Consciousness and Cognition 31 (2015) 46–59

Contents lists available at ScienceDirect

Consciousness and Cognition

journal homepage: www.elsevier.com/locate/concog

Invisible collinear structures impair search

Hiu Mei Chow [a], Chia-huei Tseng [a,b,*]

[a] Department of Psychology, The University of Hong Kong, Hong Kong
[b] Department of Psychology, National Taiwan University, Taipei, Taiwan

ARTICLE INFO

Article history:
Received 9 August 2013
Available online 6 November 2014

Keywords:
Collinearity
Visual search
Invisible
Awareness

ABSTRACT

Visual attention and perceptual grouping both help us from being overloaded by the vast amount of information, and attentional search is delayed when a target overlaps with a snake-like collinear distractor (Jingling & Tseng, 2013). We assessed whether awareness of the collinear distractor is required for this modulation. We first identified that visible long (=9 elements), but not short (=3 elements) collinear distractor slowed observers' detection of an overlapping target. Then we masked part of a long distractor (=9 elements) with continuous flashing color patches (=6 elements) so that the combined dichoptic percept to observers' awareness was a short collinear distractor (=3 elements). We found that the invisible collinear parts, like visible ones, can form a continuous contour to impair search, suggesting that conscious awareness is not a pre-requisite for contour integration and its interaction with selective attention.

1. Introduction

Visual attention and perceptual grouping help prevent us from being overwhelmed by the vast amount of input that we receive at every moment. The former system selects specific information for further processing, and the latter system organizes the complex visual scene into reduced clusters according to properties, such as proximity, similarity, good continuation, common fate, and closure (Wetheimer, 1938a, 1938b). For instance, collinear integration is a grouping of smaller elements that are oriented in a collinear way (from head to tail) as one object (contour), which makes the contour easily-detectable when it is in a field of randomly-oriented elements (Field, Hayes & Hess, 1993; Field & Hayes, 2004; Freeman, Sagi & Driver, 2001; Hess, Hayes & Field, 2003).

The relationship between selective attention and collinear integration has been intensively investigated in recent years: not only does attention exert a direct effect on collinear grouping (Freeman & Driver, 2005; Freeman et al., 2001; Freeman, Sagi & Driver, 2004), collinear grouping was also reported to modulate selective attention (Conci, Müller & Elliott, 2007; Jingling & Tseng, 2013; Kimchi, Yeshurun & Cohen-Savransky, 2007; Yeshurun, Kimchi, Sha'shoua, & Carmel, 2008). Jingling and Tseng (2013) reported a puzzling impairment effect of supra-threshold collinear grouping on visual search. In their study, they showed participants a search display of 21 rows × 27 columns containing identical vertical (or horizontal) bars, except for a randomly-selected column consisting of orthogonal bars. This task-irrelevant, but outstanding, column served as a distractor, and the column bars could be grouped into a collinear (snake-like) or non-collinear (ladder-like) organization, both possessing the same high orientation contrast compared to the background. Participants judged the orientation of a target located either on the distractor column or on the other columns. Target search was *slower* when the target

* Corresponding author at: Department of Psychology, The University of Hong Kong, Hong Kong. Fax: +852 3917 3518.
E-mail address: CH_Tseng@alumni.uci.edu (C.-h. Tseng).

http://dx.doi.org/10.1016/j.concog.2014.10.004
1053-8100/

overlapped than when the target did not overlap with the collinear distractor; whereas, there was no difference for a non-collinear distractor.

The selective attentional search impairment by a task-irrelevant collinear (but non-collinear) structure is not easily explainable by any attentional models. Attentional models predict that a highly salient structure should capture attention thus any target overlapping with this structure should be more quickly detected than non-overlapping targets. Follow-up studies showed that search impairment occurs only when the collinear distractor is defined by orientation contrast, but not color or luminance contrast (Jingling, Tseng, & Zhaoping, 2013), and the same search patterns persisted despite the increased probability of overlapping targets (Tseng, Jingling, & Oh, 2012). Jingling, Tang, and Tseng (2013) used an eye movement study to show that the proportions of short-latency saccade orienting to the target, which was commonly believed to be determined by target's bottom-up salience, was significantly reduced when the target overlapped with a global collinear structure. Although these results all suggested a low-level interaction between contour integration and attention, in all of the abovementioned studies, participants were fully aware of the outstanding distractor structure, and their eyes and attention was drawn to it even though it was task-irrelevant (Jingling, Tang, et al., 2013). Here, we ask whether awareness of the collinear structure is critical for its effect on attention allocation in a visual search task.

It was long assumed that both perceptual grouping and attentional allocation require consciousness, although this view has been challenged in recent years as empirical findings started to suggest the opposite (Koch & Tsuchiya, 2007; Koch & Tsuchiya, 2012; Lamme, 2003, 2004). Blindsight and neglect patient studies found that cues or primes presented to the blind or neglect field, despite being unnoticed by patients, could orient patients' attention (Kentridge, Heywood, & Weiskrantz, 1999, 2004). At a neurophysiological level, attention and awareness are shown to be processed by distinct neutral correlates (Fernandez-Duque, Grossi, Thornton, & Neville, 2003; Koivisto & Revonsuo, 2007; Watanabe & et al., 2011; Wyart & Tallon-Baudry, 2008). This dissociation was also supported by psychophyscial observations. For example, a subliminally singleton, be it a feature singleton (Hsieh, Colas, & Kanwisher, 2011) or an ocular singleton (Zhaoping, 2008), captured attention and improved task performance at the singleton pop-out location without participants consciously reporting them. Objects defined by color, solid contour, or orientation when presented below the detection threshold (e.g., masked by the Continuous Flash Suppression (CFS) technique, Chou & Yeh, 2012; presented in a very low contrast, Zhang & Fang, 2012; or the quick orientation reversal method, Norman, Heywood, & Kentridge, 2013), led to the same-object advantage as in the literature on above-threshold object-based attention (Egly, Driver, & Rafal, 1994). Other literature, though limited, has reported that perceptual grouping can also occur without awareness. Wang, Weng, and He (2012) found that a Kanizsa triangle (formed by grouping of three Pacmen oriented in a specific way relative to each other) broke through interocular continuous flash suppression sooner than control stimuli (which were the three Pacmen oriented in a way that a Kanizsa triangle cannot induce). Lau and Cheung (2012) similarly found that a Kanizsa square survived crowding of the inducers, in which orientation discrimination of individual inducers was poor, but judgment of perceived global shape was intact with crowding. Collinear facilitation, which refers to the facilitation of detection of a central Gabor patch when it is surrounded by flankers that are oriented in a collinear way, could be induced even when the flankers were suppressed by the CFS method (Hayashi & Murakami, 2013).

In this study, we investigated whether an invisible collinear structure by perceptual grouping will impact on selective attention in a way similar to a supra-threshold collinear structure as reported in Jingling and Tseng (2013). We first identified the critical strength of contour integration for generating search impairment in Experiment 1A, then suppressed part of the distractor by the Continuous Flash Suppression paradigm (Tsuchiya & Koch, 2005) in Experiment 1B. We found significant search impairment even when the visible length of the distractor is shorter than the critical length. In Experiment 1C and 1D we reported that, after discounting the attentional effect from flashing the Mondrian pattern, the invisible contour information still exerts search impairment. In Experiment 2 we monitored observers' percept during suppression and found that, although there were great individual differences in what observers perceived, among those who experienced successful suppression ($\geqslant$70% of trials), we are able to replicate the results in Experiment 1A and 1B. In Experiment 3, we ruled out the alternative explanation of Mondrian pattern causing the search impairment. These together suggest that unseen contour information affects selective attention and impairs search performance.

2. General method

2.1. Participants

Twenty-four observers participated in Experiment 1 (A–D) in this study. One extra participant was discarded because of low average accuracy rate (<80%) across all experiments. Another twenty-four observers participated Experiment 2, two of which data were discarded due to program error. Another thirty observers participated in Experiment 3. All participants had normal or corrected-to-normal eyesight and were kept naïve about the purpose of the experiment. They signed a consent form and received course credit for participation.

2.2. Stimuli and apparatus

The stimuli were programmed by Matlab with Psychtoolbox Version 3.0.8 (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997) against a gray background. The stimulus screen, shown by a CRT monitor (ViewSonic, 21-inch, 60 Hz), was divided into two lateral parts, each of which would be presented to one eye through a mirror-stereoscope. The mirror-stereoscope consisted of a black box of 60 cm (depth) × 50 cm (height) × 55 cm (width), with a piece of black separation cardboard at the middle, four adjustable mirrors, and a chin rest. The total viewing distance was 71.5 cm (including the distance between the two mirrors for reflection to each eye). A keyboard was used for response collection.

To promote fusion between the two eyes when images were projected, a black and white circular frame of 14.0° in diameter with a 9.06° × 9.06° gray square inside was presented on each side (Fig. 1). Our search display was presented inside the circular frame. The search display contained a 9 × 9 regular grid with a unit grid spacing of 1.06°. Homogeneous horizontal white bars (0.16° × 1.04°) were placed in the center of each unit grid (Fig. 2), except that a column of vertical bars (the collinear distractor) was orthogonal to the rest (background). The distractor column was randomly-located at a distance of −3, −1, 0, +1, and +3 columns from the center. Similarly, a target element bar was broken (0.16°) by 45° tilted clockwise [right] or anti-clockwise [left] from vertical, and also randomly located at the middle row of −3, −1, 0, +1 or +3 columns from the center. The target column and distractor column were independently-determined so that they overlapped with each other 20% of the time.

