Perceptual filling-in of the blind spot using surrounding filled-in information

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Abstract

We showed a novel visual illusion of filling-in occurring at the blind spot. We tried to see what is perceived in the blind spot when its surrounding visual information perceptually faded. It was found that when the surrounding itself perceptually disappeared under three cases of perceptual fading phenomena (*transient-induced fading*, *contrast decrement disappearance*, and *Troxler fading*), the blind spot was perceptually filled-in by information outside its immediate surround. Three movies are supplied to demonstrate the illusory phenomena.

Keywords: *blind spot*; *perceptual filling-in*; *Troxler fading*; *contrast decrement disappearance*; *transient-induced fading*

To access the movies for this article, please visit the article landing page or read the HTML version of the paper where all moves are embedded.

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It has been known that a significant part of the visual field is blind due to the lack of photoreceptors in the optic disc. However, one cannot be aware of this blind area in the visual field (i.e. the blind spot) in everyday life because the brain processes the visual information in a specific process, called perceptual filling-in. For example, Ramachandran (1992a) reported that when an observer's right eye was closed, while the left fixated on a white square, the visual image of a dark blue disk that would fall within their blind spot at a critical distance was seen as being covered by (or filled with) the color of the surrounding background. Other previous studies have consistently shown that the blind spot can be perceptually filled-in by its surrounding information (Durgin et al., 1995; Paradiso & Nakayama, 1991; Spillmann et al., 2006; Weil & Rees, 2011).

On the other hand, inverse cases of perceptual completion have been previously reported, that is, even when a visual image is received by photoreceptors, it could be induced to perceptually fade accompanying perceptual filling-in (e.g. *transient-induced fading* (Breitmeyer & Rudd, 1981; Kanai & Kamitani, 2003), *contrast decrement disappearance* (May et al., 2003), and *Troxler fading* (Troxler, 1804)). For example, Kanai and Kamitani (2003) presented a transient-induced fading paradigm, in which a red disk (called the target) perceptually disappeared and became the same color with the near-isoluminant green background when a surrounding white ring flashed for 40 ms. May et al. (2003) found that when the contrast of a peripherally viewed stimulus abruptly decreased, the stimulus itself would disappear from consciousness abruptly. In Troxler fading (Troxler, 1804), after several seconds of steady fixation, a peripheral stimulus will gradually fade and disappear partly or completely. The previous studies seem to agree that when the stimulus perceptually disappeared, the stimulus area was filled by the color of the surrounding background, instead of being perceived as either black or empty (Anstis, 2013; Bonneh et al., 2010; Kanai & Kamitani, 2003; May et al., 2003; Pritchard, 1961; Troxler, 1804).

The perceptual filling-in induced in the perceptual fading phenomenon mentioned above seems to be different from filling-in at the blind spot. In perceptual fading, to induce a target's perceptual disappearance, an inducer (such as luminance contrast change around the target in *transient-induced fading*, or contrast decrement of the

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target itself in *contrast decrement disappearance*) or several seconds of steady fixation (in *Troxler fading*) are required. As opposed to filling-in at the blind spot, as the blind spot receives no visual input, the complete filling-in process is almost instantaneous and independent of the surrounding stimulus configuration (De Weerd, 2006; Ramachandran, 1992a; Spillmann et al., 2006; Weil & Rees, 2011). It is assumed that any transition of the physical images surrounding the blind spot (e.g. the physical surround's removal or replacement with another visual pattern) will lead to an instantaneous change in the percept inside the blind spot. However, it is still unclear whether the perceptual 'removal' of a surrounding physical stimulus would also have some influence on the percept inside the blind spot. That is, if a physical stimulus surrounding the blind spot dominantly led to the percept inside it, then even when the physical surround is perceptually invisible, the blind spot area would still remain visible due to the filling-in by its physical surround. Otherwise, the perceptual filling-in process of the physical surround may influence the percept inside the blind spot area, which has been filled by its physical surround.

