Amodal completion and localization

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Abstract

In a three-line vernier acuity task, a central line was localized between two aligned line segments. Accuracy did not improve when the segments formed a unified amodally completed percept. In a two-line vernier acuity task, a line was localized below a target line placed next to a physically segmented flank stimulus. Shifts in mean points of subjective equality suggested that amodally completed segments influenced localization. Previous conflicting findings are explained by a representation that is available early to influence perceived alignment. However, position tuning is poor. This representation may be realized physiologically by interpolation responses between amodally completed segments. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Fragmentation of contours in a retinal image does not always signal the existence of gaps in the distal image. In fact, under certain constraint conditions, the fragmented retinal image continues to exist perceptually in the cortex of the observer, as modally completed illusory contours, or as amodally completed contours with an occluding surface (e.g. Kanizsa, 1955). Cortical completions in the form of illusory boundary contours have been shown, in many paradigms, to be functionally similar to physical completions (e.g. Pomerantz, Goldberg, Golder & Tetewsky, 1981; Ramachandran, 1985; Berkeley, Debruyn & Orban, 1994; Greene & Brown, 1997). The findings relate well to alert monkey data that suggest a neurophysiological basis in area V2 for the formation of anomalous (i.e. perceived by humans as illusory) contours (Peterhans & von der Heydt, 1989).

The concern of the present study is the completion of fragments without visible contours. This instance (i.e. amodal completion) occurs when an image is perceived as a whole behind an occluder. As such a completion

process is essential for the perception of an non-fragmented visual world, it is of theoretical and practical interest to various fields of vision research. Recent findings from animal neurophysiology indicate that when occluded, some receptive fields in the striate cortex of cats (Li & Li, 1994) and monkeys (Gattas, Fiorani, Rosa, Pinon, De Sousa & Soares, 1992) expand beyond their classical sizes to regions surrounding the occluder. In effect, they become regions of interpolation for stimuli (e.g. bars) placed on opposite sides of the occluder. Unlike illusory completions in area V2 (see Peterhans & von der Heydt, 1989), these striate cortex responses bridged gaps only when an occluder was present. Could interpolated receptive fields in striate cortex be the basis of early processes for amodal completion?

Psychophysical evidence suggests the existence of such early processes. For example, Weisstein (Weisstein, 1970; Weisstein, Montalvo & Ozog, 1972) has demonstrated grating specific adaptation for regions of the visual field perceived to contain an amodally complete grating behind an occluding object. Specifically, a diagram of a cube was placed in front of an adapting grating such that the grating was perceived to complete amodally behind the cube. Observers fixated the center of the cube during the adaptation period. In a control condition observers fixated the center of a hexagon that

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replaced the cube creating the impression of a hole in the adaptation grating. After adapting, a small grating patch appeared at fixation and its perceived contrast was measured. Despite the extreme similarity in proximal stimulation between these two conditions, the greater adaptation in the cube-in-front-of-grating relative to the hole-in-grating condition suggests a grating-like neural representation was formed for those parts of the adaptation grating perceived behind the cube. The basic findings of the Weisstein experiments have been replicated under stereoscopic viewing conditions (Gyoba, 1979). In addition, amodal completion (AC) has been shown to influence the perception of (i) apparent motion behind luminance-defined occluders (Shimojo & Nakayama, 1990) and behind gap-induced illusory surface occluders (Yantis, 1995), (ii) visual phantoms (Brown & Weisstein, 1991), and (iii) orientation-contingent color aftereffects (Watanabe, 1995).

Contrary to these findings, Mussap and Levi (1995) found no evidence of early representations of AC (for localization). They argued that if AC were represented at an early level then accuracy in gap vernier acuity should be expected to improve when an occluder is placed over the gap. The logic is that the neural representation of the target and comparison lines behind the occluder would essentially reduce the gap (either from propagation of the real lines, or from an interpolated activation of receptive fields (RFs) located between the lines). Their results for the occluder conditions showed that, whereas there was a diminished willingness to report that a displacement was present in a yes/no vernier acuity task, there was no accuracy improvement in a left/right forced-choice task. Mussap and Levi (1995) therefore suggest that for localization AC is represented at a later level, but not at an early level. This interpretation of results in the later level yes/no task is consistent with other findings, for example, in the study of pattern recognition, where AC has been shown to modify performance (Nakayama, Shimojo & Silverman, 1989; Sekuler & Palmer, 1992; Brown & Koch, 1993; Ringach & Shapley, 1996). In the present study the representation of AC as it relates to localization is investigated further.