In all Experiments (except 1A), a flashing Mondrian pattern was used to mask out some of the elements in the search display. Nineteen distinct Mondrian images of size 9.06° × 9.06° were pre-generated by superimposing squares of random colors of various sizes. During each flip, one of the Mondrian images was chosen randomly and drawn inside one of the circular frames. The distractor column was partially masked by Mondrian patterns, so that the visible length was 3, 5, or 9 element bars (Fig. 2E, F).

In Experiment 2, in which we asked observers to report the percept that they perceive during the trial presentation, a response screen was generated by displaying the four possible percepts binocularly.

2.3. Procedure

Participants were instructed to view the stimulus display with both eyes open. Before each experiment, they adjusted the stereoscope mirror to align a red rectangle (9.06° × 1.04°) presented to one eye with a black rectangular box of the same size projected to the other eye (Fig. 1A).

In all experiments, each trial began with a fixation display. After 100 ms, a search display gradually appeared, and reached full brightness from 0% to 100% linearly in 2 s (Fig. 1B). In experiments in which Mondrian patterns were used for masking (1B, 1C, 1D, 2, and 3), the onset of the Mondrian patch occurred immediately after the fixation display, and refreshed at a rate of 10 Mondrian images per second. Participants responded to whether the target gap that was embedded in the search display was tilted clockwise (right arrow) or counter-clockwise (left arrow) by pressing two marked arrow keys on the keyboard as quickly as possible while maintaining accuracy. Each trial was terminated when the participant made a response. Accuracy and reaction time (RT) were recorded for analysis.

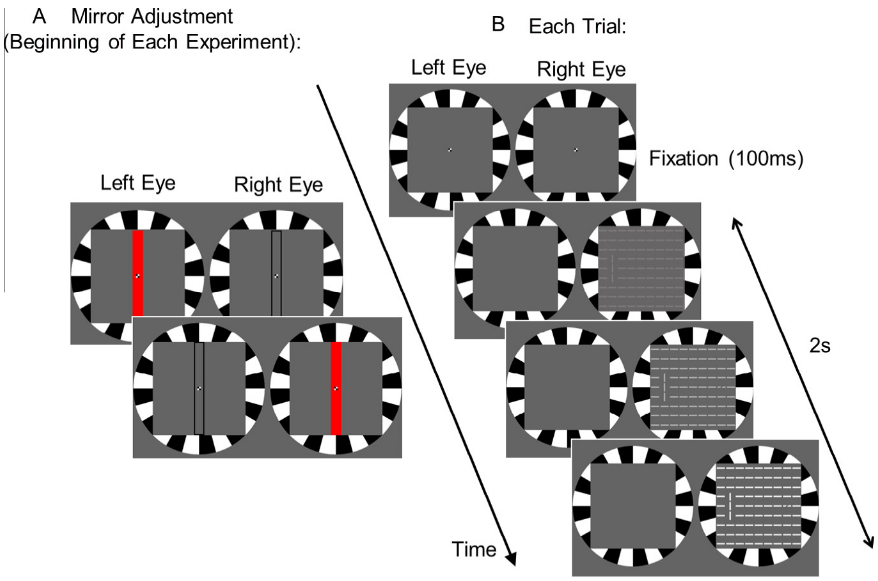


Fig. 1. Procedure. (A) Display for mirror adjustment: participant adjusted the mirrors so that the red-filled rectangle overlapped with the black rectangular box in the fused perception. Each observer performed twice to reconfirm the mirror position. (B) Each trial began with a fixation for 100 ms, followed by the search display and/or the Mondrian display gradually reaching full brightness in 2 s.

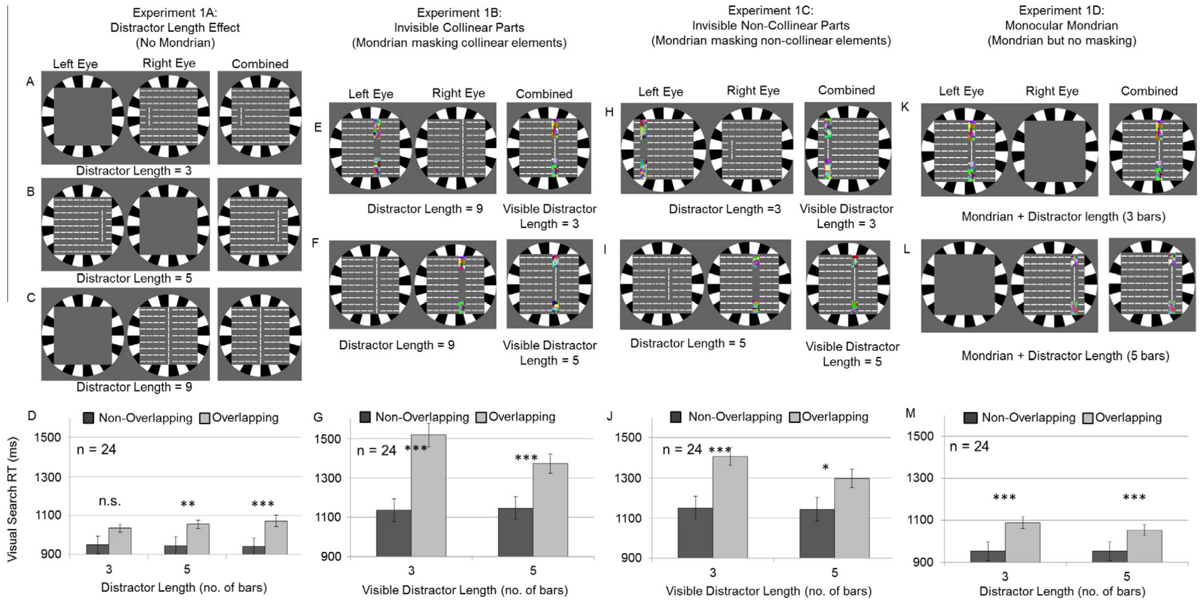


Fig. 2. Stimuli and results of Experiments 1. In Experiment 1A(A–C), a column of bar elements was oriented orthogonal to the rest of the elements (distractor), which length varied from 3, 5 and 9. In Experiment 1B(E and F), the length of collinear distractor presented to one eye was always 9 (full collinear distractor), but the size of the Mondrian pattern presented to the other eye varied in length, such that in the combined percept, the length of visible collinear distractor varied between 3 and 5 elements. In Experiment 1C (H and I), the length of collinear distractor presented to one eye was 3 and 5, while the background elements of the rest of the column were masked by Mondrian pattern of the other eye. In Experiment 1D(K and L),collinear distractor consisting of either 3 or 5 elements, while the rest of the distractor column was filled with flashing Mondrian pattern, was presented to one eye only. Mean RTs of each experiment were respectively plotted in D, G, J & M, with error bars indicating the standard error of mean $^{*}p \leqslant .05$,$^{**}p < .01$, $^{***}p < .001$. ($N = 24$).

2.4. Data analysis

In this study, the four conditions in Experiment 1 (Baseline, Binocular Mondrian, Binocular Mondrian Control, Monocular Mondrian) were labeled as separate experiment (Experiment 1A, 1B, 1C, 1D) for the convenience of communication. For each experiment, RT and accuracy were recorded and analyzed with two-way repeated measures ANOVA for the main and interaction effects of Distractor Length and Target Location on search performance. In addition, to compare the search performance across experiments, a search impairment index (SI $[i,j]$) was computed by dividing the RT difference between non-overlapping and overlapping targets by the individual mean RT for each observer i at experiment j. The search impairment index of experiment j (SI[j]) was calculated from averaging the individual SI index across all participants participating in experiment j. The sign of SI indicates whether it is a search disadvantage (positive sign) or search facilitation (negative sign) for discriminating the target orientation when the target overlaps with the task-irrelevant distractor. Zero means that the target location makes no difference to observers' performance in visual search.

$$\mathrm{SI}(i,j) = \frac{\mathrm{RT}_{\mathrm{overlapping}}(i,j) - \mathrm{RT}_{\mathrm{non\text{-}overlapping}}(i,j)}{\overline{\mathrm{RT}}(i,j)} \times 100\% \quad (1)$$

$$\overline{\mathrm{SI}}(j) = \frac{\sum_{i=1}^{n}\mathrm{SI}(i,j)}{n} \quad (2)$$

3. Experiment 1A: baseline

3.1. Experiment rationale and design

Previous reports found that the length of a collinear distractor is critical to search impairment: the search performance for overlapping targets was significantly compromised only when the distractor is longer than 9 elements in a 21 × 27 display (Jingling & Tseng , 2013) or 5 elements in a 9 × 9 display (Chow, Jingling, & Tseng, 2013). To establish the size effect baseline to be compared with subsequent experiments, the search display contained a collinear distractor of length 3, 5, or 9 element bars (Fig. 2A–C).

All participants completed a practice block of 20 trials before each experiment. Experiment 1A consisted of 300 trials and was intermixed in a block of additional 500 trials with Experiment 1C. It took about 35 min to complete. In all experiments, a break with a minimum of 10 s of rest time was given every 100 or 150 trials. Participants resumed the experiment when they were ready.

