Attention and Blind-Spot Phenomenology

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ABSTRACT: The reliability of visual filling-in at the blind spot and how it is influenced by the distribution of spatial attention in and around the blind spot were studied. Our data suggest that visual filling-in at the blind spot is 1) less reliable than it has been assumed, and 2) easier under diffused attention around the blind spot than under focal attention restricted in the blind spot. These findings put important constraints on understanding the filling-in in terms of its neural substantiation. Recent neurophysiological studies suggest that V1 neurons corresponding to the blind spot in retinotopic map extend their receptive fields far beyond the blind spot and are not silent during the filling-in (Komatsu, Kinoshita, and Murakami, 2000). For those neurons to subserve filling-in, it may be crucially important for top-down attention to match their receptive fields.

1. Introduction

The visual blind spot is formed at the back of each eye in an area called optic disk, which is essentially a hole in the retina through which the axons of ganglion cells bundle to exit the eye to form the optic nerve. It is "blind" because no photoreceptors exist there for receiving information from the world. Subtending about six degrees of visual angle, it is a surprisingly large gap in each visual field. We are not aware of the blind spot in normal binocular vision because a distal stimulus that projects to the blind spot in one eye necessarily reaches a receptive spot in the other eye. However, even with one eye covered, we remain oblivious of the blind spot, unless forced to go through a procedure designed for demonstrating the blind spot. The phenomenal absence of a gap corresponding to the blind spot has been referred to as "filling-in".

The phenomenal "filling-in" does not necessarily imply a visual percept corresponding to the blind spot: One could feel or illusorily believe to have a seamless expanse of visual space in front of the eye in the absence of complete visual awareness of it. Although visual filling-in does seem to occur in the demonstration of the blind spot, it must depend on a special mode of attention. Referring to Figure 1, the demonstration requires the observer to cover one eye (the right eye in this case), keep fixating at the cross, adjust viewing distance from the figure, and try to notice the disk. At certain viewing distance, the observer is bound to notice the disappearance of the disk and in its place the filling-in of the background (white color). Unlike normal viewing, the procedure implicitly requires directing attention to the blind spot and its surrounding peripheral field. How important the attention is for the filling-in can be appreciated by contrasting the demonstration with recent studies on "change blindness" (see Rensink, 2002, for a review) and "inattentional blindness" (e.g., Mack and Rock, 1998). In those studies, attention is effectively distracted from a supra-threshold stimulus (or a large change in a visual scene) by various means. As a result, the stimulus invariably fails to reach awareness. The visual filling-in of the blind spot, as a form of visual awareness, should be no exception for the pivotal role of attention in conscious vision.

Figure 1.

The display for finding the blind spot in the left eye

In short, we suspect a close link between the phenomenology of the blind spot and how visual spatial attention is deployed, with reliable visual filling-in possible only when the observer engages attention to the blind spot. Given the strong empirical support for change blindness and inattentional blindness, however, it would make little sense to test whether the visual filling-in, as a form of visual awareness, occurs at all in the absence of attention. What is more interesting is how spatial distributions of attention in and around the blind spot influence the percept of that region.

Directing spatial attention to the blind spot sounds oxymoronic because there is no sensory input there to be attended to. It is possible, however, to direct attention to where the blind spot appears to be in the visual field. Although no photoreceptors exist at the physiological blind spot (the optic disk), there are neurons in a monocular area of V1 corresponding to the blind spot in retinotopic map. It is possible that activities of those neurons subserve the filling-in and are modulated by attention.

We started exploring these issues by presenting a bar across the blind spot for monocular viewing. The bar was expected to look continuous across the blind spot according to a number of previous reports (e.g., Ramachandran, 1992a, 1992b). Our informal observations, however, yielded an unexpected finding: the bar looks more broken than continuous when one tries to confine attention to the blind spot in an attempt to scrutinize the percept formed there. This observation led us to suspect that a continuous bar is seen only when attention is diffused enough to cover the parts abutting the blind spot. Follow-up experiments largely confirmed this hypothesis. These results will be discussed in terms of the constraints they put on understanding the functional and neural mechanism of the visual filling-in.

