the neck muscles and articulations. Nevertheless, the pressure mechanoreceptors and the proprioceptors in the buttocks were active, and their outputs indicated the direction of the resultant of the compression forces. In the visual search task, a parallel search for vertical targets and a serial search for horizontal targets were observed (Fig. 1c).

Fourth, in the centrifuge condition, subjects were sitting immobilized in a nonpendular cabin, and a centrifugal acceleration (due to the rotation of the cabin) was imposed on them, modifying the direction of the gravito-inertial force (as coded by the vestibular system) and the resultant of the compression forces (as coded by the pressure mechanoreceptors). The latter corresponds to a force whose direction is given by a combination of cues provided by the pressure mechanoreceptors of the buttocks (baroreceptors) and by those parts of the body in contact with the side wall of the cabin. The subjective vertical and horizontal arising from these forces (measured by means of adjustment of a rod and adjustment of the cabin) were tilted about 18° (or 108°) relative to the gravitational and bodily axes. In the visual task, a rapid and spatially parallel search was observed for all target orientations except the subjective horizontal (target tilted at 108°), for which the search was serial-attentional (Fig. 1d).

Taken together, these results show that the reverse anisotropy of visual search for orientation depends to some extent on the nature of nonvisual orientation information.[1]

Interestingly, recent data from orbital flights have shown that some visual anisotropies disappear under microgravity. The orientation task used in microgravity (aboard the Russian MIR space station during various orbital flights in 1992, 1993, and 1993–1994) was not a visual search task but a bilateral-symmetry detection task (Leone, Lipshits, Gurfinkel, & Duhamel, 1994; Leone, Lipshits, McIntyre, & Gurfinkel, 1995). Subjects were required to determine as quickly and accurately as possible if a two-dimensional polygonal shape was symmetrical or not. The axis of symmetry could be vertical, horizontal, or oblique. Data obtained on the ground showed a very strong oblique effect (the detection of vertical or horizontal axes of symmetry was faster than the detection of oblique axes of symmetry), and a less strong but significant anisotropy in favor of the vertical over the horizontal (Leone et al., 1995). Data obtained in microgravity showed that if oblique effects persist, the vertical-horizontal anisotropy disappears during orbital flight (after about the 13th day of flight) and then reappears on the ground postflight; after about the 4th day postflight, its magnitude is similar to that observed in control subjects (Leone et al., 1994, 1995). Consistent with our experiments and their interpretation, Leone et al. observed a disappearance of the vertical-horizontal anisotropy on earth when subjects were in the supine position.

The fact that the oblique effect remains in microgravity underlines the limit of the effects sensory interactions have on the visual coding of orientation. But what would happen during a longer term of weightlessness? This issue will be considered during the MIR flight planned for 1999, during which the original experiments and those my colleagues and I conducted to study visual search for orientation will be replicated. The length of this orbital flight, 3 months, will permit researchers to examine the long-range effects of vestibular-visual interactions on the processing of orientation in both tasks in microgravity and postflight.

Visual Reference Frame

Figure 2 summarizes data obtained in experiments in which the orientation (upright, 18°, or 36°) of a square frame (angular size of 10° × 10°) surrounding the line displays was manipulated (Marendaz, Ohlmann, & Stivalet, 1996; Stivalet, 1995). The frame was displayed simultaneously with the configuration of line segments and was followed by a multioriented mask. In order to limit the number of experimental conditions, we presented only the 0° and 18° configurations in most of the experiments. The subjects performed the visual search task while standing upright.

The results show that the amplitude of the anisotropy varied as a function of the frame orientation. First, when the frame was upright, a serial-attentional search for vertical targets was observed (Fig. 2a), and the anisotropy was slightly more pronounced than that obtained without a visual frame (Fig. 1a). Second, when the frame was tilted at 18° from the vertical, a rapid and spatially parallel search for vertical targets was observed (Fig. 2b). Third, when the frame was tilted at 36° from the vertical, the same results as those with an upright frame were obtained: A serial-attentional search was observed for vertical targets, and a parallel search was observed for other target orientations, even when the target matched the frame (the target was tilted at 36° from the vertical; Fig. 2c).