3.2. Results/discussion

2.17% of the trials, which were 2SD more than the grand mean (*Mean* = 1.05, *SD* = 0.51), were excluded from analysis. 4.87% of the remaining trials were inaccurate and, therefore, removed from RT analysis. RTs are plotted in Fig. 2D. A 3×2 repeated measures ANOVA (Collinear Distractor Length [3, 5, 9] $\times$ Target Location [overlapping, non-overlapping]) was performed on both RT and accuracy data.

In general, observers were slower when the target overlapped with the collinear distractor column ($M = 1059$ ms) than when the target did not overlap ($M = 993$ ms), $F(1,23) = 29.027$, $MSE = .155$, $p < .001$. The interaction effect between Collinear Distractor Length and Target Location is significant, $F(2,46) = 3.824$, $MSE = .008$, $p = .029$. Post-hoc analysis revealed that only when the collinear distractor had at least five elements, was there significant search impairment of target overlapping with distractor column, but not when the collinear distractor had only three elements: (Length 3: Overlapping ($M = 1038$ ms) vs. Non-overlapping ($M = 999$ ms), $t(23) = 2.70$, Holm-adjusted $p = .089$; Length 5: Overlapping ($M = 1061$ ms) vs. Non-overlapping ($M = 993$ ms), $t(23) = 3.90$, Holm-adjusted $p = .007$; and Length 9: Overlapping ($M = 1077$ ms) vs. Non-overlapping ($M = 981$ ms), $t(23) = 5.422$, Holm-adjusted $p < .001$). No significant effect on accuracy was found (*ps* > .05), suggesting that the above results are not due to accuracy trade-off.

In this experiment, we replicated the previous finding that search impairment was observable only with a collinear distractor equal to, or longer than, 5 elements (Chow et al., 2013) with the gradual appearance of search display.

4. Experiment 1B: invisible collinear distractor impairs search

4.1. Experiment rationale and design

We examine whether awareness of a distractor is necessary for the impairment effect in the current experiment. We used continuously flashing Mondrian patterns presented to one eye to mask out awareness of part of the distractor column presented to the other eye; so that, in the combined percept, the *visible* distractor is 3 or 5 elements, where in fact the *present* distractor is always 9 elements (Fig. 2E and F). If awareness of distractor parts is required for the effect of collinear grouping on visual search, the result patterns should resemble those of Experiment 1A, i.e., there should be no search impairment at length 3, but rather at length 5. If awareness is not required, search performance should be identical in both distractor length conditions.

Experiment 1B consisted of 200 trials and were intermixed in a block of additional total 400 trials together with Experiment 1D (200 trials). It took 30 min to finish. The order of participation in the two experimental blocks was counterbalanced across participants.

4.2. Results/discussion

2.16% of the trials, which were 2SD more than the grand mean (*Mean* = 1.33, *SD* = 1.17), were excluded from analysis. 2.62% of the remaining trials were incorrect and, thus, removed from analysis of RT. RT data were plotted in Fig. 2G. A 2×2 repeated measures ANOVA (Visible Collinear Distractor Length [3, 5] $\times$ Target Location [overlapping, non-overlapping]) was performed on both RT and accuracy data.

In general, observers were slower when the target overlapped with the collinear distractor column ($M = 1447$ ms) than when the target did not overlap ($M = 1186$ ms), $F(1,23) = 45.867$, $MSE = 1.638$, $p < .001$. Observers responded slower when the visible collinear distractor was of length 3 ($M = 1351$ ms) than length 5 ($M = 1281$ ms), $F(1,23) = 9.166$, $MSE = .117$, $p = .006$. More importantly, an interaction between Visible Collinear Distractor Length and Target Location on RT was significant, $F(1,23) = 10.115$, $MSE = .148$, $p = .004$. Post-hoc analysis revealed that, for both lengths, the RT of overlapping targets is significantly longer than that of non-overlapping targets (Visible length 3: Overlapping ($M = 1521$ ms) vs. Non-overlapping ($M = 1181$ ms), $t(23) = 6.671$, Holm-adjusted $p < .001$; and Visible length 5: Overlapping ($M = 1372$ ms) vs. Non-overlapping ($M = 1190$ ms), $t(23) = 4.570$, Holm-adjusted $p < .001$). From the ANOVA results of accuracy data, all effects were insignificant (*ps* > .05). In summary, we found no evidence for speed-accuracy trade-off.

We observed significant search impairment for both lengths here even when the visible distractor length was too short to generate significant search impairment in Experiment 1A (i.e. length 3). This seems to suggest invisible collinear distractors (parts) are equally effective in exerting their effect on visual search. However, the flashing Mondrian in Experiment 1B (but not 1A) may have attracted attention and confounded our findings. Two subsequent experiments were conducted to further examine the respective contribution from the masked collinear contour and Mondrian pattern. In Experiment 1C, the search display had identical visible collinear length as in Experiment 1B, but the Mondrian patterns masked non-collinear extensions (Fig. 2H and I). In Experiment 1D, observers searched a monocular Mondrian display (Fig. 2K and L). Both cases differ from Experiment 1B only in their masked distractor parts. Any SI differences will inform us about the contribution from invisible distractor parts.

5. Experiment 1C: binocular Mondrian control experiment

5.1. Experiment rationale

To examine the unique contribution by invisible collinear distractor parts in Experiment 1B, in this experiment, the distractor column contains center collinear bars, and the two ends are non-collinear bars to be masked by the Mondrian. In one eye, participants saw the search display containing a collinear distractor of length 3 or 5 (the rest of the distractor column was filled with background elements) and, in the other eye, the flashing Mondrian pattern (Fig. 2H and I). The combined percept is exactly the same as in Experiment 1B, except that the distractor elements rendered invisible were non-collinear. It is expected the search RT pattern/search impairment of this experiment will be reduced from Experiment 1B if the invisible collinear elements in Experiment 1B were effective.

5.2. Results/discussion

2.29% of the trials, which were 2*SD* more than the grand mean (*Mean* = 1.30, *SD* = 0.92), were excluded from analysis. 4.50% incorrect trials from the remaining were removed from analysis of RT. RT data were plotted in Fig. 2J. A 2 $\times$ 2 repeated measures ANOVA (Visible Collinear Distractor Length [3,5] $\times$ Target Location [overlapping, non-overlapping]) was performed on both RT and accuracy data.

For both types of distractor lengths, in general, observers were still slower when the target overlapped with the collinear distractor column (M = 1360 ms) than when the target did not overlap (M = 1203 ms), $F(1,23) = 30.134$, $MSE = .590$, $p < .001$. Observers were also, in general, slower when the visible collinear distractor was of length 3 (M = 1313 ms) than length 5 (M = 1250 ms), $F(1,23) = 10.737$, $MSE = .096$, $p = .003$. An interaction between Visible Collinear Distractor Length and Target Location on RT was also significant, $F(1,23) = 6.591$, $MSE = .077$, $p = .017$. Post-hoc analysis revealed that, the RT disadvantage at overlapping targets is significantly bigger in Visible length 3 than Visible length 5 (Visible length 3: Overlapping (M = 1420 ms) vs. Non-overlapping (M = 1206 ms), $t(23) = 6.73$, Holm-adjusted $p < .001$; Visible length 5: Overlapping (M = 1300 ms) vs. Non-overlapping (M = 1200 ms), $t(23) = 2.505$, Holm-adjusted $p = .051$). There was no speed accuracy trade-off, as participants were more accurate at reporting the orientation of non-overlapping target (97.8%) than the overlapping target (96.1%), $F(1,23) = 8.294$, $MSE = .007$, $p = .008$.

6. Experiment 1D: monocular Mondrian control experiment

6.1. Experiment rationale

In this experiment, we presented a monocular continuously-flashing Mondrian pattern with collinear distractor varied in length (3 or 5 elements) (Fig. 2K and L). This allows us to examine the effect from the flashing Mondrian pattern alone.

6.2. Results/discussion

1.00% of the trials, which were 2SD more than the grand mean (*Mean* = 1.04, *SD* = .66), were excluded from analysis. 3.00% of the remaining trials were incorrect and, thus, removed from analysis of RT. RT data were plotted in Fig. 2M. A 2 $\times$ 2 repeated measures ANOVA (Visible Collinear Distractor Length [3,5] $\times$ Target Location [overlapping, non-overlapping]) was performed on both RT and accuracy data.

In general, observers were slower when the target overlapped with the collinear distractor column (M = 1072 ms) than when the target did not overlap (M = 991 ms), $F(1,23) = 31.037$, $MSE = .157$, $p < .001$. The main effect of length and interaction was not significant ($ps > .05$), implying that the search impairment is consistent across both lengths of collinear distractors. From the ANOVA results of accuracy data, all effects were insignificant ($ps > .05$). In summary, we found no evidence for speed-accuracy trade-off.

7. SI comparison across Experiments 1A to 1D

To compare the search impairment across different experimental conditions, we used a normalized index (Search Impairment index, SI) to perform a 2 by 4 repeated measures ANOVA (Visible Distractor Length [3,5] and Experiment [1A, 1B, 1C, 1D]). The results were summarized in Fig. 3. We found significant main effects for both factors and the interaction between them (Visible Distractor Length, $F(1,23) = 16.813$, $MSE = .142$, $p < .001$; Experiment, $F(3,69) = 14.311$, $MSE = .228$, $p < .001$; Interaction, $F(3,69) = 4.981$, $MSE = .055$, $p = .003$). To understand the interaction effect, we separated the two visible distractor lengths and performed a one-way repeated measures ANOVA of Experiment respectively.