Here, we report a novel visual illusion and provided three demonstration movies, showing that perceptual filling-in at the blind spot can be induced again by the perceptual fading of its physical surround. When the blind spot is perceptually filled-in by the color of the surrounding stimulus, by inducing the surrounding stimulus to perceptually fade (by *transient-induced fading*, *contrast decrement disappearance*, or *Troxler fading*), we found that the filled-in color in the blind spot perceptually fades together, and the blind spot is filled-in by the background color outside the surrounding stimulus. This provides a new insight into the filling-in process of the blind spot and perceptual disappearance.

Demonstrations and observation

Filling-in at the blind spot caused by the transient-induced fading of the surround

To observe how the visual information that was filled-in at the blind spot perceptually changed, we used a stimulus configuration shown in Fig. 1, that is, a red disk to indicate the area of the blind spot and a green annular surround on a gray background. Since the red disk was presented in the blind spot area, observers did not see any red color, while they fixated on the center cross. Therefore, the visibility of the red disk served as an indicator of whether steady fixation occurred. That is, the red disk would be visible if observers failed to fixate on the cross steadily and would become invisible only when fixation was maintained (e.g. Araragi et al., 2009; Tripathy & Barrett, 2006). Instead, a large 'green disk' was seen as a result of perceptual filling-in of the green color into the

blind spot area. The size and the location of the red disk were individually determined through blind spot mapping of each observer's right eye. Fifteen observers (average age: 25.3 years, standard deviation [SD] = 2.6) participated in the observation. The observers sat in front of a display (GIGABYTE, G24F 2, 60 Hz) at the viewing distance of 57 cm with their head stable on a chinrest. They viewed a black dot (0.25 deg in diameter, 0.6 cd/m^2) on a gray background (41.6 cd/m^2), with their right eye fixating on the cross. The dot moved from left to right (1.39 deg/s), systematically shifting downward after each pass, covering the right visual field. They identified locations where they could or could not see the dot. This blind spot mapping gives a conservative estimate of each observer's blind spot location and size and simply serves to aid in the stimuli preparation for subsequent main experiments. Then, based on the individually mapped blind spot area, the size and the position of the red disk (47.3 cd/m^2) were determined. The size of the red disk subtended 2.3 ± 0.4 deg in diameter, which was set smaller than the measured blind spot, so that the border area of the blind spot would be effectively covered by its surrounding green color (see the paragraph later for more details). The red disk was presented at an individually determined eccentricity of 18.1 ± 0.9 deg, that is, the distance between the center point of the red disk and the fixation cross.

Sharing the same center point with the red disk, a green annular surround was presented. As the red disk size was set to be smaller than the measured blind spot as noted earlier, the border area of the blind spot indicated by a black dashed line was always green (Fig. 1). Note that our
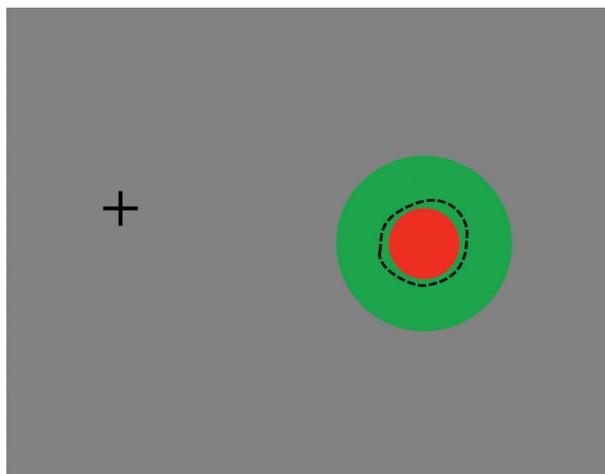
Fig. 1. Diagram of visual stimuli. The red disk was presented inside the individually mapped blind spot area, and a large green annular area surrounded the blind spot. The area indicated by a black-dashed line indicates the individually measured blind spot with some irregularity by measurement errors. The red disk was smaller than the individually measured blind spot area and not seen perceptually.

blind spot mapping procedure was not used to accurately define the boundary of the blind spot. The sizes and shapes of the blind spot varied largely among observers, so the black dashed line in Fig. 1 just indicates an example of the approximate edge of one's blind spot border area. The red disk became visible for the observers only when their right eye moved off the cross. As the size of the green annular surround (10.7 deg of the outer border in diameter) was set much larger than the measured blind spot, the gray background was never projected to the blind spot area even during fixational eye movements. The stimuli were presented to the right of the fixation cross against the gray background (41.6 cd/m^2).