2. Experiment 1: three-line vernier acuity

In Mussap and Levi's (1995) study, occlusion did not improve, or in some cases, degraded performance in their left/right vernier acuity task. Their explanation was that localization does not support AC at an early level. Here, we offer possible alternative explanations for their data. First, assuming that AC were represented at an early level, it is possible that the representation is not similar to luminance representations. This suggestion is reasonable given findings that illusory

induction is not represented in a luminance-like manner at an early level (e.g. Greene & Brown, 1997). Second, AC occurs best when the contours to be completed are aligned. This notion is supported by neurophysiological data from early visual processing areas (Gattas et al., 1992; Li & Li, 1994). However, in Mussap and Levi's (1995) study, AC was to be made on *misaligned* bars. Whereas AC may have been strong at a shape recognition level in the visual system, it may not have been optimally represented within lower-level mechanisms tuned for fine localization. Thus, it is not abundantly clear from Mussap and Levi's findings that AC is not supported at an early level for localization.

In Experiment 1, we tested the hypothesis that when conditions are optimal for AC (i.e. when lines are aligned), localization accuracy may be improved. We did this by studying performance in a three-line vernier acuity task with and without an occluder. The separated test lines were always vertically aligned and the task was to localize a centrally placed comparison line left or right of their position. Performance in the unoccluded control condition (i.e. the split flank condition) was compared with the occluded condition where the separated test lines were now perceived to be amodally complete behind the occluder. If AC facilitates localization then differences in performance should be found between the two conditions. No differences between conditions would support Mussap and Levi's (1995) position.

2.1. Methods

2.1.1. Observers

Two male adult observers (HG, LG) participated in the experiment. HG is well trained (with over 30 000 trials in various vernier acuity settings) and was aware of the purpose of the experiment. LG was unfamiliar with vernier acuity and was unaware of the experiment's purpose. Observers had normal (LG) or corrected-to-normal (HG) vision.

2.1.2. Stimuli and apparatus

Fig. 1 depicts diagrams of the displays presented on a Samsung SyncMaster 4^+ color monitor. Stimuli were viewed binocularly from a chinrest 1.83 m from the monitor. Background luminance on the screen was 33 cd/m². The outer target lines (7.5′ high × 3.78′ wide) and central comparison line (3.78′ × 3.78′) had a luminance value of 79 cd/m². The luminance of the zero disparity occluder in the AC condition was 0 cd/m². Ambient illuminance near the chinrest was about 663 lumens/m².

2.1.3. Procedure and data analyses

On each trial, the display appeared for 500 ms with the comparison line at displacements of 0′, 1.26′, 2.52′
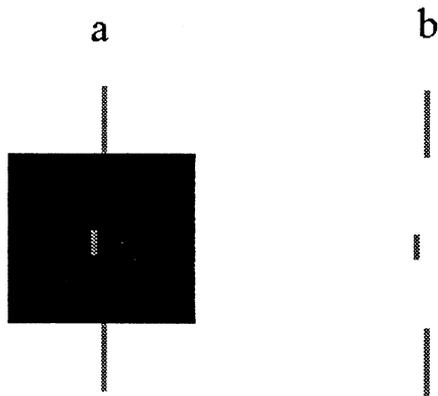
Fig. 1. Diagrams depicting three-line vernier acuity configurations used in Experiment 1. Observers readily perceived a single line behind the black occluder in (a) (i.e. AC condition), and two separate outer line segments in (b) (i.e. split condition). The task was to localize the middle comparison line left or right of the outer line(s).