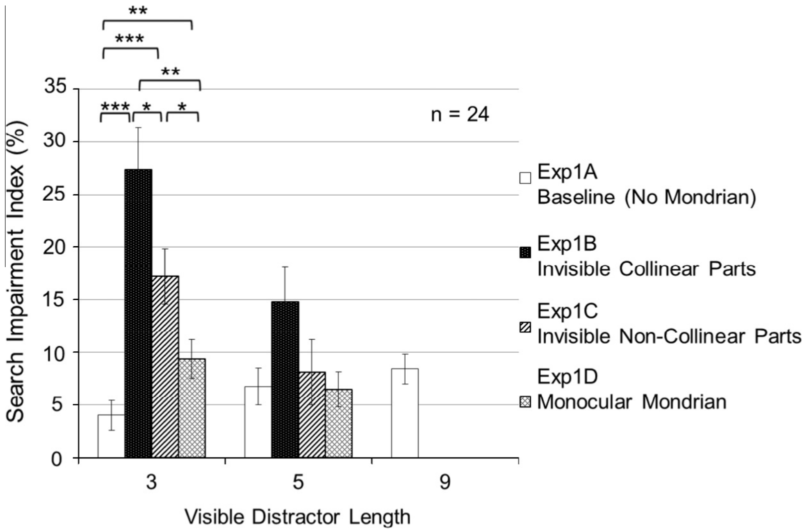


Fig. 3. Mean and Standard Error of Search Impairment index ($\overline{SI}$) for Experiments 1–4 (%). * $p < .05$, ** $p < .01$, *** $p < .001$.

7.1. Invisible collinear parts exert influence on our selective attention

For shorter distractor (Distractor Length 3), SI in Experiment 1B ($SI_{Invisible\ Collinear\_3} = 27.3\%$) is significantly larger than that of Experiment 1A ($SI_{Baseline\_3} = 4.01$, Holm-adjusted $p < .001$), Experiment 1C ($SI_{Invisible\ Non\text{-}Collinear\_3} = 17.2\%$, Holm-adjusted $p = .022$), and Experiment 1D ($SI_{Monocular\ Mondrian\_3} = 9.37\%$, Holm-adjusted $p = .001$). On top of that, SIs in Experiment 1C (Invisible Non-Collinear) and Experiment 1D (Monocular Mondrian) were significantly larger than that of Baseline Experiment 1A (Holm-adjusted $p < .001$; $p = .009$). The SI of Experiment 1C was larger than that of Experiment 1D (Holm-adjusted $p = .047$). Similar analysis was performed for Visible Distractor Length 5. Although significant main effect for Experiment was also found, $F(3,69) = 2.839$, $MSE = .037$, $p = .044$, the pairwise comparison after Holm adjustment did not yield any significant results (Holm-adjusted $ps > .25$). In other words, the normalized search impairment at Visible Distractor Length 5 is comparable across experiments.

The greater search impairment from invisible collinear distractors (Experiment 1B) than invisible non-collinear distractor (Experiment 1C) and monocular Mondrian control (Experiment 1D) for shorter distractor (length 3) supported the conjecture that the collinear parts masked by CFS exerted on our selective attention. However we did not see similar pattern in longer distractor (length 5), presumably because the effect was shadowed by the visible structure of higher collinear strength (length 5).

7.2. Are invisible and visible collinear parts comparably effective?

To answer this question, we use the baseline condition with a visible full-length collinear distractor (length 9 in Experiment 1A) as the reference point ($SI_{Baseline\_9} = 8.41\%$). We compare it with an identical display with partial collinear parts rendered invisible by CFS (Experiment 1B).

An accurate estimation requires proper consideration of the effects from Mondrian patterns – which were present only in the invisible collinear case. As Experiment 1B (Invisible Collinear) and Experiment 1C (Invisible Non-collinear) differs only in the masked collinear distractor parts, the SI difference (10.1%) between the two experiments (Exp 1B $SI_{Invisible\ Collinear\_3} = 27.3\%$, Exp 1C $SI_{Invisible\ Non\text{-}Collinear\_3} = 17.3\%$) is a good estimate of invisible collinear two-ends (size 3 at each end adds to size 6 in total). To fill in the middle section, we adopt the size 3 SI from Experiment 1A ($SI_{Baseline\_3} = 4.01\%$) to extend it to a full-length distractor (size 9). We found SI generated from invisible collinear distractor was comparable to visible collinear distractor ($SI_{Baseline\_9} = 8.41\%$, Visible length 3: $SI_{Invisible\ Collinear\_3} - SI_{Invisible\ Non\text{-}Collinear\_3} + SI_{Baseline\_3} = 14.1\%$, $t(23) = .1.44$, $p = .165$; and Visible length 5: $SI_{Invisible\ Collinear\_5} - SI_{Invisible\ Non\text{-}Collinear\_5} + SI_{Baseline\_5} = 13.5\%$, $t(23) = 1.31$, $p = .204$).

7.3. Did CFS really render the structure invisible?

Although the colored flashes of Mondrian patterns are known to be a strong suppressant, the highly salient collinear structure may prompt the “invisible collinear parts” to escape from the CFS suppression during search. Thus it is desirable to have an additional measurement to ensure participants’ unawareness. We conducted Experiment 2 to have observers give additional subjective percepts to address this concern.

7.4. Did Mondrian impair the search?

It is curious why search impairment is greater for visible distractor length 3 than 5 in Experiment 1B and 1C. We note that length of visible collinear distractor is inversely related to the size of Mondrian, and the Mondrian size is a possible explanation. The larger Mondrian size (i.e. 6) when the visible collinear distractor is small (i.e. 3) may distract attention away from the central target zone thus impair search. When Mondrian size is small (i.e. 4) at length 5, the search impairment reduces. To further elucidate the role of flashing Mondrian on search impairment and its interaction with collinear distractor, in Experiment 3, we independently manipulated the location of Mondrian patterns and collinear distractor.

8. Experiment 2: subjective report control experiment

8.1. Experiment rationale

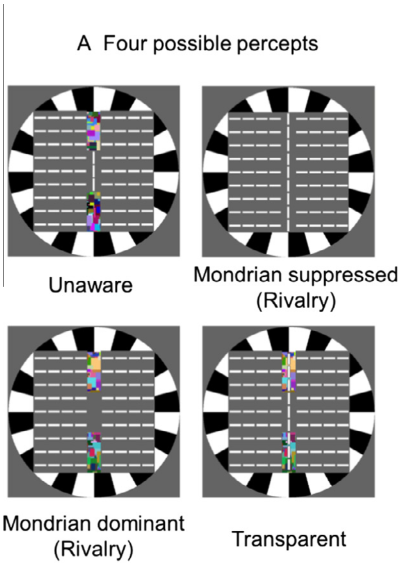
Was our CFS really effective to render invisible percept? In this experiment, we intended to supplement observers' subjective percept report during continuous flash suppression to double check whether observers were really unaware of the distractor parts. There are several challenges for this intention. First, the nature of our search task requires the distractor to be a "task-irrelevant" component (i.e. not informative about target location) and therefore should be ignored under an optimal search behavior. The request of conscious report of a task-irrelevant distractor directly violates the key design of the visual search because observers now have to attend to the structure for a secondary report. This violation may result in contamination of the search performance. Secondly, observers' on-line percept report of a structure is likely to promote rivalry in a dichoptic display at the location where their attention is redirected to (see review by Paffen & Alais, 2011).

Therefore, after considering these constraints, we decide to obtain observers' awareness report in a separate experiment instead of on-line together with the primary target search. We based on the subjective report to identify those whose awareness was successfully suppressed by CSF, and examine whether the same main findings are still obtainable when only these selected observers' visual search performance was considered.

8.2. Experiment procedure

There are three parts of Experiment 2. Twenty-four new participants first replicated Experiment 1A and 1B (called Experiment 2A and 2B here). Then they proceed to Experiment 2C in which they reported their final percept from four possible choices at the end of the presentation by pressing one of the four keyboard keys. Observers completed Experiment 2A (300 trials) and 2B (200 trials) intermixed in a block first to avoid interference of reporting percepts on their search performance. It took about 30 min.

There four possible percepts during binocular fusion that an observer can see are (Fig. 4A): (1) the flashing Mondrian patches at two ends of the distractor column successfully mask out the distractor elements ("Unaware"); (2) binocular rivalry can occur, and observers may either see the full collinear distractor display ("Mondrian Suppressed [Rivalry]"); (3) the



B Individual proportion of percepts reported by observers (%)

Subject	Unaware	Mondrian suppressed (Rivalry)	Mondrian dominant (Rivalry)	Transparent
DC	74.0	2.5	1.5	22.0
LI	55.3	0.3	6.0	38.5
BC	84.3	0.0	8.5	7.3
CT	54.5	0.3	2.8	42.5
YM	78.3	0.3	4.8	16.8
TY	92.0	0.3	0.5	7.3
WS	79.0	1.5	1.0	18.5
TH	70.5	0.3	17.0	12.3
YW	21.8	7.8	40.5	30.0
KY	67.8	3.0	13.3	16.0
JA	73.8	0.5	5.3	20.5
WL	34.9	0.0	6.8	58.3
YJ	43.8	0.3	22.8	33.3
EL	16.0	0.5	4.8	78.8
BD	91.0	0.8	1.5	6.8
ZH	23.0	2.3	48.8	26.0
YL	83.8	2.8	4.5	9.0
CY	47.3	0.3	4.5	48.0
ED	22.0	0.3	20.8	57.0
SL	10.5	1.5	29.0	59.0
KM	21.0	1.0	75.0	3.0
KY	54.3	0.0	1.8	44.0
Average	**54.5**	**1.2**	**14.6**	**29.8**

Fig. 4. (A) Four possible percepts that observers can see from our suppression trials in Experiment 2. (B) The percentage of trials in which our observers reported each percept in Experiment 2C.