In the *transient-induced fading* condition, the red disk and the green annular surround (47.6 cd/m^2) were presented throughout a trial lasting for 6.0 s (Fig. 2, upper panels (*a*)). The black ring (24.4 deg and 17.6 deg for the outer and inner diameters, respectively; 0.6 cd/m^2) was presented around the green area for 0.1 s and 2.0 s after the onset of the visual stimuli (Fig. 2, upper panel (*b*)). At the offset of visual stimuli, a noise image was presented for 6.0 s to reduce afterimages.

The observers first performed a qualitative observation session. In the qualitative observation session, three fading conditions were presented in a randomized order in one block, and each block was repeated 10 times. Thus, observers performed 30 trials in total (3 fading conditions × 10 repetitions). Between every five blocks, observers took a rest for at least 1 min to avoid visual fatigue. In every trial, they were instructed to fixate on the cross with their right eye without blinking and orally report what they perceived, including but not limited to the changes in color and size as well as the visibility of each visual element. All observers reported that they perceived a whole green target at the start of each trial (Fig. 2, lower

panel (*c*)). This indicated that the blind spot was filled by the surrounding green at the start of the observation. Fourteen observers reported invisibility of the red disk throughout all trials in the qualitative observation session, except for one observer who reported that a part of the red disk was visible when the black ring flashed in over half of the trials. This indicated that this observer's right eye moved off the fixation cross when the ring flashed. Thus, the results of this observer were excluded from the qualitative observation session, including the *contrast decrement disappearance* condition and the *Troxler fading* condition described later. As to the phenomenal reports of perceptual fading, eight observers reported that the green target completely faded away and became the same color as the gray background after the black ring flashed (Fig. 2, lower panels (*d* and *e*)). Two observers reported that after the flash of the black ring, the green target first became transparent and then disappeared completely. The other four observers reported different cases. One observer reported the entire green target without any changes throughout all trials, that is, no fading occurred. The other three observers reported that only some parts near the edge of the green target disappeared (left parts mostly), indicating that the fading only partly occurred. *Movie 1* may allow readers to experience this illusory effect as well.

Filling-in at the blind spot caused by the contrast decrement disappearance of the surround