2. Initial Observation

We first attempted to assess to what extent the blind spot is visually filled in, and to what extent it remains "blind", i.e., a spot of phenomenal uncertainty. Previous reports of the filling-in phenomena have been impressionistic, often relying on informal demonstrations. While such reports may be regarded as "existence proof" for the visual filling-in, what emerged at the blind spot can be unstable. It is important to know how frequently a naïve viewer, following proper procedures, albeit under no explicit control of attention, reports filling-in of the blind spot by its surround.

2.1 Methods

All stimulus displays were presented on a 17" color PC monitor. The display was viewed with the left eye and the right eye was covered with an eye patch. A chin rest was used to achieve steady fixation. 18 subjects were recruited from a voluntary subject pool maintained by the Department of Psychology at Grand Valley State University. All of them had normal or corrected-to-normal vision according to self-report.

The display was viewed 40cm from the monitor. During the test, we first ensured that a bright red disk 4 deg in diameter and 15 deg left of the fixation was entirely within the blind spot. This was accomplished by taking following cautionary measures. First, the distance and the height of the chin rest were individually adjusted to render the red disk invisible when fixation was properly maintained. Second, any time during a trial, if the red disk became visible again, the subject must signal it by pressing a key. When this happened the trial was discarded.

Each trial began with locating the blind spot by adjusting the head position. After the red disk disappeared from awareness, the subject pressed a key, which triggered a white vertical bar to be added into the display. The bar was centered at the same location as the red disk and partially occluded by the latter. It remained in view for 500msec, after which the subject made a choice response (again by a key press) indicating whether a continuous bar or a bar with a gap was seen. Subjects were encouraged to report as accurately as possible.

The bars were of seven different lengths (8.1, 12.5, 17.6, 20.1, 24.0, 26.7 and 29.8 deg) at a fixed width (1.4 deg) and seven different widths (0.4, 0.9, 1.1, 1.4, 2.3, 3.1, and 4.0 deg) at a fixed length (20.1 deg). Each of them was presented four times. The bars of the fixed width were presented in two sets of 14 trials----seven trials of increasing (or decreasing) lengths followed by seven trials of decreasing (or increasing) lengths. The bars of the fixed length were presented in two similarly structured sets of 14 trials each. The order of the fixed-width trials and fixed-length trials were counterbalanced across subjects.

2.2 Results and Discussion

As shown in Figure 2, the bar was reported as continuous or containing a gap about equal number of times. Across subjects and the shapes of the bar, subjects reported seeing a continuous bar on 47.3± 4.3% (95% confidence interval) of the trials. The frequency for perceiving a continuous bar was not influenced by the bar length, F(6, 102) = .584, ns. However, there was a slight trend towards significance for the effect of the bar width on perceived gap size, F(6, 102) = 1.88, p = .091.

