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Inter-trial and redundant-signals effects in visual search and discrimination tasks: Separable pre-attentive and post-selective effects

Joseph Krummenacher [a,*], Anna Grubert [a], Hermann J. Müller [b,c]

[a] *Department of Psychology, University of Fribourg, Switzerland*
[b] *Department of Psychology, Ludwig-Maximilian-University, Munich, Germany*
[c] *School of Psychology, Birkbeck College, University of London, UK*

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ABSTRACT

Feature singleton search is faster when the target-defining dimension is repeated, rather than changed, across trials (Found & Müller, 1996). A similar dimension repetition benefit has been observed in a non-search (discrimination) task with a single stimulus (Mortier, Theeuwes, & Starreveld, 2005). Two experiments examined whether these effects in the two tasks originate from the same or different processing stages. Experiment 1 revealed differential feature-specific effects, and Experiment 2 differential processing of dimensionally redundant target signals between the two types of task. These dissociations support the existence of separable, pre-attentive and post-selective sources of inter-trial effects in the two tasks.

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1. Introduction

It is well established that capacity limitations force the cognitive system to deal with only a fraction of the total sensory input at any given moment, and what is selected for preferential processing is determined by properties of the current stimulation and the state of the cognitive system. The influence of the current stimulation has been emphasized by models such as that of Itti and Koch (2000, 2001), who conceive of the selection dynamics as being determined primarily by stimulus properties. However, over the past decade, an increasing number of studies that have revealed visual selection to be also dependent on observer factors, in particular, the buffering of previously successful task settings in some form of implicit visual short-term memory. The evidence for the memory-based guidance of selection consisted of inter-trial effects in a variety of visual search tasks, from simple pop-out to singleton conjunction searches (e.g., Found & Müller, 1996; Geyer, Müller, & Krummenacher, 2006; Maljkovic & Nakayama, 1994, 1996, 2000; Müller, Heller, & Ziegler, 1995; Treisman, 1988; Weidner, Pollmann, Müller, & von Cramon, 2002; for a review, see Kristjansson & Campana, 2010). While these effects have been firmly established, there is an ongoing debate about whether they have their locus on a stage before or after focal-attentional selection. Implicit in this dichotomy is the assumption that 'memory' modulates performance via a *single mechanism* located at either a pre-attentive or a post-selective processing stage. Alternatively, however, one could envisage the existence of *separable* memory mechanisms operating at different, pre-attentive and post-selective processing stages (as proposed by, e.g., Müller, Reimann, and Krummenacher (2003) and Töllner, Gramann, Müller, Kiss, and Eimer (2008); see also Rangelov, Müller, and Zehetleitner (2010, submitted for publication); see Kristjansson and Campana (2010) for a similar argument). The present study was designed to provide further evidence of the role of such separable memory mechanisms in task performance.

1.1. Dynamics of visual selection (in singleton feature search)

Mechanisms of visual selection are often investigated using the feature singleton detection paradigm, where a target differs from homogeneous distractors in one (or several) visual features. Typically, response times (RTs) in this paradigm are fast and independent of set size. Several functional processing architectures have been proposed to explain this finding of efficient search for feature singletons (e.g., Itti & Koch, 2000, 2001; Koch & Ullman, 1985; Wolfe, 1994; Wolfe, Cave, & Franzel, 1989; Zehetleitner, Müller, & Krummenacher, 2008). According to these models, the visual scene is analyzed in terms of feature differences across all locations

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[*] Corresponding author. Address: Department of Psychology, University of Fribourg, Rue de Faucigny 2, CH - 1700 Fribourg, Switzerland.

E-mail address: joseph.krummenacher@unifr.ch (J. Krummenacher).

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in parallel, resulting in a map of feature-contrast signals that are proportional to the relative uniqueness of the stimuli at occupied locations. The feature contrast signals are first integrated into dimension-specific maps (e.g., for color, orientation, etc.) and then summed up into a supra-dimensional map of (overall-) saliencies. The locations producing the strongest signals on this map are then selected by focal attention (with the order of selection governed by overall-signal strength). In the singleton detection task, the location which contains the target will always produce the strongest saliency signal and therefore the target will be the first item to be selected, independently of the set size.

This model is essentially memory-less: the strength of the signals on the master map of saliencies depends only on the current visual stimulation. However, at variance with memory-less search for singleton feature targets, Found and Müller (1996) observed performance for a given (e.g., color-defined) singleton on trial n to depend on the target dimension on the previous trial ($n-1$): Singleton detection on the current trial (n) was faster when the previous trial ($n-1$) contained a singleton defined in the *same dimension* (e.g., a color target followed by a color target) rather than one defined in a *different dimension* (an orientation followed by a color target). Importantly, this effect was *dimension*-specific, rather than *feature*-specific, in nature, that is: a significant inter-trial benefit was observed whenever the target-defining dimension was repeated (e.g., color → color), no matter whether the specific target-defining feature was repeated (e.g., red → red) or changed (e.g., blue → red); restated, there was a significant cost only when the target-defining dimension changed (e.g., orientation → color).