In the *contrast decrement disappearance* condition, the green surround with high luminance of 59.0 cd/m^2 was first presented for 2.0 s (Fig. 3, upper panel (*a*)), then its luminance abruptly decreased to 47.6 cd/m^2 (Fig. 3, upper panel (*b*)). Meanwhile, the luminance contrast of the red disk remained the same throughout each trial. The observation procedure was the same as that in the
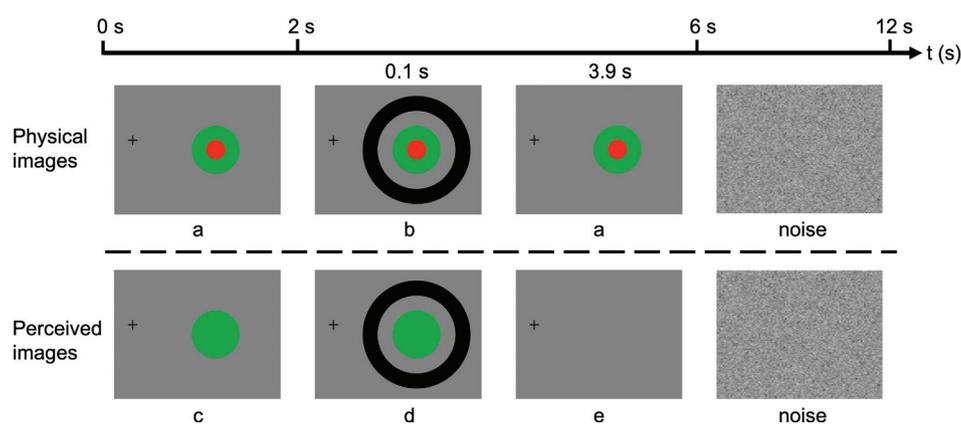
Fig. 2. Demonstration of filling-in at the blind spot by *transient-induced fading* (*Movie 1*). The horizontal line at the top indicates the passage of time in a trial. Upper panels (*a* and *b*) show the physical images that are presented on a screen. Lower panels (*c*, *d*, and *e*) show the typically reported perception. *Movie 1* should be played on a large display. Please fixate your right eye on the black cross while covering your left and adjust the viewing distance, so that the red disk can perceptually disappear, and only the green target can be seen, as illustrated in *c*.
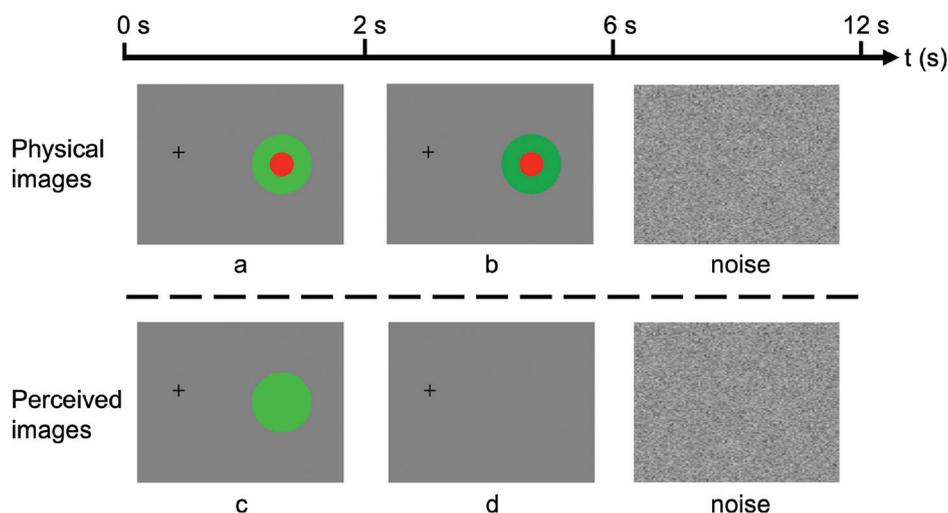
Fig. 3. Demonstration of filling-in at the blind spot by *contrast decrement disappearance* (*Movie 2*). The top arrow indicates the time passage of a trial in the *contrast decrement disappearance* condition. Upper panels (*a* and *b*) show the physically presented images. Lower panels (*c* and *d*) show the typical perception that was orally reported. As in *Movie 1*, *Movie 2* should be played on a large display. Please fixate on the black cross with your right eye, while covering your left and adjust the viewing distance to perceptually erase the red disk as illustrated in *c*.

transient-induced fading condition. The same 15 observers participated. Seven observers reported that at the start of the observation, they saw a whole green disk, then the green target abruptly disappeared and became the same gray color as the background (Fig. 3, lower panels (*c* and *d*)). This indicated that the green area in high luminance around the red disk filled-in the blind spot area at the beginning of a trial. But, when the green target's luminance decreased, the green area perceptually disappeared immediately and completely. Three observers reported that they observed the entire green disk at first and then it turned darker before completely disappearing. These 10 observers were the same as those who reported the green disk's complete disappearance in the *transient-induced fading* condition. After excluding the observer who reported seeing red in the *transient-induced fading* condition, the other four observers reported the same observation results with *Movie 1*, that is, no fading was perceived by one, or partial disappearance of the green area was perceived by three. *Movie 2* will enable readers to observe the illusory effect.