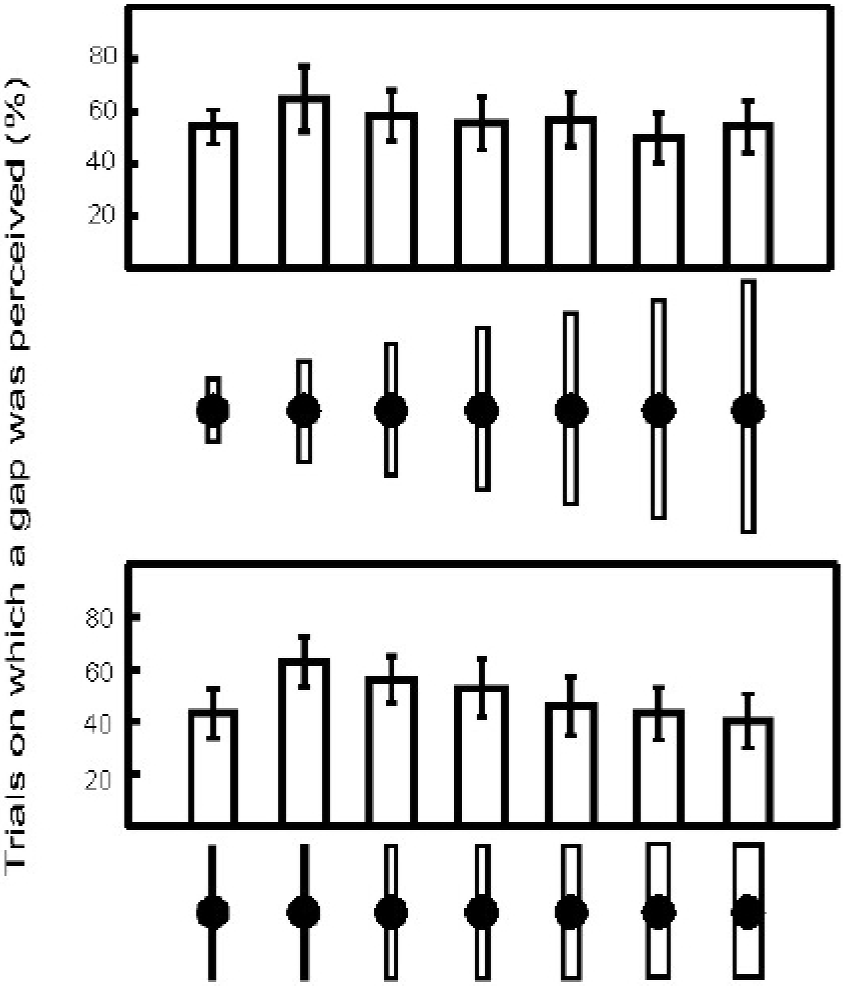

Figure 2.

Mean percentage of trials in which the bar across the blind spot was reported to contain a gap as a function of the length of the bar (top graph) and as a function of the width of the bar (bottom graph) in the Initial Observation.

The approximately 50% chance of filling-in at the blind spot is lower than expected. It is, however, consistent with (though not predicted by) the hypothesis that the visual filling-in depends on diffused spatial attention around the blind spot. Specifically, the nearly 50% failures of filling-in of the bar at the blind spot might stem from subjects' tendency to confine their attention to the blind spot----a tendency encouraged by the instruction that emphasized perceptual accuracy. The control of attention could vary across trials and subjects. In two follow-up experiments, the role of attention in the filling-in was tested directly by manipulating attention in and around the blind spot.

3. Experiment 1

In the first experiment the vertical bar was presented either across the blind spot or at the mirror location on the opposite side of the fixation. By varying the probability with which the bar was presented across the blind spot within a block of trials, we hoped to manipulate subjects' attention towards one side (spatially certain) or both sides (spatially uncertain) of the fixation before the stimulus onset. If diffused attention were more conducive to the filling-in, a more continuous bar should be perceived across the blind spot when its location is uncertain. It should be so especially if the bar stays on the screen so briefly that refocusing attention to the unexpected side is difficult. Presenting the bar at the opposite hemifield also created a desirable control condition for assessing whether the effect of attention is specific to the blind spot.

3.1 Method

Subjects completed three blocks of trials, which differed from one another in the likelihood of the target stimulus (20.1 by 1.4 deg vertical bar) being presented in each hemifield of the viewing eye (the left eye). In block one, the spatially certain block, the bar was consistently presented in the left hemifield at 15 deg eccentricity, which corresponds to the blind spot on the nasal side of the retina. In block two, the spatially uncertain block, the location of the bar was unpredictable across trials: 50% at the same location as in block 1, and 50% at the mirror location in the right hemifield, which maps to a receptive area on the temporal side of the retina. Block three constituted a control condition, in which the bar was consistently presented at the mirror location in the right hemifield. At the location corresponding to the blind spot, the bar was occluded by a red disk 4 deg in diameter. At the mirror location, it contained a gap varying in size equivalent to, or between those of the matching bars #3 and #4 (Figure 3), which simulates the percept of the bar across the blind spot. There were 24 trials in each block. One group of subjects (n = 28) completed block one and block two with the order counterbalanced within the group. A second group (n = 10) completed block three followed by block two. The bar was presented for either 250msec or 500msec, counterbalanced within each block.

