Research Article

What You See Is What You Get

Functional Equivalence of a Perceptually Filled-In Surface and a Physically Presented Stimulus

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ABSTRACT—A perceptually filled-in surface, such as occurs during sustained attention to a peripheral stimulus (Troxler fading), can be functionally equivalent to a physically presented stimulus. Observers failed to detect probes that were presented in the location of a filled-in surface that had the same surface attributes as the probes; this was true even though physically, the probes contrasted with the background. Probe stimuli with surface characteristics different from those of the filled-in surface were detected more often, though not quite as often as when there was no filled-in surface. Together, these findings support the idea that there are two components in perceptual filling: a neural filling-in component and a sustained-attention component, which actively suppresses perceptual processing at the filled-in location. More broadly, they illustrate the interplay of basic visual mechanisms in the creation and representation of visual surfaces and in the coding and detection of changes to these surfaces.

In recent years, there has been a newfound interest in studying perceptual filling in—the experience of a continued surface across a blind spot or an otherwise compromised region of the visual field (Pessoa, Thompson, & Noz, 1998)—because it can provide insight into a wide variety of visual processes (e.g., Arrington, 1994; Caputo, 1998; Grossberg & Todorovic, 1988; Mendola, Conner, Sharma, Bahekar, & Lemieux, 2006; Paradiso & Nakayama, 1991; Watanabe & Cavanagh, 1991). Here we demonstrate that a physical stimulus that shares all of the surface attributes of a perceptually filled-in surface can go undetected when it is presented within the region of that filled-in surface, even though physically, the stimulus contrasts with the background. This indicates a functional equivalence of the perceptually created surface and the physically presented stimulus.

We focus on Troxler fading, wherein sustained attention to a peripheral object causes the eventual disappearance (fading) of that object from visual awareness, often for several seconds (Troxler, 1804). During Troxler fading, the background surface spreads across the area of the attended object. Unlike filling in across the optic-disc blind spot of the retina, where there are no photoreceptors, Troxler fading occurs at locations in the visual field where early sensory mechanisms are intact.

Research has shown that a number of factors influence the time to fading in Troxler fading, that is, the interval between the onset of the attended stimulus (the target) and the time at which it fades. These factors include luminance contrast (e.g., Clarke, 1957, 1960; Krauskopf, 1957; Livingstone & Hubel, 1987; Welchman & Harris, 2001), color contrast (e.g., Friedman, Zhou, & von der Heydt, 1999; Millodot, 1967; Sakaguchi, 2001), and target size and eccentricity (e.g., De Weerd, Desimone, & Ungerleider, 1998; Millodot, 1967). The filling-in phenomenon itself, however, remains unstudied. As Welchman and Harris (2001) put it, “Future work must more thoroughly examine what happens once the target has disappeared, rather than simply what determines how long it takes to go” (p. 2117). This was a goal of the present study, which was concerned with the quality of the perceptually filled-in surface over the location of the target.

The experiment probed observers’ ability to perceive stimuli that were presented inside the target while the target was faded (see Fig. 1). In the critical condition, the probe stimuli had the same hue, luminance, and texture as the background of the display. These attributes corresponded to the attributes of the filled-in surface, because the background surface perceptually filled in across the target location. If the filled-in surface was not detectable, then the probe stimuli would be invisible, because they would contrast with the filled-in surface in no way. If, however, the filled-in surface fell short of functional equivalence to a physical stimulus, then the
signal contrast of the probe relative to the background would make the probe detectable.

**EXPERIMENT 1: BACKGROUND-COLORED PROBES**

Experiment 1 examined performance in the critical condition, when probes were identical to the background against which the target was presented.

**Method**

**Participants**
Sixteen undergraduates were tested. All reported normal or corrected-to-normal visual acuity and color vision.

**Stimuli and Apparatus**
The display consisted of a gray fixation cross (0.2° × 0.2° of visual angle) presented throughout the trial on a red background. A matrix (1.1° vertical and horizontal separation) of small (randomly 1.5′ or 0.29′) gray dots provided texture. The target stimulus was a green disc (1.6′), set to be closely equiluminant with the background using the flicker-fusion method (Cavanagh, MacLeod, & Anstis, 1987). An adaptive staircase method was used to set target eccentricity for each participant (see Procedure). The probe stimulus was a 0.29° dot presented at the center of the target disc; it was identical in hue, saturation, and luminance to the red background of the display. A two-button button box was used for collecting responses.