Mondrian display containing no collinear distractor ("Mondrian Dominant [Rivalry]"); or (4) transparent overlapping of the distractor elements on top of the Mondrian pattern ("Transparent"). Only (1) would actually achieve the critical claim that our observers were unaware of parts of the stimuli.

Experiment 2C contained 400 trials. There were four presentation durations (900, 1200, 1500, 1800 ms), chosen based on the average search RT in Experiment 2B. Each duration had equal number of trials and was randomly selected for each trial. An additional 200 monocular catch trials (50 trials for each of the four possible percepts) where images were presented to one eye (randomly selected) without binocular suppression/rivalry involved were included to ensure that observers understood our percept instruction. In summary, all participants completed 600 trials, which took about 35 min.

8.3. Results/discussion

The average accuracy at catch trials from all 22 participants is 88.2%, indicating their full understanding of the task.

Because the interaction between percentage of the report percepts and presentation duration was not significant, $F(9,189) = 1.029$, $MSE = .002$, $p = .419$, we collapsed across presentation duration and plotted the individual percentage of the reported four percepts in Experiment 2C is included in Fig. 4B. As shown in the table, the effect of suppression-masking differed greatly across observers, consistent with other reports (Aafjes, Hueting, & Visser, 1966; Carter & Pettigrew, 2003; Crain, 1961; Frederiksen & Guilford, 1934; Kanai, Bahrami, & Rees, 2010; Miller et al., 2009; Ukai, Ando, & Kuze, 2003). The "Unaware" percept report ranged from 16% to 91%. While the percentage of trials of seeing "Mondrian suppressed (Rivalry)" is small, the percentages of "Mondrian dominant (Rivalry)" and "Transparent" percepts can be high, depending on the individual observers. The unexpected and relatively high proportion of trials in which observers reported "Transparent" can be due to the fact that in our search task, the target was always presented to one eye. This may highlight the information from this eye and promote fusion between the two images, which forms the "Transparent" percept. Nonetheless we did not observe the location of target affecting perceptual dominance ratio as a 2 by 4 repeated measures ANOVA (Target Location [overlapping, non-overlapping] vs. Percept [Unaware, Mondrian suppressed, Mondrian dominant, Transparent]) found no significant interaction, $F(3,63) = .833$, $MSE = .001$, $p = .481$. This suggests that if rivalry happens, it is equally likely to happen to search displays where target is overlapping with the collinear distractor and not.

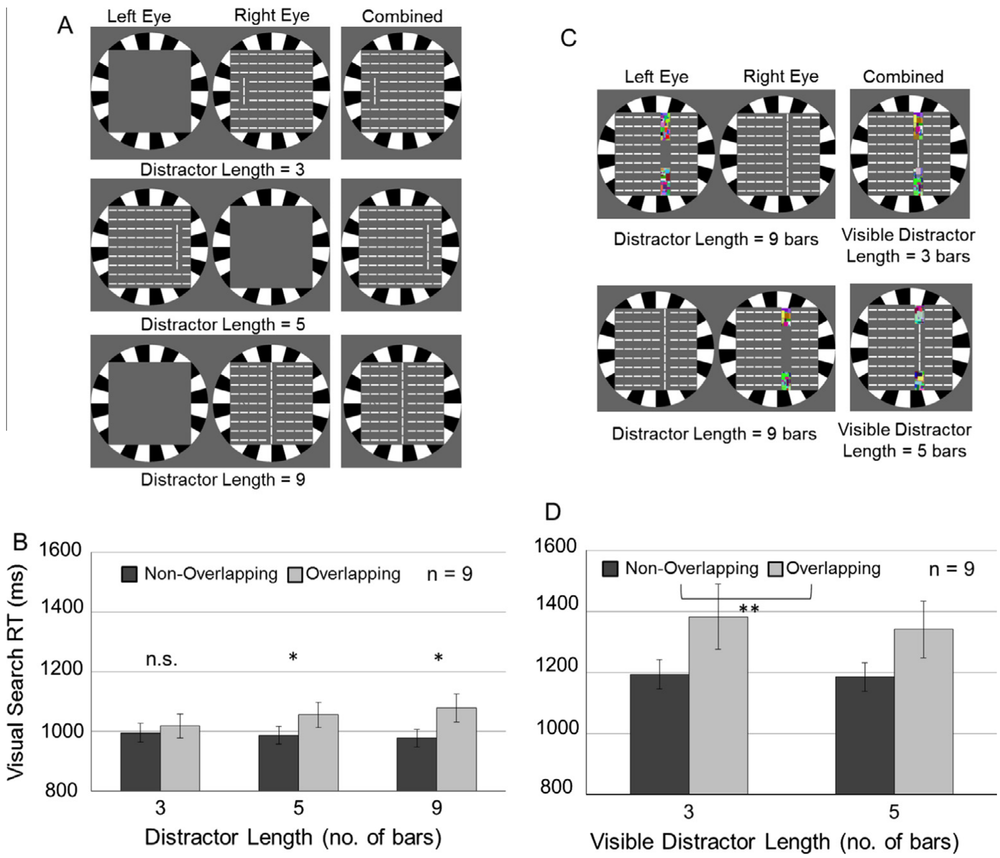


Fig. 5. For the nine observers who reported more than 70% of the time the percept of "Unaware" (which successful suppression occurs) in Experiment 2C, their RT pattern to search tasks was plotted in B and D and showed a similar pattern to Experiment1 and 2. * $p < .05$ ** $p < .01$.

To be conservative, we only included nine observers who had reported an "Unaware" percept equal to, or greater than, 70% for subsequent analysis. For those selected participants, we analyzed their search performance in Experiment 2A and 2B the same way as in Experiment 1. The same criteria were applied for discarding data (i.e., 2*SD* above grand mean), and 2.26% and 2.52 % of trials were removed for the analysis in Experiment 2A and 2B respectively. An additional 1.36% and 1.71% of trials were removed from RT analysis because they were incorrect.

With only these 9 participants, we were still able to replicate the same results in Experiment 1A (Fig. 5B): the main effects of Target Location and Distractor Length, as well as interaction were all significant (Target location: $F(1,8) = 9.378$, $MSE = .056$, $p = .016$; Distractor Length: $F(2,16) = 3.774$, $MSE = .002$, $p = .045$; Interaction: $F(2,16) = 4.721$, $MSE = .007$, $p = .024$.) Short distractors (= 3 elements) did not cause search impairment (Non-overlapping 996 ms vs. Overlapping 1019 ms, $t(8) = .840$, Holm-adjusted $p = .425$, while long distractors (= 5 or 9 elements) caused search impairment (Length 5: Non-overlapping 987 ms vs. Overlapping 1055 ms, $t(8) = 3.283$, $p = .022$; and Length 9: Non-overlapping 977 ms vs. Overlapping 1079 ms, $t(8) = 3.596$, $p = .021$).

In Experiment 2B where continuous flash masking was applied, the number of visible elements forming a collinear distractor was 3 or 5. We also replicated the most important finding in Experiment 1B with 9 participants only: even when the visible length was too short to impair search (i.e. length 3), when together with the invisible parts, it could generate the same effect as a full-length collinear distractor (Fig. 5D). Repeated measures ANOVA found a significant main effect of Target Location: observers were faster at reporting non-overlapping targets (1190 ms) than overlapping targets (1362 ms), $F(1,8) = 5.986$, $MSE = .270$, $p = .040$. The visible distractor length effect and interaction effect were both insignificant ($ps > .3$). No significant effect on accuracy was found ($ps > .1$), suggesting that the above results are not due to accuracy trade-off.

One may be concerned that our selection of observers with a high proportion of "Unaware" percept may bias the result by including observers with a particular search profile only (e.g. longer RT). To examine the individual differences better, we plotted observers' proportion of reporting "Unaware" against their own mean search RT (Fig. 6A) as well as search impairment index (Fig. 6B). We found that observers who reported "Unaware" of stimuli had significantly shorter RT (Length 3: $r = -.57$, $p = .006$; Length 5: $r = -.58$, $p = .005$), but it did not correlate with SI index which was the normalized RT difference between overlapping and non-overlapping target (Length 3: $r = -.009$, $p = .968$; Length 5: $r = -.267$, $p = .229$). This means that we may have selected observers that have a general faster search time, but this does not confound our main findings and conclusion.

In summary, we replicate the enhancement of search impairment by *successfully suppressed* collinear distractors, which confirm the contribution of invisible collinear distractors to selective attention, and our findings are not confounded by observers being aware of the masked elements.