How can we interpret the latter result? One possible explanation is similar to that provided for the rod-and-frame task (RFT), in which subjects are asked to place a rod in an upright position inside a square frame. In fact, the frame effect obtained in visual search for orientation is very similar to that observed in the RFT, in which the size of rod-adjustment errors depends on the degree of the frame's tilt. Figure 2d summarizes the data obtained by Spinelli, Antonucci, Goodenough, and Pizzamiglio (1991) with an RFT frame having an angular size of 10.5°. They found that errors varied sinusoidally in relation to frame orientation, with a peak of errors when the frame was tilted at 15°. A Fourier analysis of the errors indicated that the data could be accounted for by a 90° and a 45° sine wave. The presence of the second component of 45° cycle length might be interpreted as a tendency toward reversal in error direction. This tendency might be explained by the hypothesis that for a frame tilted from 0° to 22.5°, the

1. Interestingly, even if the experiments do not say anything about the possible level of intersensory integration (early vs. late), recent data from the haptic perception of orientation have also shown the dramatic role of gravitational cues (provided by the scanning arm-hand system) in the occurrence of the classical anisotropy (Gentaz & Hatwell, 1996). For example, when the orientation task was performed in a horizontal plane (Experiment 1), the oblique effect was present when the forearm was unsupported in the air (in this case, antigravitational forces were elicited during scanning) and was absent when the forearm was supported (by remaining in physical contact with the surface of the apparatus).