**Tasks**
Participants fixated the central cross throughout each trial. The primary task was to concentrate on the target disc and report its fading by pressing and holding down the left button. Participants released this button whenever the target disc came back to visual awareness. The secondary task was to press the right button whenever a probe was inside the target disc.

**Procedure**
The 1-hr session began with a tracking phase, during which target eccentricity was set to support approximately 71%-correct probe detection, using an adaptive staircase procedure (Levitt, 1971). The tracking phase resulted in a mean target eccentricity of 8.9° of visual angle, with a standard deviation of 1.3°. Following the tracking phase, the experimenter introduced the participant to the Troxler fading phenomenon in five familiarization trials; in 10 subsequent practice trials, the participant was instructed how to respond to the different events in the trials.

Following practice, data were collected from two 20-trial blocks. Trials were 35 s long. Participants initiated each trial by pressing a button. The target disc appeared 500 ms later, remaining present in the display for the remainder of the trial. Each probe was presented for 100 ms inside the target disc. Probe onset was contingent on the responses in the primary task (fading report). While no fading was reported (i.e., the left button was not pressed), every 3 s (± 500 ms) there was a 50% chance that a probe would be presented; 500 ms following the report of fading, there was a 50% chance that a probe would be presented, and if participants continued to report the target as faded, every 1.5 s (± 500 ms) there was a 50% chance that a probe would be presented.

**Results and Discussion**
The results suggest that a perceptually filled-in surface can be functionally equivalent to a physical stimulus.
Fading Report
Reports of fadings were comparable in number, duration, and latency to those reported in previous studies (e.g., De Weerd et al., 1998; Lou, 1999; Sakaguchi, 2001; Welchman & Harris, 2001). Troxler fading was reported by all observers. On average, fading first occurred 10.54 s after the beginning of the trial. There were an average of 2.59 fadings per trial, and mean duration of the fadings was 2.74 s.

During each 35-s trial, the target disc was faded for an average total duration of 7 s (20% of the duration of the trial) and was visible for an average of 28 s. On average, per participant, 100.7 probes were presented during target-faded intervals, and 165.1 probes were presented during target-visible intervals. A right button press was counted as a false alarm when no probe had appeared in the 1.5-s interval leading to that response.

Probe Detection
Hit rates were submitted to a one-way analysis of variance (ANOVA) with target report (target visible vs. target faded) as the independent variable. Target report had a significant influence; although participants were fairly good at detecting probes that appeared while the target was reported as visible (mean hit rate = 59.4%), they had a difficult time detecting probes that appeared when the target was reported as having faded (mean hit rate = 10.8%), $F(1, 15) = 259.64, p < .05, p_{rep} > .99$ (Killeen, 2005), $\eta^2 = .95$. False alarm rates were submitted to an analogous one-way ANOVA. There was a small, but nonsignificant, tendency toward more false alarms during target-visible intervals (4.3%) than during target-faded intervals (2.3%), $F(1, 15) = 4.5, p > .05, p_{rep} = .87, \eta^2 = .23$. In signal detection terms, signal sensitivity was high ($d' = 2.13$) during target-visible intervals and was severely reduced during target-faded intervals ($d' = 0.61$), $F(1, 15) = 60.27, p < .0001, p_{rep} > .99, \eta^2 = .80$. In contrast, response criteria appeared to be largely unaffected by target-report condition: $\beta = 1.33$ and 2.05 for target-visible and target-faded intervals, respectively, $F(1, 15) = 1.79, p > .05, p_{rep} = .71, \eta^2 = .11$.

A separate experiment identical in all aspects to Experiment 1 except that probe frequency was higher (there was a 50% chance of a probe appearing every 1.5 s, rather than every 3 s, during target-visible intervals) replicated the results: The hit rate dropped from 59% during target-visible intervals to 9% during target-faded intervals, $F(1, 15) = 262.05, p < .0001, p_{rep} > .99, \eta^2 = .95$.