9. Experiment 3: impairment by Mondrian patterns?

9.1. Experimental rationale

The flashing Mondrian patterns used in the experiments are attention-capturing themselves and always appear together with the collinear structure in Experiment 1 and 2. Although the effect from collinearity is evident, the possible involvement of Mondrian is also speculated. Particularly, we observed an opposite bigger search impairment at size 3 than size 5 in Experiment 1B and 1C, which could origin from their accompanied Mondrian patterns. To isolate the effect of Mondrian pattern from the collinear distractor on visual search, we designed Experiment 3.

We independently manipulated the locations of the Mondrian patterns and collinear distractor (−3, −1, +1, +3 from center) in a monocular search display. Only in 25% of the trials, the Mondrian patterns were in the same column aligned with the

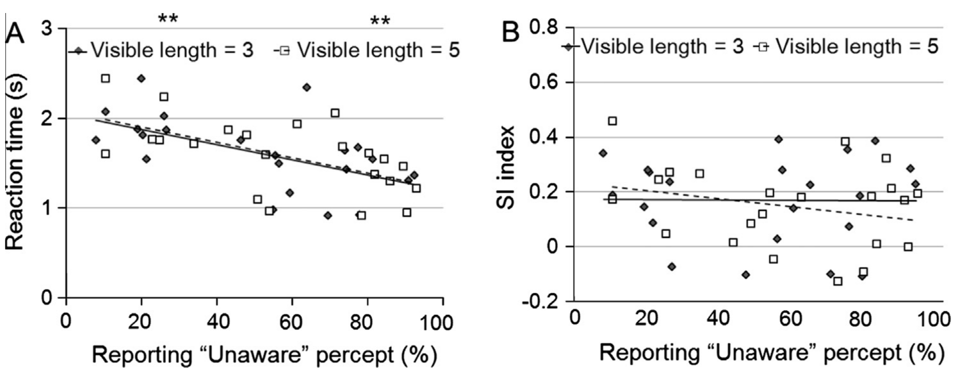


Fig. 6. The relationship between proportion of trials reporting "Unaware" percept and (A) general search RT, as well as (B) the normalized RT difference between overlapping and non-overlapping target in Experiment 2. ** $p < .01$.

collinear distractor, and for the rest of the trials, they appear in a different column from the collinear distractor (Fig. 6A and B). The target of each trial falls into one of the four categories: overlapping with Mondrian pattern (yes or no) × overlapping with collinear distractor (yes or no). The collinear structure is either 3 or 5 bars, which corresponds to two lengths of Mondrian patterns as illustrated in Fig. 6A and B.

A group of 30 naïve participants who did not participate previous experiments completed this experiment, which consisted 512 trials intermixed of different overlapping conditions.

9.2. Results/discussion

1.22% of the trials were excluded from analysis because the RTs exceeded more than 2*SD* above grand mean RT (*Mean* = 1.08, *SD* = 0.63). Inaccurate trials (2.53% of the remaining trials) were also removed from RT analysis. A 2 × 2 × 2 repeated measures ANOVA was performed on both RT and accuracy data (Total Mondrian distractor length [6, 4] × Target Location with Collinear distractor [Yes, No] × Target Location with Mondrian pattern [Yes, No]). No main effect or interaction was found with the Mondrian distractor length (*ps* > .4), thus RT data of the two lengths was collapsed and plotted in Fig. 7C. Targets overlapping with Mondrian pattern column were significantly easier to be identified (1054 ms) than not (1105 ms), $F(1,29) = 33.061$, $MSE = .154$, $p < .001$. This is opposite to our initial speculation that Mondrian slowed the search. We also replicated our finding that targets overlapping with collinear distractor, are significantly harder (1152 ms) to be detected than not (1007 ms), $F(1,29) = 74.031$, $MSE = 1.254$, $p < .001$. There was also a significant interaction effect between the two factors, $F(1,29) = 7.285$, $MSE = .020$, $p = .011$. Post-hoc analysis revealed significant search impairment by target overlapping with collinear distractor (Holm-adjusted *ps* < .001), regardless of whether it is overlapping with Mondrian pattern or not. Interestingly, collinear search impairment is bigger when target is not overlapping with Mondrian pattern (RT difference = 163 ms, $t(29) = 9.868$, $p < .001$) than when target is overlapping with Mondrian pattern (RT difference = 126 ms, $t(29) = 6.463$, $p < .001$). The effects on accuracy were insignificant (*ps* > .4).

In this experiment, we found that Mondrian distractor in general facilitated target search if Mondrian and target were aligned in the same column – even though the Mondrian patterns were at two ends and target was always at the middle row without being spatially overlapped. This is possibly done by attention capture through “object-based attentional selection” in which the region between the two Mondrian patterns also benefits from the Mondrian effect (e.g. Egly et al., 1994). This conjecture is beyond the scope of current study but should be further consolidated in future research. Nonetheless our

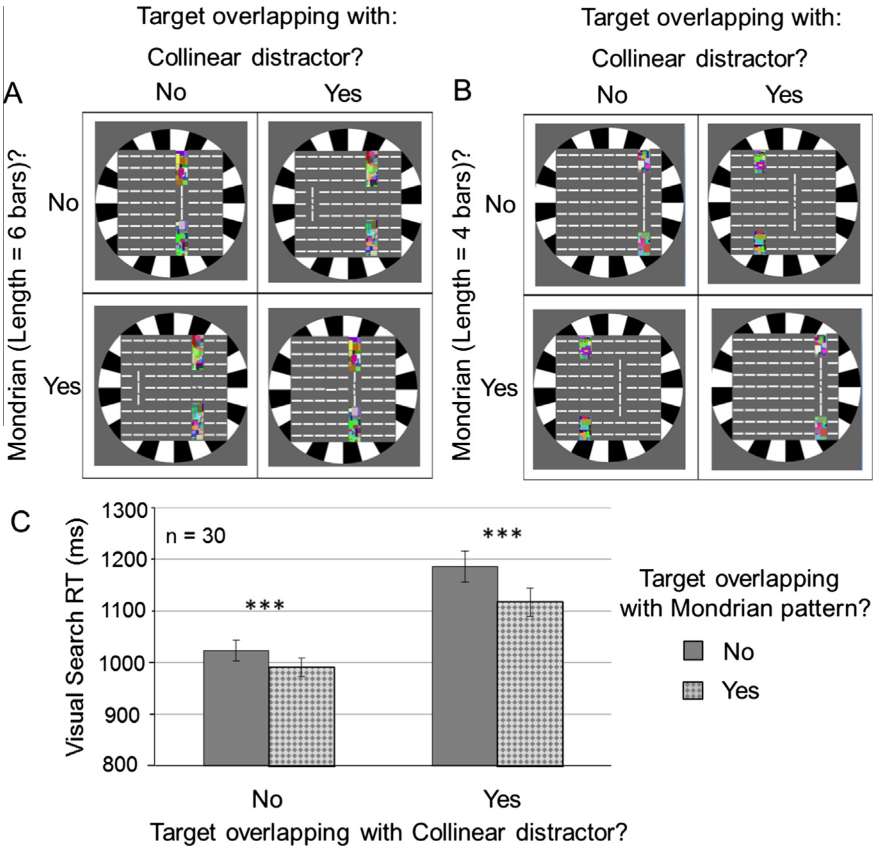


Fig. 7. The monocular stimuli for Experiment 3 with (A) long Mondrian length = 6 bars, (B) Mondrian length = 4 bars, and (C) results, * $p < .001$.

findings suggest that Mondrian pattern itself is unlikely to be the reason of impairment observed in previous experiments as it causes facilitation instead. The fact that Mondrian patterns enhanced collinear impairment was also intriguing, and it leaves another open question for future research as well.

10. General discussion

Our study investigated whether awareness is required for collinear integration to exert an effect on selective attention. We did so by first establishing a distractor size effect for search impairment in Experiment 1A. In Experiment 1B, we found that, when part of the collinear distractor was rendered invisible by a continuous flashing pattern, it produced the same significant search impairment. After replacing invisible contour with a non-collinear one (Experiment 1C), controlling the attentional effect with monocular Mandarin (Experiment 1D), and taking observers' subjective report into consideration (Experiment 2), we conclude that invisible collinear contour was as effective as visible contour in impairing visible search of a visible local target. Our experiment 3 found that Mondrian pattern itself generates search facilitation as opposed to impairment, thus rejecting it alone as contributing to the search impairment observed in previous experiments.

Our conclusion that invisible collinear distractor parts enhance search impairment is mainly driven by the greater SI observed in Experiment 1B where the invisible parts were collinear than Experiment 1C where the invisible parts were non-collinear or Experiment 1D where the display was monocular and there were no invisible parts. However, one can propose two alternative explanations to explain the effects.

One speculation is that the interocular suppression from the Mondrian patches may spread to the area in the middle embedded by the Mondrian patches, creating the binocular rivalry percept of which the Mondrian pattern is dominant ("Mondrian dominant (Rivalry)" percept in Experiment 2C). Previous studies have reported that interocular suppression can spread beyond the boundaries of the suppressed stimulus (Blake & Camisa, 1979; Kaufman, 1963; Levelt, 1965). Additionally, in a more recent study, Maruya and Blake (2009), by masking part of a contour of a larger figure, found that the suppression spread over several degrees along the contours of the figure, but not to the disconnected locations, although they are closer to the manipulated suppression site. It is not known whether spreading of interocular suppression is specific to concrete contour (as in Maruya & Blake, 2009), or if it can be extended to contour formed by perceptual grouping (as in our study), or even illusory contour. It is possible that, in our experiments, such spread of interocular suppression suppressed overlapping targets more than non-overlapping targets and enhanced search impairment. This may thus explain why we see a greater SI index in Experiment 1B and 1C (with interocular suppression) than in Experiment 1A and 1D (both monocular). However, this does not change our conclusion, as interocular suppression is equally common in Experiment 1B (invisible collinear elements) and 1C (invisible non-collinear elements). ; The significantly larger impairment in Experiment 1B than 1C suggests the role of invisible collinear distractors on the search task.