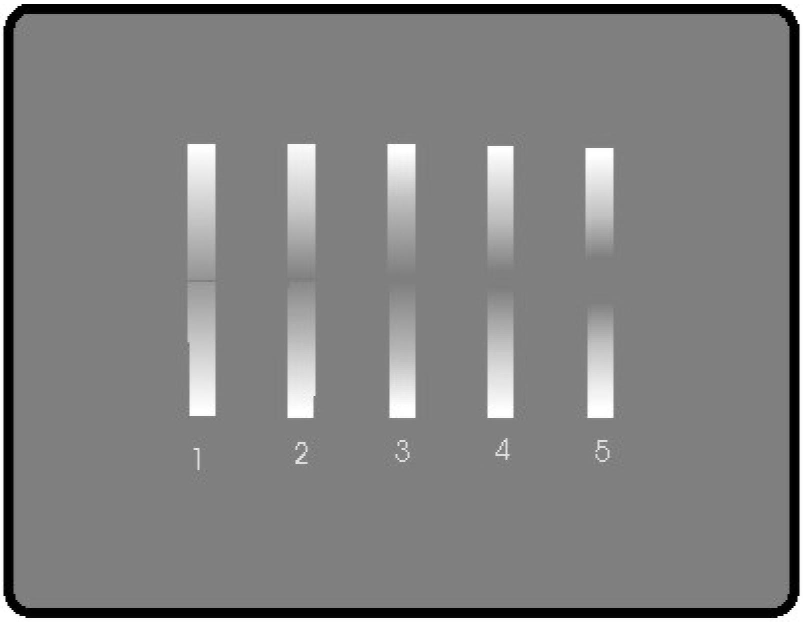

Figure 3.

Reference bars used in Experiment 1 and Experiment 2 to match with observers' percepts of the bar across the blind spot. The bars are numbered (1 through 5) and the numbers were used to calculate the perceived gap size.

Subject population, apparatus, and the procedure for locating the blind spot remained the same as in the initial observation. In particular, those trials during which the red disk was reported visible were not included in the analyses. The filling-in was measured on a 5-point scale, with each point represented by a bar (Figure 3) varying from being nearly continuous (bar #1) to containing a wide gap (bar # 5). Subjects were required to select one of the five bars that best matches the percept of the bar across the blind spot.

3.2 Results and Discussion

On average, the perceived gap size was 3.07±0.33 (95% confidence interval), which roughly corresponds to the third bar among the five comparison bars (Figure 3). As shown in Figure 4A, there was an effect of spatial certainty in the predicted direction: the bar was perceived more continuous in the spatially uncertain condition (mean perceived gap size = 2.91) than in the spatially certain condition (mean perceived gap size = 3.24), F[1, 27] = 3.60, p = .069. The size of this effect was not dependant on the duration of the bar, F[1, 27] = 0.53, ns. Nor was the main effect of stimulus duration statistically significant, F[1, 27] = 2.72, p > 0.1.