It was possible that the decrease in probe detectability during target-faded intervals was caused by the need to simultaneously report that the target had faded and that a probe had appeared, rather than by a failure to detect the probe. Therefore, two additional control experiments were conducted to evaluate the extent of dual-task interference in Experiment 1. Two primary tasks, matched for overall task difficulty, were used in these experiments: (a) reporting whether a target disc was present or absent in the display and (b) reporting whether an auditory tone was either on or off. The primary-task stimuli occurred as often and lasted as long as the reports of fading episodes in Experiment 1 and its replication. In both cases, the secondary task was to report the onset of a probe that appeared as often as probes in Experiment 1 and its replication. In the control experiments, participants were very good at reporting the state of the target (on or off), but a dual-task cost was observed in probe detection: Hit rates for probes were 10% lower when the primary task required a response (target-on hit rate = 36.5%) than when the primary task did not require a response (target-off hit rate = 47.3%). However, this cost was constrained in time to those intervals when both tasks required action within a 500-ms window. Hit rates for probes occurring outside that window showed no dual-task cost (hit rates were 50.9% and 50.0% for probes during target-off and target-on intervals, respectively). Thus, the severe drop in probe-detection accuracy during Troxler fading cannot be accounted for by dual-task interference alone, but instead seems to reflect a perceptual limitation in perceiving background-colored probes during Troxler fading. Together, the results from Experiment 1, its replication, and these two control experiments suggest that a perceptually filled-in surface can be functionally equivalent to a physical surface.

EXPERIMENT 2: NON-BACKGROUND-COLORED PROBES

During Troxler fading, to what extent can observers detect probes inside the filled-in target area when those probes have surface characteristics different from those of both the target and the background? Under the logic for Experiment 1, such probes should be detectable because they should contrast not only with the physical background, but also with the perceived background (i.e., the filled-in surface). It is possible, however, that the reduction in probe detectability observed in Experiment 1 was caused by a more general gain reduction of signals from stimuli presented at locations of perceptually filled-in surfaces. If so, then the detectability of probes that are different from the background should be reduced during Troxler fading.

Method
As in Experiment 1, 16 undergraduates were tested. All reported normal or corrected-to-normal visual acuity and color vision.
The method of Experiment 2 was identical to that of Experiment 1 except as noted here.

**Stimuli**
The target color was changed from green to an equiluminant blue. Probes were either red or green. The background color was red for one block and green for the other. The tracking phase resulted in a mean target eccentricity of 9.1° of visual angle, with a standard deviation of 1.6°.

**Design**
A two-factor within-subjects design was used, with target report (visible vs. faded) and probe type (same color as background vs. different color from background) as independent variables. Half of the probes that were presented during a trial were same-color probes, and the other half were different-color probes.

**Procedure**
Probe events were independent of responses. The target disc appeared 500 ms after the initiation of the trial and remained in the display for the remainder of the trial. The rest of the 35-s trial was divided into twenty-three 1.5-s episodes. Nothing occurred during either of the first 2 episodes or during the last episode of a trial. The remaining 20 episodes were randomly divided into 10 probe episodes and 10 no-probe episodes. At the end of a probe episode (± 200 ms), a probe was presented inside the target disc for 100 ms, whereas no probe was presented at the end of a no-probe episode.

**Results and Discussion**

**Fading Report**
Troxler fading was reported by all observers. There was an average of 3.15 fadings per trial, and the average duration of a fading was 2.15 s. An average of 45.2 and 42.1 same- and different-color probes, respectively, were presented per participant during target-faded intervals, and an average of 155 and 158 same- and different-color probes, respectively, were presented per participant during target-visible intervals.

**Probe Detection**
A preliminary analysis of hit rates confirmed that same- and different-color probes were equally detectable during target-visible intervals, with hit rates of 52.6% and 52.3%, respectively, *t*(15) < 1. Similarly, a comparison of false alarm rates confirmed that participants had similar response biases across the two target-report conditions; false alarm rates were 4.1% and 2.7%, respectively, *t*(15) = 1.31, *p* > .05, *p*<sub>rep</sub> = .71, η<sup>2</sup> = .10.

Note that all analyses were restricted to time intervals in which probes appeared at least 500 ms before or after a response to the fading task, to minimize the influence of dual-task interference.

Only hit-rate data were included in the two-way ANOVA evaluating the effects of target report and probe type because false alarm rates could not be independently measured for same- and different-color probes (the two types of probes were mixed within trials). However, as noted, false alarm rates were identical across the two types of target-report intervals. Therefore, any differences in hit rates could be attributed to differences in probe detectability and not to differences in response bias.

The ANOVA revealed significant effects of target report, *F*(1, 15) = 18.75, *p* = .001, *p*<sub>rep</sub> = .99, η<sup>2</sup> = .55, and of probe type, *F*(1, 15) = 4.79, *p* = .045, *p*<sub>rep</sub> = .88, η<sup>2</sup> = .24, and a significant Target Report × Probe Type interaction, *F*(1, 15) = 12.36, *p* = .003, *p*<sub>rep</sub> = .98, η<sup>2</sup> = .45 (see Fig. 2) Whereas participants detected same- and different-color probes to the same extent during target-visible intervals, they detected different-color probes more often (hit rate = 31.8%) than same-color probes (hit rate = 20.1%) during target-faded intervals.