Another speculation is that the possibility that the visible collinear structure helps the invisible structure to break through continuous flash suppression, resulting in "Transparent" percept in Experiment 2. This may explain why there is larger SI in Experiment 1B than Experiment 1C. However, it is unknown how 30% of such "Transparent" percept (from Experiment 2) can account for the difference. And if the physical length is not suppressed properly and driving the effect, we should have observed larger SI difference between visible length 3 and 5 in Experiment 1C (the physical length varied between 3 and 5) than the SI difference between visible length 3 and 5 in Experiment 1B (the physical length was always 9 in both conditions), which does not seem to be the case from our results.

Both speculations are not well supported. The most plausible explanation for our effect is that invisible collinear distractor impairs search. The current results across experiments give us three main findings. First, search impairment is enhanced by invisible contour parts, suggesting that awareness of the full length contour is not necessary for the effect of contour on selective attention in a search task. The finding of dissociation between attention and awareness is consistent with other findings that a subliminally-presented stimulus can cause special attentional phenomenon, such as attention capture (Astle, Nobre, & Screif, 2010; Hsieh et al., 2011; Jiang, Costello, Fang, Huang, & He, 2006; Kentridge et al., 2004; Koch & Tsuchiya, 2007; Ivanoff & Klein, 2003; McCormick, 1997) and object-based attention (Chou & Yeh, 2012; Norman et al., 2013; Zhang & Fang, 2012). What we add to the literature is that invisible mid-level properties, such as collinear grouping, can affect attention by using a new search phenomenon.

Second, the invisible contour parts can join the visible contour parts to form a full-length contour to influence visual attention, which indirectly suggests that collinear integration does not require awareness of all elements. This finding is in line with studies that showed that perceptual grouping can occur under inattention (Kimchi & Razpurker-Apfeld, 2004; Moore & Egeth, 1997; Pitts, Martińez, and Hillyard, 2011. Moore and Egeth (1997) asked participants to judge which of the two target lines are longer and found that the judgment was subject to conventional illusions (Ponzo Illusion and Muller-Lyer Illusion) produced by an above-threshold, but task-irrelevant, background organization; subjects were unable to report this background organization retrospectively. More recently, Pitts et al. (2011) isolated neural activity associated with specific stages of visual perception and awareness of display containing a contour or not, and found that the Nd1 component was elicited by contour patterns during inattentional blindness and was dissociated from components associated with awareness (which occur at a later time point in Nd2 component). In these studies, contour information is always presented above threshold but, because of diverted attention to the central task, the contour information is rendered in the "inattention" state and, thus, is not reported by participants. More recent studies showed that invisible flankers masked by CFS

(Hayashi & Murakami, 2013) and flankers of invisible orientation (second-derivative of a Gaussian when temporally-fused with an orthogonal pattern) (Hayashi & Murakami, 2012) were able to induce collinear facilitation. Using different collinear phenomenon that involve interaction between contour integration and visual search, our report adds new findings to the field, as we introduced sub-threshold contour information in our experimental design and demonstrated that collinear parts rendered invisible can be joined with visible collinear parts to enhance search impairment.

Third, our findings inform the role of awareness in primary visual cortex (V1). There is inconsistent literature about the role of V1 as the locus of awareness of general visual information: some argue that awareness modulation is reflected in V1 (e.g. Maier et al., 2008; Polonsky, Blake, Braun, & Heeger, 2000; Tong & Engel, 2001) and some argue the opposite (e.g. Watanabe & et al., 2011). Collinearity as illustrated in our collinear search impairment and other studies using collinear facilitation helps address the awareness question as (1) collinear information is reported to be consistent with the dynamics of long-range horizontal interactions within primary visual cortex (V1) (Cass & Alais, 2006), and (2) collinear search impairment operates at a monocular level (Chow et al., 2013) which is again a property of V1. In Chow et al. (2013), different parts of the collinear distractor were presented to different eyes through a mirror stereoscope. It was found that search impairment was determined by the monocular distractor length – search impairment was not significant if the monocular distractor was too short, even when the binocular fused length was longer than the critical length. By showing awareness is not required for a collinear search phenomenon that highly correlates with V1 properties, the current finding supports that awareness modulation is not necessarily implicated in V1.

The current findings leave us with at least two potential future research questions. First, the general RT and SI is larger when the presentation is dichoptic (Experiment 1B, 1C, 2B) than monocular (Experiment 1A,1D, 2A, 3). While much established in the literature is that RT is usually faster in binocular display than monocular display due to binocular summation (Blake, Martens, & Di Gianfilippo, 1980; Blake, Sloane, & Fox, 1981; Harwerth, Smith, & Levi, 1980), less is known about the difference between dichoptic and monocular displays. Previous research has found that, in a dichoptic display, both bottom-up and top-down attention can modulate visual processing at eye-specific level (Ooi & He, 1999; Tan & Hsieh, 2013; Zhang, Jiang, & He, 2012; Zhaoping, 2008, 2012). We speculated that the shorter RT in our monocular display could be due to eye-specific attentional prioritization induced by the salient flashing Mondrian patterns. For instance, in a monocular display where the Mondrian is presented to the same eye as the search display is (e.g. Experiment 1D), the salient Mondrian patterns activated the eye-specific attentional system which prioritizes the other information presented to the same eye (i.e. the search display), resulting in faster general search RT in comparison to search display present in the opposite eye (e.g. Experiment 1B and 1C). The role of eye-specific attention allocation and suppression in contributing to the differences in search speed in dichoptic and monocular displays awaits for confirmation with future research. Second, although the current study has shown that invisible collinear segments can be joined with visible parts to impair search, it remains unknown whether a *completely invisible* collinear distractor still exert search impairment. Future research can probe into addressing these two issues related to the current findings.

Nonetheless, our research findings add to the present literature on attention and awareness with an intermediate level of stimulus (collinear grouping). It supports the assertion that dissociation of attention and awareness covers a wide range of stimulus types and attentional mechanisms.

Acknowledgments

This work was supported by the General Research Fund from The Research Grants Council of Hong Kong, China; and The Hong Kong University Seed Funding Programme for Basic Research to Dr. Tseng. We gratefully thank Matt Oxner for programming support and Leon Ieong, May Yeung, and Sunny Lee for their assistance in data collection.

References

Astle, D. E., Nobre, A. C., & Screif, G. (2010). Subliminally presented and stored objects capture attention. *Journal of Neuroscience, 30*(10), 3567–3571.
Blake, R., & Camisa, J. (1979). On the inhibitory nature of binocular rivalry suppression. *Journal of Experimental Psychology: Human Perception and Performance, 5*, 315–323.
Blake, R., Martens, W., & Di Gianfilippo, A. (1980). Reaction time as a measure of binocular interaction in human vision. *Investigative Ophthalmology & Visual Science, 19*(8), 930–941.
Blake, R., Sloane, M., & Fox, R. (1981). Further developments in binocular summation. *Perception & Psychophysics, 30*(3), 266–276.
Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10*, 433–436.
Carter, O. L., & Pettigrew, J. (2003). A common oscillator for perceptual rivalries? *Perception, 32*, 295–305.
Chou, W.-L., & Yeh, S.-L. (2012). Object-based attention occurs regardless of object awareness. *Psychonomic Bulletin and Review, 19*, 225–231.
Chow, H. M., Jingling, L., Tseng, C. H., 2013. Collinear integration affects visual search at V1. *Journal of Vision*, *13*, (article 24).
Conci, M., Müller, H. J., & Elliott, M. A. (2007). Closure of salient regions determines search for a collinear target configuration. *Perception & Psychophysics, 69*(1), 32–47.
Crain, K. (1961). Binocular rivalry. *Journal of General Psychology, 64*, 259–283.
Egly, R., Driver, J., & Rafal, R. D. (1994). Shifting visual attention between objects and locations: Evidence from normal and parietal lesion subjects. *Journal of Experimental Psychology: General, 123*, 161–177.
FFernandez-Duque, D., Grossi, G., Thornton, I. M., & Neville, H. J. (2003). Representation of change: Separate electrophysiological markers of attention, awareness, and implicit processing. *Journal of Cognitive Neuroscience, 15*, 491–507.
Field, D. J., Hayes, A., & Hess, R. (1993). Contour Integration by the Human Visual System: Evidence for a Local 'Association Field. *Vision Research, 33*(2), 173–193.
Field, D.J., Hayes, A. (2004). Contour integration and the lateral connections of V1 neurons in the visual neurosciences. L. M. Chalupa, & J. S. Werner (Eds.): MIT Press.