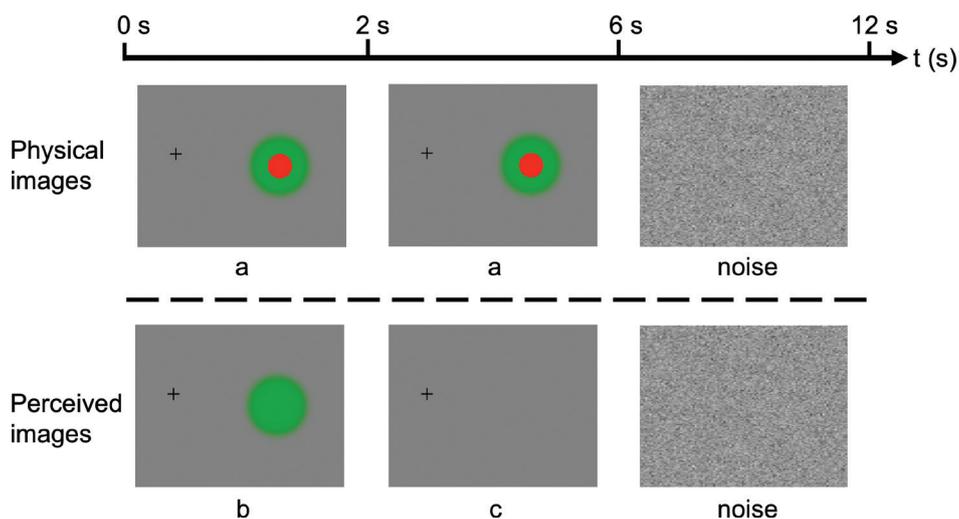*Filling-in at the blind spot caused by Troxler fading of the surround*

In the *Troxler fading* condition, the red disk and the edge-blurred green surround (47.6 cd/m^2) were presented throughout the trial lasting for 6.0 s (Fig. 4, upper panels (*a*)). The same 15 observers observed the display. Ten observers reported that they observed the edge-blurred green target at first and then it gradually faded and eventually became the same gray color with background (Fig. 4, lower panels (*b* and *c*)). These 10 observers were

the same as those who reported the green disk's complete disappearance in the *transient-induced fading* condition and the *contrast decrement disappearance* condition. After excluding the observer who reported seeing red in the *transient-induced fading* condition, the other four observers reported the same observations as *Movies 1* and *2*, that is, no fading was perceived by one, or partial disappearance of the green area was perceived by three.

Measurement of the perceptual fading

Using data from the 10 observers who reported complete fading, we measured the time course of the perceptual fading in the above-noted three phenomena to confirm the occurrence of each type of fading and filling-in at the blind spot against the gray background. Three fading conditions were presented in a randomized order in one block, and each block was repeated 10 times. Between every five blocks, observers took a rest for at least 1 min to avoid visual fatigue. Thus, the fading measurement session consisted of a total of 30 trials (3 fading conditions × 10 repetitions). The task of the observers was to press the space key at the exact moment the stimuli faded and was perceived as the same color as the gray background. They could release the key if they perceived that the stimuli had reappeared.

Then, we used a time course sampling and a value assignment method used in a previous study (Jiang et al., 2024) to quantitatively analyze the results. The key status (pressed or released) was sampled with 0.1 s intervals. The value of '1' was assigned if the 'space' key was pressed or held down and '0' if no key was pressed during the interval. To acquire the percentage of the visibility of