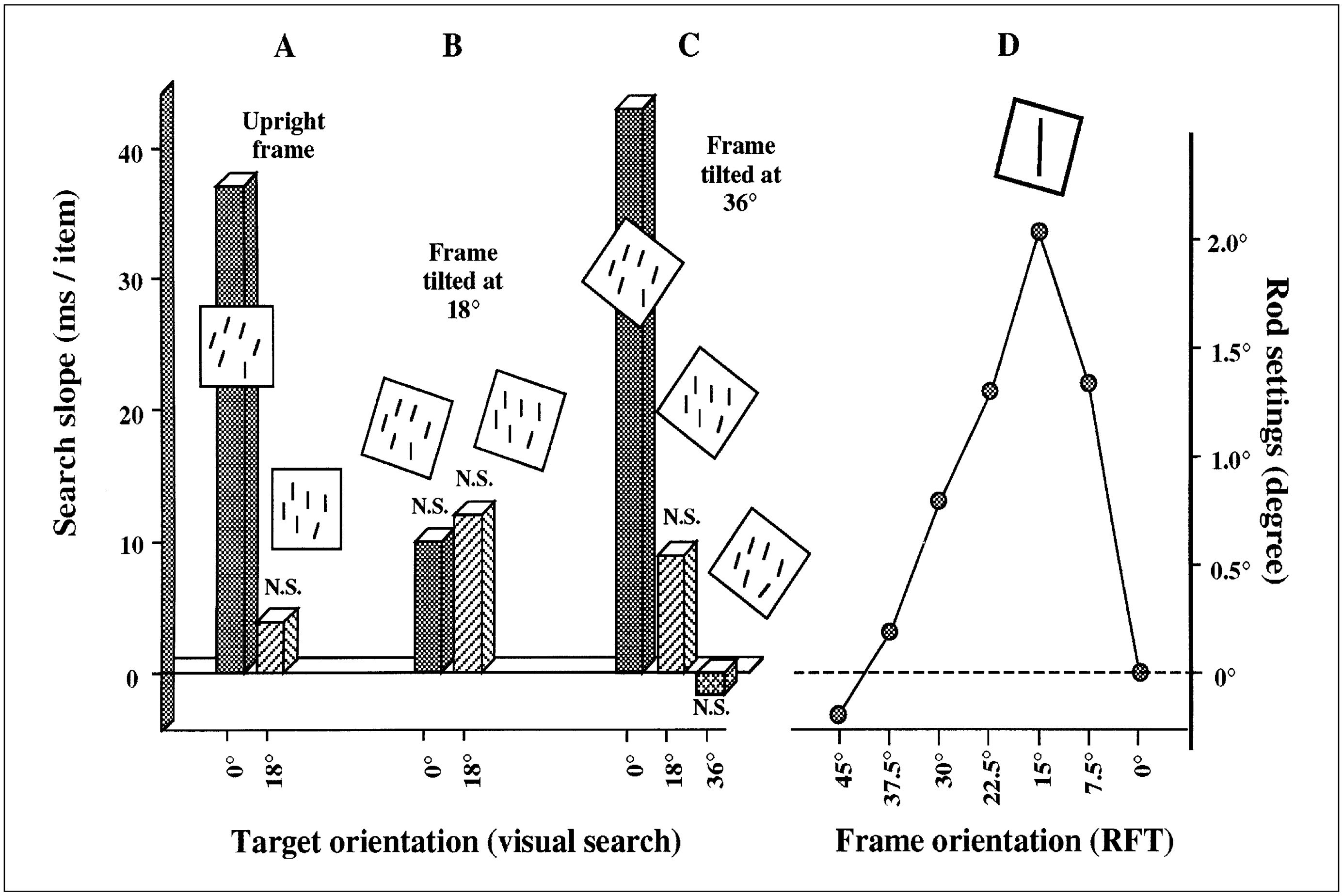

Fig. 2. Search slopes in visual search for oriented line segments as a function of target orientation and frame orientation (a, b, c), and rod adjustments to the subjective vertical in the rod-and-frame task (RFT) as a function of frame orientation (d). In all experimental conditions, the frame size was about 10° of visual angle. In the visual search task, the frame was (a) upright, (b) tilted at 18°, or (c) tilted at 36°; in the RFT, the frame orientation varied from 0° to 45°, by 7.5° steps. The frame effect seems to show the same type of anisotropy in the two tasks (see the text). (Panels a, b, and c were adapted from Marendaz, Ohlmann, & Stivalet, 1996, and panel d was adapted from Spinelli, Antonucci, Goodenough, & Pizzamiglio, 1991.)

subject uses mainly one side of the frame as a reference, whereas from 22.5° to 45°, the axis of frame symmetry (the vertical diagonal) is the main reference.

These experiments show that the anisotropy in visual search for orientation depends also on the visual frame. In fact, a visual frame can generate three types of effects: It can modify the angular contrast (the virtual angle between frame contours and line segments may produce a slight distortion in the perception of the line segments' orientation; e.g., see Howard, 1982), act as a distractor (comparable to the line segment distractors), or constitute a spatial reference system. However, the first two types of effects cannot account completely for the findings: The angular contrast cannot explain the similar effects found when the frame was upright and tilted at 36°, and a frame acting as a distractor suggests a serial search when the target's orientation matched that of the frame. (In this case, the target would become conjunctive, sharing its orientation with the frame and sharing its size with the other line segments; Treisman's feature integration theory predicts serial target detection in this kind of situation because no particular basic visual feature indicates the presence of the target.) However, no serial search was observed when the target's orientation matched that of the frame tilted at 36°. Therefore, the contextual frame may act as a spatial frame of reference that determines the encoding of line segment orientation in combination with other nonvisual cues.

This account is consistent with the data reported by Treisman (1985) for a frame tilted at 18°. The experimental conditions were similar to those described here except that the frame was smaller (7.7° × 6.8°) and, more important, the head was immobilized, diminishing the weight of cues for the gravitational vertical. In this situation, Treisman observed a stronger frame effect: The anisotropy was reversed (search for 18° was serial-attentional, and search for the vertical was parallel), but this anisotropy was of a lower amplitude relative to that obtained with an upright frame as a result of a conflict between visual and gravitational reference frames.

IMPLICATIONS FOR EARLY VISUAL PROCESSING

The spatial reference frame implicated in visual search for oriented lines is not only retinal but dynamically determined by various sensory cues to orientation (visual, vestibular, somatosensory). These findings suggest that intersensory integration and perceptual organization are involved at an early level of processing. I discuss this possibility in the current framework of visual search and visual neuroscience.

Early Sensory Integration

One way of interpreting the relation between visual search performance and nonvisual orientation cues is to postulate that the encoding of line orientation is specified not solely in terms of retinal coordinates, but dynamically in relation to a reference system that is also determined by the subject's body orientation. In psychophysical terms, this means that vestibular, proprioceptive, and somatosensory orientation cues dynamically calibrate the tuning values of the orientation filters (Marendaz et al., 1993).