Frederiksen, N. O., & Guilford, J. P. (1934). Personality traits and fluctuations of the outline cube. *American Journal of Psychology, 46*, 470–474.
Freeman, E., Sagi, D., & Driver, J. (2001). Lateral interactions between targets and flankers in low-level vision depend on attention to the flankers. *Nature Neuroscience, 4*, 1032–1036.
Freeman, E. D., & Driver, J. (2005). Task-dependent modulation of target-flanker lateral interactions in vision. *Perception & Psychophysics, 67*(4), 624–637.
Freeman, E. D., Sagi, D., & Driver, J. (2004). Configuration-specific attentional modulation of flanker-target lateral interactions. *Perception, 33*(2), 181–194.
Harwerth, R. S., Smith, E. L., & Levi, D. M. (1980). Suprathreshold binocular interactions for grating patterns. *Perception & Psychophysics, 27*, 43–50.
Hayashi, D., & Murakami, I. (2012). Collinear facilitation by flankers with invisible orientation. *Journal of Vision, 12*(9), 98.
Hayashi, D., & Murakami, I. (2013). Collinear facilitation by invisible flankers. *Journal of Vision, 13*(8), 32.
Hess, R. F., Hayes, A., & Field, D. J. (2003). Contour integration and cortical processing. *Journal of Physiology-Paris, 97*(2–3), 105–119.
Hsieh, P.-L., Colas, J. T., & Kanwisher, N. (2011). Pop-out without awareness: Unseen feature singletons capture attention only when top-down attention is available. *Psychological Science, 22*(9), 1220–1226.
Ivanoff, J., & Klein, R. M. (2003). Orienting of attention without awareness is affected by measurement-induced attentional control settings. *Journal of Vision, 3*(1), 32–40.
Jiang, Y., Costello, P., Fang, F., Huang, M., & He, S. (2006). A gender- and sexual orientation-dependent spatial attentional effect of invisible images. *Proceedings of the National Academy of Sciences of the United States of America, 103*(45), 17048–17052.
Jingling, L., Tang, D.-L., & Tseng, C.-H. (2013). Salient collinear grouping diminishes local salience in visual search: An eye movement study. *Journal of Vision, 13*(12) (article 6).
Jingling, L., Tseng, C. H., & Zhaoping, L. (2013). Orientation is different: Interaction between contour integration and feature contrasts in visual search. *Journal of Vision, 13*(3) (article 26).
Jingling, L., & Tseng, C.-H. (2013). Collinearity impairs local element visual search. *Journal of Experimental Psychology: Human Perception and Performance, 39*(1), 156–167.
Kanai, R., Bahrami, B., & Rees, G. (2010). Human parietal cortex structure predicts individual differences in perceptual rivalry. *Current Biology, 20*(18), 1626–1630.
Kaufman, L. (1963). On the spread of suppression and binocular rivalry. *Vision Research, 3*, 401–415.
Kentridge, R. W., Heywood, C. A., & Weiskrantz, L. (1999). Attention without awareness in blindsight. *Proceedings of the Royal Society of London, Series B, 266*, 1805–1811.
Kentridge, R. W., Heywood, C. A., & Weiskrantz, L. (2004). Spatial attention speeds discrimination without awareness in blindsight. *Neuropsychologia, 42*(6), 831–835.
Kimchi, R., & Razpurker-Apfeld, I. (2004). Perceptual grouping and attention: Not all groupings are equal. *Psychonomic Bulletin and Review, 11*(4), 687–696.
Kimchi, R., Yeshurun, Y., & Cohen-Savransky, A. (2007). Automatic, stimulus-driven attentional capture by objecthood. *Psychonomic Bulletin Review, 14*(1), 166–172.
Kleiner, M., Brainard, D., & Pelli, D. (2007). What's new in Psychtoolbox-3? *Perception, 36*(ECVP Abstract Supplement).
Koch, C., & Tsuchiya, N. (2007). Attention and consciousness: Two distinct brain processes. *Trends in Cognitive Science, 11*(1), 16–22.
Koch, C., & Tsuchiya, N. (2012). Attention and consciousness: Related yet different. *Trends in Cognitive Sciences, 16*(2), 103–105.
Koivisto, M., & Revonsuo, A. (2007). Electrophysiological correlates of visual consciousness and selective attention. *NeuroReport, 18*, 753–756.
Lamme, V. A. (2003). Why visual attention and awareness are different. *Trends in Cognitive Science, 7*, 12–18.
Lamme, V. A. (2004). Separate neural definitions of visual consciousness and visual attention: A case for phenomenal awareness. *Neural Network, 17*, 861–872.
Lau, J. S. F., & Cheung, S.-H. (2012). Illusory contour formation survives crowding. *Journal of Vision, 12*(6), 15.
Levelt, W. (1965). *On binocular rivalry*. The Hague: Mouton.
Maier, A., Wilke, M., Aura, C., Zhu, C., Ye, F. Q., & Leopold, D. A. (2008). Divergence of fMRI and neural signals in V1 during perceptual suppression in the awake monkey. *Nature Neuroscience, 11*(10), 1193–1200.
Maruya, K., & Blake, R. (2009). Spatial spread of interocular suppression is guided by stimulus configuration. *Perception, 38*(2), 215–231.
McCormick, P. A. (1997). Orienting attention without awareness. *Journal of Experimental Psychology: Human Perception and Performance, 23*(1), 168–180.
Miller, S. M., Hansell, N. K., Ngo, T. T., Liu, G. B., Pettigrew, J. D., Martin, N. G., et al (2009). Genetic contribution to individual variation in binocular rivalry rate. *Proceedings of National Academy of Science USA, 107*, 2664–2668.
Moore, C. M., & Egeth, H. (1997). Perception without attention: Evidence of grouping under condition of inattention. *Journal of Experimental Psychology: Human Perception and Performance, 23*(2), 339–352.
Norman, L. J., Heywood, C. A., & Kentridge, R. W. (2013). Object-based attention without awareness. *Psychological Science, 10*(2), 1–8.
Ooi, T. L., & He, Z. J. (1999). Binocular rivalry and visual awareness: The role of attention. *Perception, 28*(5), 551–574.
Aafjes, M., Hueting, J. E., & Visser, P. (1966). Individual and interindividual differences in binocular retinal rivalry in man. *Psychophysiology, 3*, 18–22.
Paffen, C. L. E., & Alais, D. (2011). Attentional modulation of binocular rivalry. *Frontiers in Human Neuroscience, 5* (article 105).
Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10*, 437–442.
Pitts, M. A., Martińez, A., & Hillyard, S. A. (2011). Visual processing of contour patterns under conditions of inattentional blindness. *Journal of Cognitive Neuroscience, 24*(2), 287–303.
Polonsky, A., Blake, R., Braun, J., & Heeger, D. J. (2000). Neuronal activity in human primary visual cortex correlates with perception during binocular rivalry. *Nature Neuroscience, 3*(11), 1153–1159.
Tan, J. H., & Hsieh, P. (2013). Eye-specific information biases perceived direction of bistable motion. *Journal of Vision, 13*(11), 1–8.
Tong, F., & Engel, S. A. (2001). Interocular rivalry revealed in the human cortical blind-spot representation. *Nature, 411*, 195–199.
Tseng, C. H., Jingling, L., & Oh, W. (2012). A collinear distractor impairs local element search regardless of its probability occurrence. In *The 34th annual meeting of the cognitive science society*, Sapporo, 2012.
Tsuchiya, N., & Koch, C. (2005). Continuous flash suppression reduces negative afterimages. *Nature Neuroscience, 8*, 1096–1101.
Ukai, K., Ando, H., & Kuze, J. (2003). Binocular rivalry alternation rate declines with age. *Perceptual & Motor Skills, 97*, 393–397.
Wang, L., Weng, X., & He, S. (2012). Perceptual grouping without awareness: Superiority of Kanizsa triangle in breaking interocular suppression. *PLoS One, 7*(6), e40106. http://dx.doi.org/10.1371/journal.pone.0040106.
Watanabe, M., Cheng, K., Murayama, Y., Ueno, K., Asamizuya, T., Tanaka, K., et al (2011). Attention but not awareness modulates the BOLD signal in the human V1 during binocular suppression. *Science, 334*(6057), 829–831.
Wetheimer, M. (1938a). Gestalt theory. In W. D. Ellis (Ed.), *A source book of gestalt psychology* (pp. 1–11). New York: The Humanities Press.
Wetheimer, M. (1938b). The general theoretical situation. In W. D. Ellis (Ed.), *A source book of gestalt psychology* (pp. 12–16). New York: The Humanities Press.
Wyart, V., & Tallon-Baudry, C. (2008). Neural dissociation between visual awareness and spatial attention. *The Journal of Neuroscience, 28*(10), 2667–2679.
Yeshurun, Y., Kimchi, R., Sha'shoua, G., & Carmel, T. (2008). Perceptual objects capture attention. *Vision Research, 49*, 1329–1335.
Zhang, X., & Fang, F. (2012). Object-based attention guided by an invisible object. *Experimental Brain Research, 223*(3), 397–404.
Zhang, P., Jiang, Y., & He, S. (2012). Voluntary attention modulates processing of eye-specific visual information. *Psychological Science, 22*(3), 254–260.
Zhaoping, L. (2008). Attention capture by eye of origin singletons even without awareness – A hallmark of a bottom-up saliency map in the primary visual cortex. *Journal of Vision, 8*(5) (article 1).
Zhaoping, L. (2012). Gaze capture by eye of origin singletons: Interdependence with awareness. *Journal of Vision, 12*(2), 1–22.