Vision Research 101 (2014) 125–137

Contents lists available at ScienceDirect

Vision Research

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

Constraints on dilution from a narrow attentional zoom reveal how spatial and color cues direct selection ☆

Zhe Chen [a,*], Kyle R. Cave [b]

[a] Department of Psychology, University of Canterbury, Christchurch, New Zealand
[b] Department of Psychology, University of Massachusetts, Amherst, MA, USA

ARTICLE INFO

Article history:
Received 3 February 2014
Received in revised form 14 June 2014
Available online 25 June 2014

Keywords:
Selective attention
Distractor interference
Perceptual load
Dilution
Attentional focus

ABSTRACT

Distractor interference is subject to dilution from other nontarget elements, and the level of dilution is affected by attention. This study explores the nature of dilution when the location and color of the target is known in advance. Experiments 1 and 2 show that attention is effectively limited to the precued region, so that it is the nontarget letters appearing at the cued locations that are responsible for most of the dilution, and not those appearing at the uncued locations. Furthermore, this dilution occurs relatively early in processing. Experiment 3 demonstrates that top-down attentional control can prevent dilution, because foreknowledge of the target color leads to quick attention shifts. Experiment 4 illustrates bottom-up attentional control in preventing dilution when the distractor is a color singleton that is segregated from the diluting nontargets. The results show that dilution is modulated by both top-down and bottom-up factors, that it can occur even when attention is restricted to a relatively small region, and that it occurs early in processing, but not so early that it avoids the effects of attention. They provide new challenges for earlier accounts suggesting that dilution is widespread and unfettered by attention. Likewise, some parts of the results are difficult to reconcile with the alternative perceptual load theory, but they do support a form of dilution that is limited by attentional boundaries. Because of that link to attention, dilution is a useful tool for measuring how attention is guided by information about target location and color.

1. Introduction

Among the many experimental tools that have been used to study the allocation of visual attention, one of the most useful has been the interference from a distractor object placed near a visual target. Eriksen and Hoffman (1973) and Eriksen and Eriksen (1974) demonstrated this interference with a simple task that required participants to report a single letter. The response could be speeded or slowed by distractor letters near the target, depending on whether the response associated with the distractors was congruent or incongruent with the correct response to the target. Even though participants knew exactly where the target letter would appear, they were unable to prevent the distractors from being processed and activating responses. This congruency effect demonstrates that the distractors were receiving a certain amount of spatial attention.

Just as a target stimulus is subject to interference from distractors, recent experiments have demonstrated that the interference from a distractor is also subject to interference from other objects in the display. This interference of distractor interference is known as dilution (Kahneman & Chajczyk, 1983; Tsal & Benoni, 2010; Wilson, Muroi, & MacLeod, 2011), because the presence of additional stimuli weakens, or dilutes, the interference from the distractor. Dilution has come to play a theoretically important role in the debate over how attention is affected by perceptual load. Lavie (1995; Lavie & Tsal, 1994) has proposed that visual attention is a resource with a limited capacity, and it will be allocated as necessary to perform perceptual tasks. If attentional capacity remains unused after the demands of a task have been met, then this surplus capacity is automatically allocated to stimuli that are irrelevant to the task. This theory of perceptual load has been supported by experiments demonstrating a decrease in distractor interference as perceptual load increases. (See Lavie, 2005, for a review.)

There have been a number of theoretical challenges to perceptual load theory. For example, the perceptual load effect can be

☆ In all the experiments reported in this paper, response latencies greater than 2000 ms were excluded. These constituted less than 2% of the total data in each experiment. Only trials with correct responses were included in the RT results in the tables, figures, and statistical analyses.

* Corresponding author. Address: Department of Psychology, University of Canterbury, Private Bag 4800, Christchurch, New Zealand.
E-mail address: zhe.chen@canterbury.ac.nz (Z. Chen).

http://dx.doi.org/10.1016/j.visres.2014.06.006
0042-6989/

eliminated or reversed when the location of the target is known in advance (Chen & Cave, 2013; Johnson, McGrath, & McNeil, 2002; Paquet & Craig, 1997), when the relevant and irrelevant information are part of the same object (Chen, 2003), when perceptual grouping is used to segregate the target from the distractors (Baylis & Driver, 1992; Cosman & Vecera, 2012; Yeh & Lin, 2013), and when perceptual load is manipulated within a block rather than between different blocks (Murray & Jones, 2002; Theeuwes, Kramer, & Belopolsky, 2004). Experiments that vary the relative salience of the target and the distractor (Biggs & Gibson, 2013; Eltiti, Wallace, & Fox, 2005; Yeshurun & Marciano, 2013), the extent of attentional focus required of the task (Chen & Cave, 2013; Chen & Chan, 2007; Miller, 1991), and the spatial uncertainty associated with the distractor or target (Marciano & Yeshurun, 2011; Wilson, Muroi, & MacLeod, 2011) have also found results inconsistent with the prediction of the perceptual load theory. Furthermore, a study by Kyllingsbaek, Sy, and Giesbrecht (2011) using a partial report technique (Sperling, 1960) demonstrates that adding irrelevant letters at known distractor locations lowers the number of target letters being reported, suggesting that a certain proportion of attention is allocated to irrelevant stimuli in the display while the target is being processed instead of after the processing of the target is completed.