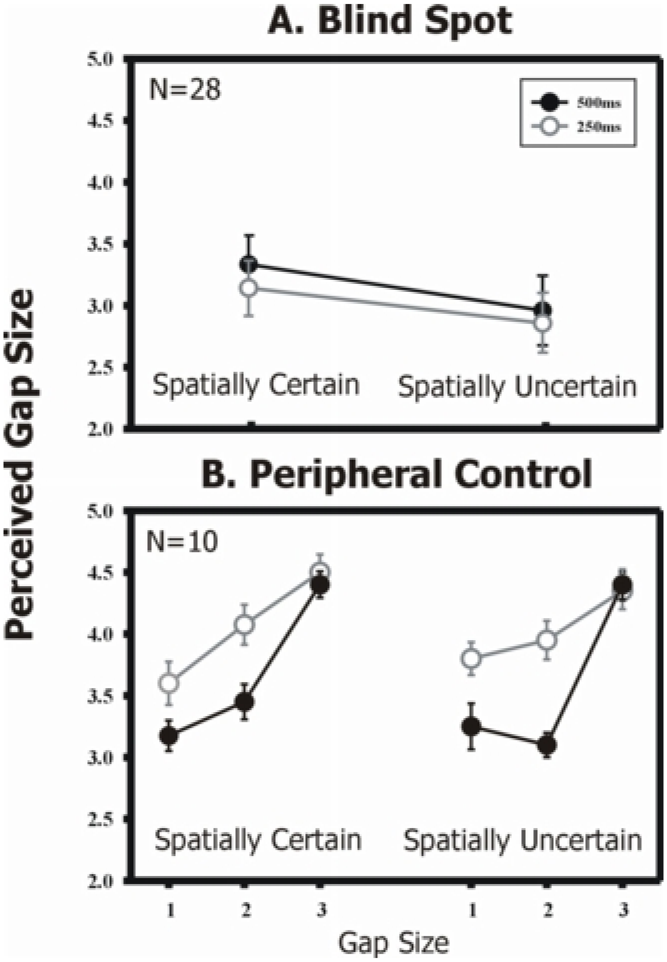

Figure 4.

Perceived gap size as a funciton of spatial certainty, duration and gap size (peripheral control only) of the bar in Experiment 1. In the spatially certain condition, the bar was consistently presented either on the blind spot side or on the opposite side. In the spatially uncertain condition, the bar occurred randomly and equal times on both sides. The top panel represents the perception of the bar across the blind spot, the bottom panel represents the perception of the bar with a gap in the opposite peripheral field. The gap sizes 1, 2 and 3 were eqivalent to, and between, those in reference bars #3 and #4 (Figure 3), in increasing order.

In contrast, the perception of the bar containing a gap in the opposite hemifield was more veridical and stable. The perceived gap size increased with the real gap size of the bar with small variation for each combination of the spatial certainty, the stimulus duration, and the gap size of the bar (Figure 4B). Most importantly, the spatial certainty of the bar was not found on its perceived gap size, F[1, 9] = 0.31, ns.

These results suggested two interim conclusions. First, consistent with our hypothesis, the spread of attention affects perceived filling-in in a somewhat counterintuitive way: diffused rather than focal attention is optimal for the filling-in. Second, because the effect of attention was absent in the otherwise comparable peripheral visual field that contains no blind spot, it must have to do with whatever special processes associated with perceptual interpolation at the blind spot.

4. Experiment 2

In the second experiment, the perceived gap size of the bar across the blind spot was measured under two conditions that differed in how much attention was distributed to the blind spot relative to both ends of the bar. In one condition, subjects were instructed to focus their attention on the blind spot, whereas in the other condition, they were prevented from allocating full attention to the blind spot by a secondary task that demanded attention to both ends of the bar. This fine-tuned attentional manipulation was expected to provide converging evidence for our hypothesis that the filling-in is contingent on diffused attention surrounding the blind spot.

4.1 Method

Each observer completed two blocks of 48 trials. As in Experiment 1, all stimulus displays contained a bar occluded by a red disk at the location corresponding to the blind spot. The bar was presented in horizontal, vertical, or either of the two diagonal orientations. The duration of the stimulus varied across 500msec, 1000msec, and 2000msec, with equal frequencies. On half of the trials, the bar contained a thin yellow stripe at one end, and on another half of the trials it was either all-white or yellow-striped at both ends. For one block of trials (the single task condition), this variation in the stimulus was irrelevant to the task; subjects were simply told to judge the continuity of the bar and to ignore everything else. For the other block of trials (the dual task condition), they must make a speeded choice response within a 1.5 second window, to indicate whether both ends of the bar were of the same color, prior to making an unspeeded response about the perceived gap size of the bar. The order of the two conditions (single task vs. dual task) was counterbalanced across subjects.

Sixteen naïve subjects were tested. They were from the same population as in the initial observation and Experiment one. Other aspects of the methods, including the apparatus, the procedure for locating the blind spot, and for monitoring correct fixation during the trials, and the dependent measure for perceived gap size were the same as in Experiment 1.

4.2 Results and Discussion

The perceived gap size of the bar across the blind spot was 3.32±0.26 (95% confidence interval), which was only slightly larger than what was observed in Experiment 1. As shown in Figure 5, the dual task condition yielded perception of a more continuous bar across the blind spot (mean gap size = 3.12) than the single task condition (mean gap size = 3.54), F[1, 15]= 5.83, p < .05 (see Figure 4). The duration of the bar did not seem to affect the perceived gap size, F[2, 30] = 1.25, ns. Nor did it seem to interact with attention, F[2, 30] = 0.89, ns.