Fig. 4. Demonstration of filling-in at the blind spot by *Troxler fading* (*Movie 3*). The time course of a trial in the *Troxler fading* condition is illustrated. Upper panels (*a*) show the physical images throughout a trial. Lower panels (*b* and *c*) show the typical perception. In *Movie 3*, please fixate on the cross with your right eye while covering your left after adjusting the viewing distance.
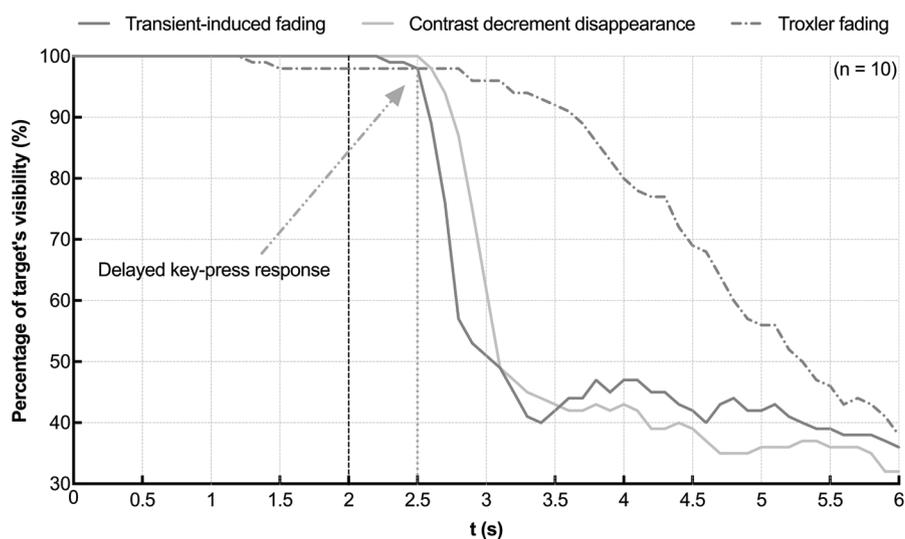
Fig. 5. The measured time course of the green target's fading perception. The horizontal axis indicated the presentation time of visual stimuli in a trial lasting for 6.0 s. The vertical axis indicated the percentage of the target's visibility. The vertical black dashed line at 2.0 s indicated the onset of the black-ring flash in *transient-induced fading* or luminance decrease of the green disk in *contrast decrement disappearance*. The vertical gray-dashed line at around 2.5 s indicated the delayed timing in key-press response due to the observer's reaction time and the latency of the perceptual fading. Although the black ring flashed for 0.1 s at 2.0 s from the beginning of the trial in the *transient-induced fading* condition, the response curve reflected the occurrence of the perceptual fading by the transient with a time lag due to reaction time. Similarly, although the contrast of the target decreased at 2.0 s from the beginning in the *contrast decrement disappearance* condition, the curve reflected the occurrence of the perceptual fading with a time lag due to reaction time.

the green 'disk', we first calculated each observer's and each condition's percentage of '0' responses at each time point across 10 trials. This value represented the percentage of the visibility of the green 'disk' at that time point. Next, the individually acquired percentages were averaged across 10 observers at each of 60 time points (0.1 s ~ 6.0 s) and plotted separately for each condition (Fig. 5).

As shown in Fig. 5, for the first 2.0 s, the green 'disk' rarely faded under the three conditions. The green 'disk' perceptually faded suddenly at around 2.5 s in the *transient-induced fading* and the *contrast decrement disappearance* conditions. In the *Troxler fading* condition, the green 'disk' gradually faded as time passed. Thus, the three kinds of perceptual fading occurred as intended, and in more than

half of the trials, the entire screen (excluding the fixation point) was perceived as gray, including the blind spot area, confirming that the gray color of the background filled-in the blind spot area through the physically green area.

Discussion

We have tested the effects of three fading illusions on perceptual filling-in at the blind spot and provided three demonstration movies for readers to experience the effects. It is well known that the blind spot is perceptually filled-in by the information surrounding it. We tried to see what is perceived in the blind spot when the surrounding area itself illusorily fades and is filled-in by the color of the outer visual field (background). All 15 observers reported perceiving an entire green disk presented against a gray background at the onset of the trials. Then, 10 observers typically reported perceptual disappearance of the green disk under three kinds of fading phenomena, indicating that the background gray color filled-in the blind spot area.

The perception of a whole green disk at the start of a trial indicated that the blind spot, including the red disk area, was filled-in by its surrounding green. One may argue that even if the red disk image moved out of the blind spot due to fixational eye movements, it may have remained invisible by Troxler fading. While the filling-in process at the blind spot is known to occur instantaneously (Ramachandran, 1992b; Spillmann et al., 2006; Weil & Rees, 2011), several seconds of stabilization of the retinal image are needed to induce Troxler fading (Kanai & Kamitani, 2003; Troxler, 1804; Weil & Rees, 2011). Therefore, it is likely that whenever the red disk was invisible, the red disk was surely inside the blind spot. In our demonstrations, the green color seen in the blind spot instantaneously changed into the gray of the background when the surround perceptually fades. Though the physical color surrounding the blind spot is kept as green on the retina, the filled-in green in the blind spot does not remain the same with its surrounding physical green but perceptually disappears. We demonstrated here that filling-in at the blind spot could be induced by its surrounding information, even when the surrounding itself perceptually fades and is filled-in by the background.