In sum, the probe-detection data for same-color probes were consistent with the results of Experiment 1: The probe-detection rate was high during target-visible intervals and low during target-faded intervals. Although the data for different-color probes showed a similar pattern, the decrease in detectability was smaller for same-color probes than for different-color probes when neither was presented, then it is possible to calculate *d*' for same- and different-color probes during target-visible and target-faded intervals. Estimates based on this assumption indicated that both same- and different-color probes had relatively high *d*' values during target-visible intervals (*d*' = 1.94 and 1.93, respectively), with a response bias comparable to that of Experiment 1 (*β* = 1.67). However, the average *d*' was smaller for same-color probes than for different-color probes during target-faded intervals (0.26 and 0.61, respectively). In contrast, response bias remained relatively stable between target-visible and target-faded intervals (*β* = 1.87 and 1.54, respectively).

Sakaguchi (2001) reported that time to fading was the same for blue targets on red backgrounds as for blue targets on green backgrounds. Thus, there was little concern about the effect that changing the target and background colors would have on the quality of the fading. Furthermore, a pilot experiment confirmed that probe-detection hit rates were identical for green and red probes on the blue target, for both background colors (green and red).

![Fig. 2. Mean probe-detection hit rates in Experiment 2 as a function of target-report condition (visible vs. faded) and probe type (same color vs. different color). The error bars indicate standard errors of the mean.](image-url)
during target-faded intervals was significantly smaller for different-color probes than for same-color probes.

**GENERAL DISCUSSION**

Using a dual-task probe-detection method, the current study demonstrated a functional equivalence between a perceptually completed surface and a physically presented probe stimulus. Observers failed to detect probes that were presented within the area of a perceptually filled-in surface when the probes had the same surface characteristics as that perceptually filled-in surface (Experiment 1). However, participants were better able to detect probes that were presented within the area of a perceptually filled-in surface when the probes had surface characteristics different from those of the filled-in surface (Experiment 2). This result indicates that the failure to detect probes that matched the perceptually filled-in surface was not simply due to a reduction in the gain of signals from stimuli in the location of the filled-in surface. We now consider the broader significance of these findings.

De Weerd et al. (1998) proposed that perceptual filling in reflects a failure of figure-ground segregation in which the neural signal representing the boundary of the target decreases in strength, and eventually fails altogether, because of the adaptation that occurs with steady fixation. Once the boundary representation fails, neural filling in causes background features to fill in the target area, which is no longer defined by any boundary. In other words, because the neural filling-in signals representing the background surface no longer stop at the edge of the target (because this edge is no longer represented), the background features are carried from the surrounding area into the target area. According to De Weerd et al., then, the filled-in area is in fact represented and perceived (for opposing views, see Dennett, 1991, 1992; Durig, Tripathy, & Levi, 1995; O’Regan, 1998). That is, Troxler fading represents the momentary failure of a specific aspect of the representation of the scene (i.e., the target’s border), not a larger failure of perception at this location.

The data reported here are in general agreement with the account of perceptual filling in proposed by De Weerd et al. (1998). If the target location during filling in was indeed represented and seen as the background color, rather than the target color, then background-colored probes should have been effectively invisible, as they appeared to be in Experiments 1 and 2. However, this theory does not immediately account for the reduction in detectability of non-background-colored (different) probes during filling in, in Experiment 2. Yet these results seem consistent with a recent study by Lou (1999), in which he found evidence that perceptual processing was actively inhibited at locations that had been attended, but not fixated, for long periods of time (see also Mennemeier et al., 1994, and De Weerd, Gattass, Desimone, & Ungerleider, 1995, for possibly related neurophysiological data on monkeys experiencing perceptual filling in), as was the case in the current experiments. Thus, it seems that during Troxler fading, the perception of novel events at the faded area depends both on the physical characteristics of the events (whether they contrast with the filled-in background or not) and on the degree to which sustained attention suppresses perceptual processing at the filled-in location.

**CONCLUSIONS**

The present study demonstrates that a perceptually filled-in surface can be functionally equivalent to a physically presented stimulus. This finding is consistent with the view that perception is an active neural process that generates surfaces based both on sensory stimulation (reflecting physical evidence) and on internal neural computations (not necessarily linked directly to physical evidence). This finding also supports an integrated view of perceptual filling in that involves both neural filling-in processes (lateral spreading of perceived features) and neural suppression of perceptual processing (due to prolonged periods of attending to but not fixating peripheral locations).

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