or 3.78′ to the left or right of the collinear target lines. Display duration was sufficient for the perception of AC (e.g. Sekuler & Palmer, 1992). The comparison line's vertical position was centered between the separated test lines. Within a session, three blocks of trials were presented via the method of constant stimuli. The vertical separations between the test lines in the trial blocks were 15′, 50.7′ and 84.54′. In a single block, observers received 50 trials per comparison line dis-

placement. The task was to indicate, via the computer keyboard, whether the comparison line was perceived to be to the left or right of the test line configuration. Inter-trial interval was fixed at 2 s. A block of trials lasted approximately 15 min and including short breaks, a session was completed within 60 min. Observers participated in three sessions each in the split flank and AC flank conditions. The effect of the occluder on three-line vernier acuity thresholds was assessed. The percentage of 'right key' responses was plotted as a function of actual positions of the comparison line. The data were fitted by best fitting sigmoids defined by a Boltzman equation[1] (see Press, Teukolsky, Veetterling & Flannery, 1992). Vernier acuity threshold for each block of trials was based on 350 responses and was defined as the width of the sigmoids.

2.1.4. Results and discussion

Phenomenologically, the test line configuration was readily perceived by both observers as a single line behind the occluder. In the split flank condition, this unified percept was absent. Thus, the stimulus configu-

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[1] Fitted point

$$= \frac{(\text{least \% 'right key'} - \text{most \% 'right key'})}{1 + e^{\wedge}((\text{comparison line displacement-point of subjective equality})/\text{width of sigmoid})}$$
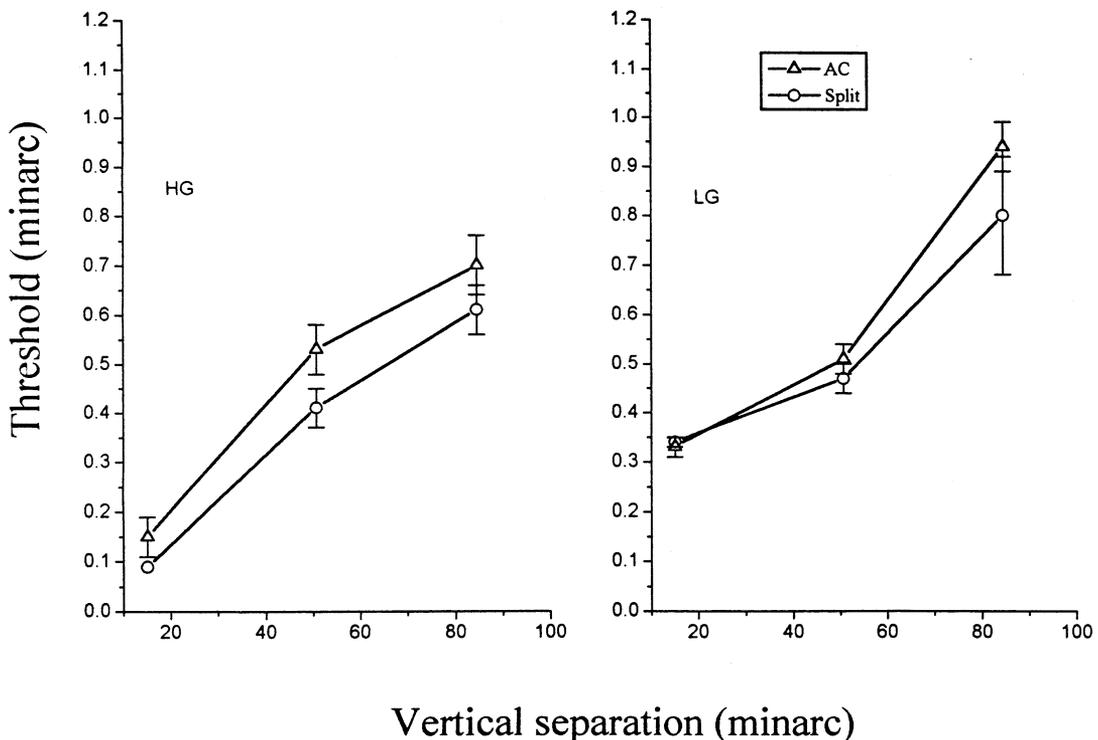

Vertical separation (minarc)

Fig. 2. Thresholds (i.e. the width of psychometric functions) as a function of vertical separations between the outer lines. Thresholds were not reliably smaller in the AC condition. Thus, accuracy of localization was not improved by AC.

ration in the AC condition affected pattern recognition, or higher-level visual processing (e.g. Nakayama et al., 1989; Sekuler & Palmer, 1992; Brown & Koch, 1993; Mussap & Levi, 1995; Ringach & Shapley, 1996). However, as was found by Mussap and Levi (1995), AC did not facilitate vernier acuity judgements. Fig. 2 shows that whereas performance declined as a function of the gap between the target lines, thresholds were not lowered when the target configuration was perceived as a single line behind an occluder.