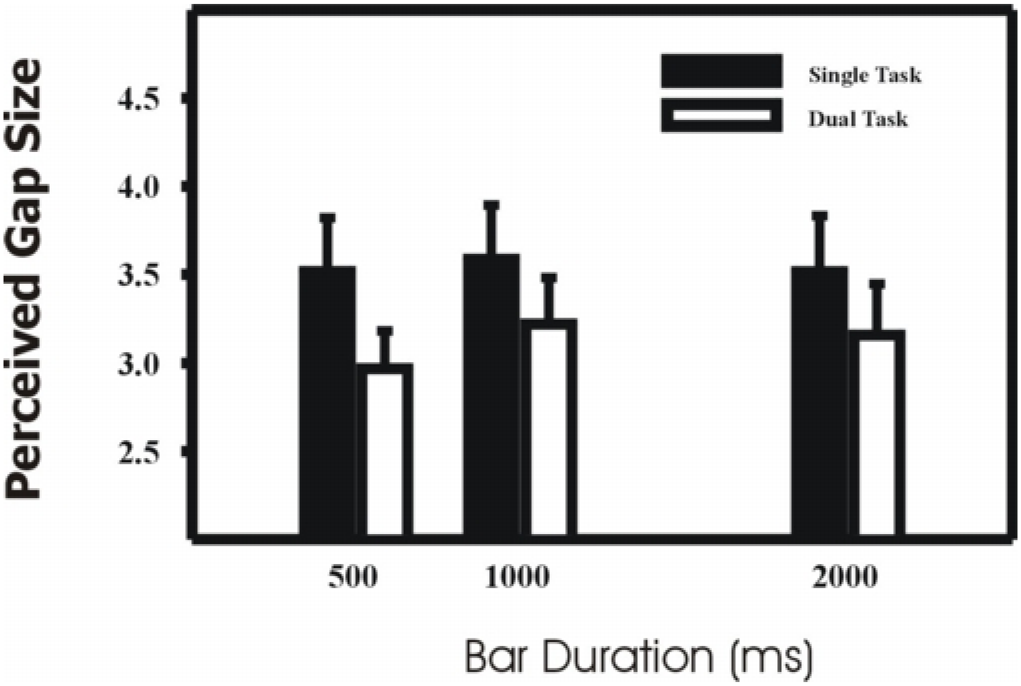

Figure 5.

Perceived gap size as a function of stimulus duration and task demand (single task vs. dual task) in Experiment 2. The open bars represent the dual task condition.

The strength of this experiment was in the fine-tuned attentional manipulation. Specifically, subjects in the dual task condition had to diffuse their attention in space to cover both ends of the bar whereas in the single task condition they were required to confine attention exclusively to the blind spot. As such, the experiment offered a more direct test of the hypothesis that visual filling-in at the blind spot is contingent on diffused attention around the blind spot. Not surprisingly, the results provided a stronger support for the hypothesis.

5. General Discussion

Most previous studies on blind spot filling-in began with a demonstration of the phenomenon and proceeded to discuss its implications or challenges to theories of visual perception. Some studies found that perceptual organization (Kawabata, 1983) or "cognitive factors" (Brown and Thurmond, 1994) influence the content of filling-in.

Those studies assumed, however, that whatever is filled at the blind spot has the same or similar visual quality as those from retinal input. We demonstrated that the filling-in phenomenon is more fleeting and elusive than it has been thought. We subsequently showed that the unstable filling-in phenomenon is intimately associated with spatial allocation of attention: the optimal condition for perceiving the filling-in is when attention is diffused around the blind spot; focusing attention closely on the blind spot is not conducive to the filling-in.

The elusiveness of the filling-in is consistent with a few previous studies that explored the "perceptual consequences" of the filled-in percepts. For example, He and Davies (2001) found that in a binocular rivalry involving a filled-in percept of the blind spot in one eye, the filled-in percept is less dominant than its competing percept with retinal input from the other eye. Similarly, Cumming and Friend (1980) reported that, unlike its veridical counterpart, a filled-in percept of a grating in the blind spot does not lead to the tilt aftereffect, which is believed to reflect the opponent properties of orientation-sensitive neurons in V1.