One possibility for the filling-in process observed in the present study is that the green 'disk' including the blind spot area simultaneously disappeared as a one-object representation. Kanai and Kamitani (2003) have shown that there exists an object-based aspect in the fading effect. They presented a varied number of flashed disks sequentially alongside a bar, which produced apparent motion, as if a disk was moving from one side to another. Then, they found that as the flash moved, the bar did not disappear gradually from one end to the other. Instead, the entire bar was induced to fade by just one flash. Their observation indicates that the unit of fading is an object, rather than features in a local area. In the present study, the green color that filled-in the red disk area in the blind spot is seen to simultaneously fade when the surrounding green color perceptually fades. Our observation may indicate a consistent object-based mechanism like that of Kanai and Kamitani (2003), where some higher-level processes at the object representation level might be involved in the perceptual filling-in phenomena.

Another possibility we propose is that the green area surrounding the blind spot was first filled-in with the gray background, then the blind spot was filled-in by its surrounding 'gray' color with a normal blind-spot filling-in process. Spillmann et al. (2006) found that even when a very narrow region immediately bordering the blind spot was stimulated, uniform filling-in of color and texture can be observed. Their results indicated that perceptual filling-in of the blind spot depends on local processes generated along the edge of the cortical representation of the blind-spot region. Some psychophysical and neurophysiological experiments have also shown that the completion in the blind spot involves active information processing in the non-stimulated cortical area corresponding to a scotoma when the surround is stimulated (De Weerd et al., 1995; Komatsu, 2006; Ramachandran, 1992b). Our demonstration may show a consistent idea that the filling-in signals stimulated from the surround invade the blind spot by regenerating a representation of the missing information at the physiological edge of the cortical representation.

Ramachandran and Gregory (1991) reported filling-in at an artificial scotoma, that is, a gray square presented on a twinkling noise background perceptually disappeared, and the twinkling noise perceptually filled the square area. Even after the twinkling background changed into a homogenous gray background, the twinkling noise was perceived at the square area for 2 or 3 s (Ramachandran & Gregory, 1991) or even 10 s (Ramachandran, 1992a). This indicates that the neural activities were induced inside the filled-in area and persisted for a period of time, independently of the surround. For the physiological blind spot, we usually do not experience any remaining filled-in image there when the surrounding image changes. The filling-in process at the blind spot may be different from that at the artificial scotoma, in that there is no neural activity corresponding to the perceived image, independent of that corresponding to the surround. However, it has been reported that the cells that originally correspond to the visual cortex inside the scotoma can be excited by visual stimuli that lay outside the scotoma (Gilbert & Wiesel, 1991; Ramachandran, 1992b; Ramachandran et al., 1993). There are also some physiological studies, showing that neuron activity occurs in the retinotopic representation of the blind spot when visual stimuli inducing perceptual filling-in are presented across the blind spot (Fiorani Júnior et al., 1992; Komatsu & Murakami, 1994;

Komatsu et al., 2000). These findings indicate that an actual neural representation can be created in the region of the blind spot by the surrounding neural activity.

In addition, Chen et al. (2017) reported a filling-in rivalry phenomenon occurring between two filled-in percepts in the blind spot. They presented a blue and yellow isoluminant cross (which continuously moved along a circular trajectory) with the intersection point being within the blind spot. They then found that either of the two bars would alternately rival to be filled-in as complete across the blind spot area and appear in front of the other bar. Their findings revealed that higher-level representations are competing during filling-in rivalry. According to their findings, our study might suggest that after the blind spot was filled-in, the perceptual fading still worked for the blind spot representation as a rivaling representation. This could provide evidence that filling-in of the blind spot involves higher-level processes and shares some common mechanisms with filling-in of the normal visual field.

Altogether, our observation shows that the filling-in process at the blind spot, which has been known to be independent of physical stimulus configuration, can be affected by its surrounding's illusory fading. Whether the perceptual fading observed at the filled-in blind spot area occurs at the level of object representation or depends on active neural interpolation from the surrounding cannot be clearly determined from our demonstration. Exploring these two points further may provide novel insight as to the commonalities and differences underlying visual fading processing mechanisms.

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