The present methodology is probably more sensitive to AC than that of Mussap and Levi (1995) because the target lines were aligned. Yet, AC still did not facilitate localization accuracy. Hence, the present results convergently validate those of Mussap and Levi (1995). Given that visibility of a contour can be critical for localization accuracy (Wang & Levi, 1994), the absence of a visible boundary in AC may account for this lack of facilitation. Mussap and Levi (1995) suggested two possible representations for this invisible percept. In one representation, a neural line response that propagates behind the occluder is instantiated. This line propagation may reasonably be expected to maintain the fine localization tuning associated with the real lines. Subtly different from this, is an interpolation representation in which RFs behind the occluder are activated, without propagation of a line (detailed illustrations appear in the paper by Mussap and Levi, 1995). An interpolation representation cannot be expected a priori to maintain the fine tuning of the real line ends abutting the occluder. The lack of facilitation to localization accuracy argues against a line propagation representation. However, the findings may be explained by an interpolation representation with coarse localization tuning behind the occluder. Furthermore, an interpolation representation can account for poorer localization accuracy in AC conditions (e.g. in Mussap & Levi, 1995; Fig. 2, here). Hypothetically, such a representation might be expected to interact with the representation of real lines. Experiment 2 tested this hypothesis.

3. Experiment 2: spatial interactions in two-line vernier acuity

Localization is generally done effortlessly and with superb accuracy (Westheimer, 1979). However, it can be biased by interactions from the neural persistence of a previously inspected contour (Hock & Eastman, 1995; Pollack, 1958; Ganz, 1966) and by interactions from the simultaneous presence of a nearby contour (Rentschler, Hilz & Grimm, 1975; Badcock & Westheimer, 1985a,b; Greene & Brown, 1995, 1997; Hock & Eastman, 1995; Rivest & Cavanagh, 1996). Bias occurs as a shift in the apparent location of contours such that they appear closer (i.e. attraction effect), or farther apart (i.e. repulsion effect) than they really are. As documented in the more recent literature, shifts are influenced by spatial, temporal and transient/sustained factors. For briefly presented displays with small (i.e. 2′–5′) separations between equally long flank and target lines, attraction has occurred when the flank and target lines have the same direction of luminance contrast (Badcock & Westheimer, 1985a; Hock & Eastman, 1995), and when the transient onset of the flank line interacts with the target line (Hock & Eastman, 1995). Brief presentations with small separations between flank and target lines have effected a repulsion effect when (i) a gap is introduced to a longer-than-target flank such that there is no overlap in the horizontal direction between flank and target (i.e. split flank; Badcock & Westheimer, 1985b), (ii) the transient offset of the flank line interacts with the target line, both of which have the same direction of luminance contrast (Hock & Eastman, 1995), and, (iii) the flank and target lines have opposite directions of luminance contrast (Badcock & Westheimer, 1985a). The sustained presence of a flank (with the same contrast polarity as the target) has been shown to elicit an attraction effect that tends towards repulsion with increasing separation from the target (Hock & Eastman, 1995). Finally, minimal (repulsion) shifts have been elicited by a longer-than-target flank, to which a central gap has been introduced such that there is *some* overlap in the horizontal direction between flank and target (Badcock & Westheimer, 1985b). Repulsion becomes stronger as the spatial overlap between flank and target is reduced (i.e. with wider gaps in the flank).

Systematic shifts have inspired descriptions of functional mechanisms of localization (e.g. Badcock & Westheimer, 1985a,b; Hock & Eastman, 1995; Rivest & Cavanagh, 1996; Greene & Brown, 1997). One such mechanism is an elongated two-process representation for thin lines (Badcock & Westheimer, 1985b). The representation consists of an elliptical long-range surround zone wrapped around an antagonistic short-range central zone.