The negative effect of focal attention on filling-in is puzzling but by no means unique. It seems comparable with the case where focal attention to a peripheral stimulus facilitates the disappearance of the stimulus from awareness (Lou, 1999). In both cases, attention has a negative effect on conscious awareness. However, there is an important difference. That is, compared with the time (at least a few seconds) it takes for an attended peripheral stimulus to disappear from awareness, the absence of filling-in at the blind spot seems instantaneously noticeable, as it was reported for considerably shorter stimulus durations (250msec and 500msec). Consequently, the effect of focal attention at the blind spot is more likely to block the filling-in rather than to occasion the fading of a filled-in percept.

5.1 Theoretical Implications

We believe that these results put important constraints on theoretical interpretations of the filling-in phenomena. The filling-in of the blind spot intrigues psychologists and philosophers essentially because it raises the question of how the brain represents something when there is no sensory input. As a prime example for debunking "Cartesian materialism" (the notion that brain represents every phenomenal state in an isomorphic fashion), Dennett (1991) argued that brain does nothing analogous to the phenomenal filling-in at the blind spot. According to Dennett, the blind spot appears to be filled because there is no evidence on the contrary. In other words, the filling-in was considered a default belief rather than a visual experience. Dennett's position was challenged by others who showed that the filling-in of the blind spot is something seen rather than believed (Churchland & Ramachandran, 1993; Ramachandran, 1993b).

As far as the phenomenology is concerned, Dennett and his critics may be reconciled on the ground of the conditions of attention associated with the filling-in of the blind spot. Dennett seemed to have in mind the normal viewing condition that requires attention to foveal stimuli. Given the strong empirical support for change blindness and inattentional blindness, Dennett could be right in arguing against visual filling-in at the blind spot when the blind spot lies outside of attention. On the other hand, the filling-in demonstrated by many perceptual psychologists, while visually real, might be contingent on attention in the way suggested by the present study. That is, the filling-in might be possible only when the distribution of attention is diffused around the blind spot.

The discovery about how attention influences the filling-in, or visual completion of a bar across the blind spot squares well with recent neurophysiological studies on monkeys. Those studies (Fiorani, Rosa, Gattass, & Rocha-Miranda, 1992; Komatsu, Kinoshita, & Murakami, 2000) found, first of all, that the brain does provide something, rather than nothing (contrary to Dennett) at the blind spot. Some neurons in the monocular region corresponding to the blind spot were found to respond to stimuli surrounding the blind spot, as if they were implementing the "filling" or perceptual interpolation. Those neurons have receptive fields that are either much larger than the blind spot, or "nonclassic", in the sense that they respond to spatially discrete stimuli around the blind spot (Komatsu et al). The visual filling-in may well depend on the extent to which the 'resolution' of top-down attention matches the receptive fields of those neurons. Thus, diffused attention around the blind spot can be expected to match the exceptionally large receptive fields better than focal attention, giving rise to more reliable visual filling-in. This explanation is plausible given the massive feedback connections to V1 from "higher" cortical areas and the recent compelling neurophysiological evidence for attentional modulation of responses of V1 neurons (see Posner & Gilbert, 1999; Lamme, Supèr, & Spekreijse, 1998).

5.2 External Validity

Could conclusions reached from the present study apply to any background surrounding the blind spot? To the extent that it is essentially a perceptual process, the filling-in must be limited by the architecture of the visual system. Previous studies (e.g., Ramachandran, 1992a, 1992b, 1993a) seemed to suggest that only certain types of simple patterns ever fill in the blind spot. Among those are gratings, spokes, random dots, and plain colors. Gratings and spokes consist of multiple bars; hence their filling-in may involve reiterations of the same perceptual mechanisms that subserve the filling-in of a single bar. It is less clear whether the phenomenal filling-in of a repetitive pattern or homogenous background involves the same mechanism and influenced by attention in the same way found in the present study. Further investigations into those issues are needed.

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