To account for the effects of dimensional repetition on singleton detection times, Müller and colleagues (e.g., Found & Müller, 1996; Müller & Krummenacher, 2006; Müller et al., 1995) formulated a Dimension-Weighting Account (DWA), according to which the signal summation from the various dimensional modules to the overall-saliency map is modulated by *dimension-specific weights*. Increased dimensional weights (e.g., for color) increase the speed or efficiency with which the signals from that dimension (e.g., color dimension map) are transferred to the saliency map. The weights themselves are sensitive to the recent trial history: a color singleton presented on a given trial leads to an increase of the color weight (and a decrease of the weights for other dimensions), which in turn facilitates the processing of color signals on the subsequent trial – giving rise to the dimension repetition benefit.

On this account, dimension-specific inter-trial effects are expected if detection responses are based on the overall-saliency map: an above-threshold signal on this map indicates only that the stimulus at a particular location is featurally different in some dimension(s) from the other elements, but the information about the featural (and dimensional) target identity is lost in the hierarchical integration process (feature contrast → dimension-specific saliency → overall-saliency). Consequently, if explicit identity information is required for response, the resulting RTs are delayed (and this delay is larger for information about featural identity than for information about dimensional identity, indicative of a hierarchical backtracking process; Müller, Krummenacher, & Heller, 2004; Müller et al., 1995). Nevertheless, (implicit) dimension repetition effects remain evident in responses based on the overall-saliency, because of the (competitive) weighting of dimension-specific saliency signals integrated by this map.

1.2. Alternative explanation of dimension repetition benefits

Instead of assuming that dimensional weights modulate preattentive saliency computation, alternative accounts to the DWA, suggested independently by different authors (e.g., Cohen & Magen, 1999; Cohen & Shoup, 1997, 2000; Theeuwes, 1991, 1992, 2004), propose that the dimension repetition benefits originate from later, *post-selective* stages of processing. According to these authors, basic stimulus properties are the main (or sole) determinants of the saliency computation processes and, consequently, the search dynamics, while dimension repetition effects arise at the post-selective stage of response selection.

The assumption that dimension-specific inter-trial effects originate from stages after completion of the search (i.e., focal-attentional selection) implies that significant dimension repetition/change effects should arise even in tasks that do not require search for a target. Mortier, Theeuwes, and Starreveld (2005) tested this prediction in a study with two tasks that varied in their demands on target selection. In the *singleton search* task, observers had to discern the presence (vs. absence) of a singleton target in displays with varying numbers of distractor items. Mortier et al. compared two (blocked) search conditions: (i) *intra-dimension search*, where the singleton, when present, always differed from distractors in color; and (ii) *cross-dimension search*, where the singleton differed in color, shape, or size. The *non-search* task was designed as to eliminate the search component from the task by presenting only one item on every trial (see also Goolsby & Suzuki, 2001). On some trials, the presented stimulus was a small gray circle, identical to distractor items from the search task. This circle was also treated as a distractor in the non-search task and required one ('target-absent') response. If the presented item was different from the distractor (in whatever visual attribute), another response ('target-present') was required. Analogously to the search task, for the non-search task there were two blocked conditions: (i) an *intra-dimension* condition, where the critical difference was always in color; and (ii) a *cross-dimension* condition, where the difference could be in color, shape, or size. Thus, in brief, Mortier et al. (2005) compared performance in two tasks in which the selection process was either relatively difficult (search task) or the search component was minimized (non-search task).

Participants responded faster to the target stimulus in the intra-dimension than in the cross-dimension condition, in both tasks. In the cross-dimension condition of both tasks, responses were faster when the relevant dimension repeated across consecutive trials compared to when the dimension changed (i.e., significant dimension repetition benefits were observed in both search and non-search tasks). Mortier et al. took the significant dimension repetition benefits in the non-search task to argue in favor of a post-selective account of dimension-based effects: "the present study showed that specific effects typically attributed to top-down guidance of search processes, also occur in conditions in which there is no search" – from which they concluded that "these effects are the result of later processes, presumably response selection" (Mortier et al., 2005, p. 556).

1.3. Single versus multiple loci of dimensional inter-trial effects

Thus, based on the similarity of the behavioral data from search and non-search tasks, Mortier et al. (2005) interpret the dimension repetition benefits as originating from post-selective processing stages in both tasks. However, instead of assuming a single (namely: post-selective) dimension weighting system, one could also assume the existence of two weighting mechanisms operating at different processing stages. One mechanism would modulate saliency signal computations, as elaborated in the DWA, and generate the dimension repetition benefits in the search task. The other weighting mechanism would modulate post-selective processes and produce the dimension repetition benefits in the non-search task. Note that the notion of multiple dimension weighting systems (operating on different stages of processing) is compatible with the DWA. The DWA assumes only that at least part of the dimension repetition benefits observed in the *singleton detection* task stem from the weighting of dimension-specific saliency sig-

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