At small flank-to-target separations, within the central zone, the direction of shift is sensitive to contrast polarity (Badcock & Westheimer, 1985a). Otherwise, if target and flank are each within one of the opponent zones, shifts occur irrespective of contrast (Badcock & Westheimer, 1985a,b). Finally, when the flank is segmented vertically, such that it overlaps the central and surround zones of the target, competition from the two opponent zones can lead to minimal net shifts (Badcock & Westheimer, 1985a,b). This final axiom was utilized in Experiment 2. A central gap was introduced to a longer-than-target flank, and the flank was placed next to a target line such that there was some overlap in the horizontal direction between flank and target. It was hypothesized that AC across the gap in the flank would
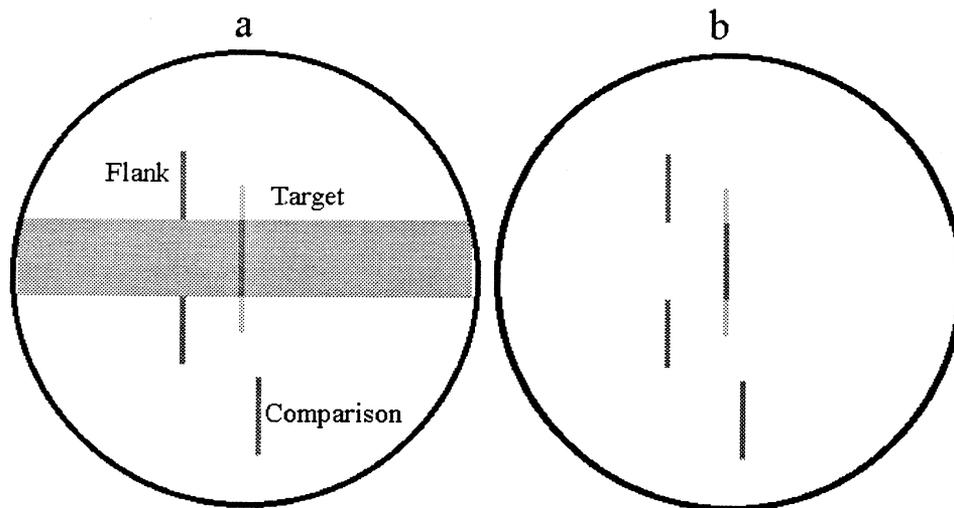
Fig. 3. Diagrams depicting the stimulus configurations used in Experiment 2. A blue filter (a) was placed on the screen surface such that it was physically in front of the computer generated lines in 3D space (i.e. AC flank condition). In (b), the stimulus was the same, with the filter peeled off the screen surface (i.e. split flank condition).

weight competition from the opponent zones towards an attraction effect.

3.1. Methods

3.1.1. Observers

Eleven naive observers participated in the experiment. All observers had normal vision and were unaware of the purpose of the experiment.

3.1.2. Stimuli and apparatus

Fig. 3 depicts diagrams of the stimuli used. The target line was always to the right of the flank. The two experimental conditions were termed AC flank (Fig. 3a) and split flank (Fig. 3b). Background luminance was 33 cd/m^2. The line stimuli were configured in a tripartite manner. The ends of the target line were 72″ high and 72″ wide, with a luminance of 79 cd/m^2. The flank ends were 3.6′ high and 72″ wide, with a lower luminance of 57 cd/m^2. The middle part of the tripartite stimulus configuration was 8.4′ high.

Unlike the computer-generated occluder in Experiment 1, the present 'occluder' was an 8.4′ high × 1° wide translucent blue plastic filter placed physically on the screen of the monitor. The filter reduced background luminance by 12%. The intensity of the part of the target line that overlapped the filter in space was set by each observer such that it appeared behind the translucent filter in 3-D space. Thus the target did not appear to adhere to the surface of the filter (called depth capture; e.g. Watanabe & Cavanagh, 1992). In the AC flank condition (Fig. 3a) the flank appeared as a line with intensity too low to be visible through the translucent filter. Thus, for this condition, the blue filter appeared translucent for the target but opaque for the flank which

appeared amodally complete behind it. In the split flank condition, the blue filter was removed such that the flank was perceived as two separate lines partially overlapping the target in the vertical direction. The comparison line positioned 6′ below the stimulus configuration, had the same luminance and size dimensions as the middle part of the target. Stimuli were viewed through a 1° diameter circular aperture in a black cardboard mask placed in front of a CTX brand color monitor. Viewing was binocular from a chinrest 2.86 m from the display. Ambient illuminance around observers was about 800 lumens/m^2. Pilot observations indicated that stimulus dimensions were suitable for the vernier acuity task.