A related objection to perceptual load theory focuses on experiments (e.g., Lavie & Cox, 1997, 2000) in which perceptual load is increased by adding additional objects to the stimulus display. These extra objects increase perceptual load because they are relevant to the task, and their inclusion lowers the interference from a critical distractor. Both Wilson, Muroi, and MacLeod (2011) and Tsal and Benoni (2010; Benoni & Tsal, 2010) have proposed dilution as an alternative to perceptual load theory for explaining these results. Their experiments demonstrate that distractor interference can be lowered by adding additional objects that are NOT relevant to the task. These additional items should not increase perceptual load, but their presence nonetheless seems to dilute the distractor interference. Tsal and Benoni claim that the same dilution is responsible for the results of the earlier perceptual load experiments. Lavie and Torralbo (2010) counter that these results can still be explained within the perceptual load theory, because the additional items added to the stimulus array compete with the distractor for the attentional capacity that is not allocated to the target.

Different forms of dilution have been proposed. Tsal and Benoni (2010) did not make strong claims about the mechanisms underlying dilution, but they suggested a simple and straightforward form of dilution in which every object in a search array could interfere with every other object, regardless of whether they were relevant to the task or whether their locations had been cued. This dilution could be caused by interference among basic perceptual properties at an early preattentive processing stage, and so we will refer to it as preattentive dilution. Wilson, Muroi, and MacLeod (2011) proposed a different mechanism for dilution, which shares some of the same theoretical assumptions as perceptual load theory. Their dilution mechanism operates after attention has selected a single object as the target. The nontarget stimuli compete for any attentional capacity not allocated to the target, causing each to dilute the effects of the others. We will describe this account as post-selection dilution.

Both of these accounts predict that dilution will be widespread across the different objects in the search array, regardless of whether attention is broadly distributed or zoomed into a small region. Chen and Cave (2013) suggested that the widespread dilution in earlier experiments may have been due to the abrupt onsets of the search array, which could broaden the allocation of attention. In Chen and Cave's experiments, the stimulus letters were created by removing segments from items that were already visible, as done by Yantis and Jonides (1984). When abrupt onsets were eliminated, the results showed that the level of dilution depended on whether or not the nonrelevant stimuli were within the attended region in the display. Dilution could be eliminated if participants could use foreknowledge about the location of upcoming targets to focus attention narrowly. They also found that attention could effectively block dilution if it was allocated based on the target's color. Additionally, dilution was only produced by letters in their normal upright orientation, and not by inverted letters, indicating that dilution occurs at the level of letter representations, and is not simply interference among simple visual features.

The new experiments presented here will test whether the inter-object interference that produces dilution is widespread across the display, as predicted by preattentive dilution and post-selection dilution, or whether that interference is limited to the region selected by attentional zoom. The earlier experiments by Chen and Cave (2013) tested how attentional zoom limits interference in a simple paradigm in which the locations to be attended were always accurately cued, and uncued locations were completely irrelevant to the task. The new experiments will test dilution under more complex circumstances, with spatial cues that are sometimes invalid. Uncued locations can still be occupied by targets, and are thus still relevant to the task. The results of Experiment 1 show that attention can be effectively constricted to the cued region, so that dilution only arises from stimuli within this region. Experiment 2 shows that this dilution occurs relatively early in the trial. The remaining experiments demonstrate that dilution is also limited by attention that is driven by top-down (Experiment 3) or bottom-up (Experiment 4) color information. These demonstrations of dilution being limited by attentional zoom conflict with the predictions from both preattentive dilution or post-selection dilution, which assume that dilution is more widespread. The results are also difficult to reconcile with perceptual load theory, as explained below, but are consistent with an account based on zoom-limited dilution.

Also, because of the link between dilution and attentional zoom, these experiments provide a new and more precise view of how attention is allocated when spatial expectations are imprecise. In these experiments with spatial cues that are not completely reliable, participants must be prepared for targets that appear outside the cued region, and thus they might be expected to distribute attention more broadly. However, the results show that even with the possibility of invalid cues, spatial attention is still focused mainly at the cued locations, although foreknowledge of the target color can also allow a quick reallocation of attention after the stimulus appears. Dilution is also subject to the effects of color boundaries segregating the stimuli into separate groups. Furthermore, dilution in invalid trials is shown to occur relatively early in visual processing; probably before attention has shifted away from cued locations. With a better understanding of when and how dilution occurs in this paradigm, we also get a clearer picture of the other aspects of attentional allocation, including the joint effect of the spatial and color cues, and the bottom-up effects of color differences in the display.

2. Experiment 1

In the first two experiments by Chen and Cave (2013), either two or six locations could be cued. The target always appeared at a cued location, so that when only two locations were cued, attention could be focused relatively narrowly to exclude many of the stimulus locations. The second of these experiments showed that dilution occurred when attention was broadly distributed in the 6-letter condition, but not when it was more narrowly focused in