Such a calibration implies that intersensory integration occurs at an early level of visual processing. Has such an integration of vestibular and somatosensory signals been observed at the level of neurophysiology, in the primary visual pathways? The most clear response comes from the work of Sauvan and Peterhans (1995, 1997; see also Metzler & Spinelli, 1979; Tomko, Barbaro, & Ali, 1981). These authors showed that 7% of the (examined) neurons in striate cortex (V1) and 40% in extrastriate cortex (V2, V3, and V3a) of the alert monkey are of a compensatory type, showing no change in the preferred stimulus orientation whatever the body tilt. This finding suggests that the encoding of orientation to which these cells respond is defined by a gravitational reference frame. From a functional viewpoint, this finding suggests that the mechanisms producing selectivity of visual orientation in cortical neurons include extraretinal signals (vestibular from otolith organs; proprioceptive from the neck muscles, the joints, and the gravity receptors of the trunk) about the direction of gravity, and that this information is integrated at an early stage of visual processing.

Early Perceptual Organization

The results from the experiments in which a visual frame was applied suggest that the frame acts as a spatial reference system that determines, in combination with nonvisual reference frames, the coding of the orientation of line segments. The effect of the visual frame suggests that the spatial properties of the background configuration precede and partially determine visual search performance. The effect of the visual frame could constitute evidence in favor of the assumption that surface representation must precede some perceptual functions such as texture perception, visual search, and visual motion (Grossberg, Mingolla, & Ross, 1994; Nakayama, He, & Shimojo, 1995; Rensink & Enns, 1995; Treisman, 1993). The assumption stems notably from experimental work showing an effect of surface segregation on visual search. Enns and Rensink (in press) have provided an illustrative example of the effects of the local surface on visual search. In one condition, the subjects were asked to search for an incomplete black square with a curved notch in one corner, among complete black-square and white-circle distractors (mosaic condition). In this condition, the target popped out (mean search slopes were 6 ms/item on target-present trials and 7 ms/item on target-absent trials). In another condition, the subjects searched for the same target, except that a white circle was placed over the notch (occlusion condition). From a phenomenological viewpoint, this latter display gives the impression of figure occlusion, as if a complete black square were behind the circle. When in the time course of visual processing does object completion take place? If visual search takes place before object completion, subjects should have searched at the same rate in the occlusion condition as in the mosaic condition; but if visual search takes place after object completion, a slower search time would be expected. Data obtained in the occlusion condition showed that the search was serial-attentional (mean search slopes were 36 ms/item in target-present trials and 66 ms/item in target-absent trials), suggesting that figure-background segregation and object completion occur in parallel across the visual field before visual search.

However, in the case of a search for oriented lines, it is not clear that the frame effect belongs to the category of surface effects. At a theoretical level, the frame effect could simply stem from the coarse-to-fine time course of frequency analysis of visual space (e.g., Ginsburg, 1986; Hughes, Nozawa, & Kitterle, 1996). For instance, it is possible to imagine a model in which the dynamic behavior is given by the sequential extraction of orientation primitives from low frequencies to high frequencies. The dominant orientations in the low frequencies represent the extraction of the frame orientation, which influences the perception of the lines at high frequencies. Such a model does not require the concept of surface, which would involve restricting the interactions between low-pass and high-pass filters to the surface defined by the frame. So, whether the frame effect originates in surface effects remains an open issue.

CONCLUSION

The spatial reference frame supporting visual search for oriented lines is not only retinal but dynamically determined by various sensory cues to orientation (visual, vestibular, somatosensory). These findings suggest that intersensory integration and perceptual organization are involved at an early level of processing preceding visual search. This viewpoint is consistent with the idea, currently supported by several authors, that the primary goal of the rapid and parallel processes of early vision is to recover as much of the scene structure as possible (e.g., Nakayama et al., 1995; Rensink & Enns, 1995). Our experiments specify that the recovery of this scene structure involves multisensory processes. However, the multisensory character of early visual processes could be particular to perception involved in identification. In fact, as noted in the introduction, there is some evidence that the reference frame is essentially retinal when the goal of visual perception is action (Goodale, 1996). If this assertion is right, the functional account of the reverse anisotropy discussed in this article suggests that this anisotropy may disappear when subjects are asked not to detect but immediately to reach and grasp the target. This is a strong prediction that my colleagues and I are testing in further experiments.

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