3.1.3. Procedure

Each trial was initiated by pressing the space bar key. In the AC condition, trials were only initiated when the flank appeared amodally complete behind the occluder. The flank and target stimuli stayed on the screen for the duration of each block of trials. On each trial, the comparison line appeared for 500 ms at offsets of 0″, 14.4″, 28.8″ or 43.2″ to the left or right of the target line. The task was to indicate via the computer keyboard whether the comparison line was perceived to the left or right of the target line. Trials were blocked by Flank to target separators (FTTSs). There were four FTTSs, 2.4′, 4.8′ 7.2′ and 0′ (i.e. the no-flank control condition). In a single block, observers received 50 trials per comparison line displacement via the method of constant stimuli. A block of trials lasted approximately 15 min, with a complete session, including short breaks, being completed within 75 min. Observers participated in both experimental conditions, with the constraint that they could participate in one session only during any given day.

3.1.4. Results

For both flank conditions, a mean psychometric curve was plotted for each FTTS ($n = 11$ observers). Each such curve was fitted with the best sigmoid as in Experiment 1. Fig. 4 shows shifts in the point of subjective equality (PSE) for flank trials relative to no-flank baseline trials. Error bars reflect the standard error associated with the calculated PSEs. Generally, baseline PSE in both AC and split flank conditions was biased leftwards of objective equality (i.e. PSE of 0″ in Fig. 4) by about 6″. There was no significant difference between the two baseline conditions ($P > 0.05$ from error bars; see Dunlap & May, 1989). Thus, a line representing the mean of both baselines was used for comparing performance in both conditions. Points above baseline represent a shift of PSE towards the flank (i.e. attraction effect) and points below baseline represent a shift of PSE away from the flank (i.e. repulsion effect). For the AC flank condition, there was an attraction effect when the flank was close to the target (i.e. 2.4′–4.8′ FTTS). This effect declined when the flank appeared beyond 4.8′. In contrast, for the split flank condition, there was little systematic effect of the flanks within the FTTSs tested. A comparison of AC and split flank conditions shows different shift magnitudes at the 2.4′ FTTS. Beyond this small FTTS, shifts became increasingly similar. Thus, the results suggest an influence of AC in this localization task.

4. Discussion

Grossberg (1987, 1994) has argued that the generation of all boundary contours is done without visible

Fig. 4. Performance in Experiment 2. Shifts in mean points of subjective equality suggest that AC flanks influenced localization.

contrast. In addition, boundary contour completion is accomplished simultaneously at different depths (Grossberg, 1994). Visible feature filling-in occurs within surface boundary contours, such that figure regions are seen at closer depths than ground regions. Partially occluded shapes are recognized, and are able to modify pattern recognition performance (Nakayama et al., 1989; Sekuler & Palmer, 1992; Brown & Koch, 1993; Ringach & Shapley, 1996) because of invisible boundary contour completion in depth. In Experiment 2, we hypothesized that AC may be accomplished by an interpolation representation that was capable of interacting with a luminance-defined representation. Similar interactions have been observed between luminance-defined boundaries and, illusory and color-defined boundaries (Greene & Brown, 1995; Rivest & Cavanagh, 1996; Greene & Brown, 1997). An interpolation response as hypothesized for AC may be accomplished by grouping of line-ends by early mechanisms of vision, to form a boundary contour representation as envisioned by Grossberg (1994). Compared to the subtly different line propagation representation discussed in Experiment 1 (Section 2.1.4; see also Mussap & Levi, 1995), an interpolation representation cannot be expected a priori to maintain fine tuning for localization.

The present findings supported our hypothesis, in that for the smallest FTTS, the AC flank elicited a shift in PSE relative to baseline. No reliable shift was apparent for the split flank at this FTTS. At other (i.e. larger) FTTSs, AC flank and split flank performances became increasingly similar. The findings are consistent with two-process representations for localization (Badcock & Westheimer, 1985a,b; Levi & Waugh, 1996). For small FTTSs, interactions were sensitive to AC, and for wider FTTSs, shifts were similar irrespective of the percept (or local contrast). Similar two-process representations have been articulated in various forms to account for localization accuracy (e.g. Levi & Waugh, 1996) and contrast sensitivity facilitation by line-ends (Yu and Levi, 1997).

Experiment 2 indicates that the invisible representation of AC can influence the internal representation for localization. Thus, in retrospect it is possible that the central comparison line in Experiment 1 may have been susceptible to perturbing influences from the amodal representation behind the occluder.[2] Such an interference could have hindered vernier performance in the AC condition to effect the results exhibited in Experiment 1. However, we discount the strength of such an explanation for two reasons. Firstly, even with such an interference, localization about a central gap can reasonably be expected to show net improvement if the
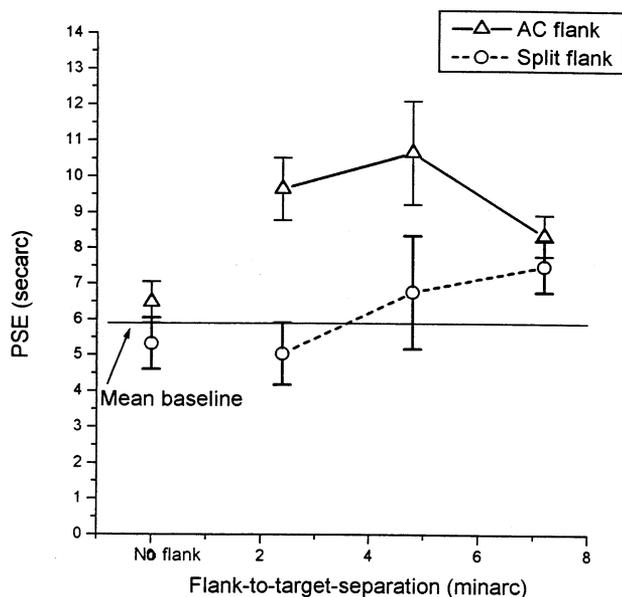
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[2] We thank an anonymous reviewer for bringing this to our attention.

gap is completed by a luminance line, or an illusory line (see Pomerantz et al., 1981), or even an amodal contour representation. Secondly, in the study by Mussap and Levi (1995), the stimuli were configured such that there was no potential for interference from the amodal representation, yet the results in our Experiment 1 are similar to theirs.

Combined, the findings of our experiments reconcile AC's failure to facilitate localization accuracy (Mussap & Levi, 1995; Experiment 1) with findings that indicate effects of AC on early level tasks. Early level effects have been shown for contrast adaptation (Weisstein, 1970; Weisstein et al., 1972), the perception of apparent motion (Shimojo & Nakayama, 1990; Yantis, 1995), the perception of orientation-contingent color aftereffects (Watanabe, 1995), and the perception of visual phantoms (Brown & Weisstein, 1991). Here, we argue that AC is accessible to early mechanisms of localization, but does not necessarily facilitate localization accuracy. Earlier findings by Greene and Brown (1997) with illusory lines suggest that a primary contributor to interactions of the sort reported here is the boundary contour, not the filling-in feature that makes lines visible (e.g. luminance and illusory contrast; see Grossberg, 1987, 1994 for detailed discussions of invisible boundary contours made visible by feature filling-in). Localization accuracy is to a large degree, dependent on line visibility (Waugh & Levi, 1993; Wang & Levi, 1994), a condition not available with AC. In this regard, it is worthwhile to note that gap completions that result in the formation of (visible) illusory boundary contours *do* facilitate localization accuracy (Pomerantz et al., 1981). Physiologically, the coarse localization tuning with amodally completed lines may reflect the involvement of wider long-range RF mechanisms.

The present results are consistent with recent neurophysiological data. When occluded, some RFs in area V1 of monkeys (Gattas et al., 1992) and area 17 of cats (Li & Li, 1994) expand beyond their classical sizes to regions surrounding the occluder. As a result, they become regions of interpolation for stimuli (e.g. bars) placed on opposite sides of the occluder. These types of RFs may be the basis of early processes for AC. Finally, the findings provide psychophysical evidence for the existence of an AC representation whose influences extend to early mechanisms of localization. Future work must investigate the spatial and temporal limits of this representation.

Acknowledgements

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