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

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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 Crumon, 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.
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 \( \to \) color), no matter whether the specific target-defining feature was repeated (e.g., red \( \to \) red) or changed (e.g., blue \( \to \) red); restated, there was a significant cost only when the target-defining dimension changed (e.g., orientation \( \to \) 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 \( \to \) dimension-specific saliency \( \to \) 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 pre-attentive 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-
nals, without excluding the possibility that there may be other, post-selective processing stages sensitive to the inter-trial sequence of perceptual dimensions (see Krummenacher, Müller, & Heller, 2001; Müller & Krummenacher, 2006; Töllner et al., 2008).

1.4. Purpose of the present study

The present study was designed to examine whether the dimension repetition benefits in these two tasks originate from the same, or from different – pre-attentive and, respectively, post-selective – stages of processing. A pre-selective locus of dimension repetition benefits would predict that the inter-trial effects in a search task are dimension-specific in nature (i.e., there should be no cost of a feature change with a repeated dimension), because feature identity plays no role in the (pre-attentive) computations that single out the target amongst the homogeneous distractors (see above). By contrast, a discrimination task with a single stimulus (along the lines of Mortier et al. (2005)) may well involve a feature-specific component, because the (post-selective) discrimination required involves feature-based matching of the target against a standard held in working memory. Recall that in the discrimination task of Mortier et al. (2005), a given (single) stimulus presented was to be compared against a standard: a small gray circle, which (in case of a match) required a ‘target-absent’ response. If the presented item was different from the standard (in whatever visual attribute), another (‘target-present’) response was required. The fact that Mortier et al. found a dimension repetition benefit indicates that observers do not simply solve this task by deciding ‘target-present’ in case of a mismatch of the presented item with the standard in working memory. Rather, they appear to check the identity of the matching item. Conceivably, this involves comparing the stimulus against target feature templates held in working memory, per dimension – that is, the matching process might switch from one possible feature in one dimension to another feature within the same dimension (e.g., check all color features first), before it switches to another possible feature in a different dimension (check shape features etc.). Consequently, there would be feature-specific effects in the discrimination task (besides dimension-specific effects) – but not in the search task where detection of an above-threshold master map signal is sufficient for response (so that there should only be a dimension-specific effect). In contrast, on a unitary account on which all dimension-based effects originate at a post-selective stage of processing, there should be feature-specific effects in both search and non-search tasks.

On the logical task analysis provided above, the prediction of feature-specific effects in the non-search task of Mortier et al. (2005) would also be consistent with Huang and Pashler’s (2007) recent Boolean Map Theory (BMT) of how visual (feature) information accesses awareness. Huang and Pashler propose that gating sensory information to conscious awareness requires the construction of a Boolean map representation. On this proposal, (i) conscious visual information is indexed by location, that is, a specific feature is bound to a particular location; (ii) at any given point in time, a Boolean map codes one feature value per dimension only and one dimension only (e.g., color: red, or orientation: vertical); (iii) all objects characterized by the same feature (e.g., color: red) are represented in one Boolean map (multiple location coding).

Importantly in the context of the present study, a Boolean map is generated either from information coded in feature maps, or by combining (via the operations of intersection or union) already constructed Boolean maps. There are two starting points for constructing Boolean maps: starting with a feature value returns a map with all the locations at which the particular feature is present (feature-location mechanism); starting with a location returns the feature value for the particular location (location-feature mechanism). Top-down controlled selection of a particular feature for comparison with a template is achieved exclusively by the feature-location routine.

With regard to the non-search task of Mortier et al. (2005), this would imply that observers start template matching with one feature (template) in one dimension (e.g., is the item at the selected location red?), then proceed to the next feature in the same dimension (is it blue), and then change dimension (is it left-tilted?) and so on, until either a match is detected (respond target-present) or all templates have been checked without returning a match (respond target-absent). Assuming that observers start template matching with the feature (in the dimension) that returned a match on the last trial, this would generate both feature- and dimension-specific inter-trial effects.1

The present experiments were designed to examine for dissociations in processing between the two types of task, in order to decide whether or not an account assuming a unitary, post-selective source of inter-trial effects in search and non-search tasks is tenable.

2. Experiment 1

Experiment 1 compared the pattern of inter-trial effects performance between singleton feature search (e.g., Found & Müller, 1996), where targets were presented (on target-present trials) at an unpredictable position within an array of homogeneous distractors, and a non-search task (Mortier et al., 2005), where the same targets (or, on target-absent trials, a distractor) were presented in isolation at a fixed position in the display center, thus effectively removing the search component from the singleton feature search task (Goolsby & Suzuki, 2001). The aim of this comparison was to examine whether the former task would only produce dimension-specific inter-trial effects, whereas the latter would produce feature-specific effects. For the reasons elaborated in the Introduction, dimension-specific effects would be indicative of pre-selective saliency coding, whereas feature-specific effects would be indicative of post-selective discrimination processes. Two further conditions were introduced in Experiment 1: a multi-item condition (as in the search task), however with the target position fixed (in the display center); and a single-item condition (as in the non-search task), however with the target position variable. These conditions were introduced to permit the effects of feature contrast as such and target location variability as such to be examined.

2.1. Method

2.1.1. Participants

Twelve observers (five female; age range 23–29 years, median age 25.5 years) participated in Experiment 1. All had normal or corrected-to-normal vision, all reported normal color vision. Participants were paid at a rate of CHF 10 (approximately $ 9) per hour or received course credits. All observers were naive as to the purpose of the experiment; most of them had no previous experience with visual-search experiments.

2.1.2. Apparatus, stimuli, task

Experiment 1 compared two basic task conditions: multiple items (feature contrast) and single item (no feature contrast). In

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1 While the number of steps involved in Boolean map construction could, thus, explain performance (inter-trial effects) in the non-search task, BMT cannot as such account for the evidence of co-activation of detection responses by target signals defined redundantly in multiple dimensions (compared to targets defined in one dimension only) in the singleton search task. However, assuming that target detection does not require that the target-defining features are consciously represented, but rather that target-present responses can be triggering on the basis of a pre-selective saliency representation (along the lines proposed by DWA), the puzzle can be solved (this has been acknowledged by L. Huang, personal communication, July 19th, 2008).
each of these, the target location could be either randomly variable or constant (in the display center). In the multiple-item conditions, displays comprised of a 7 × 7 item array of (search) items. On target-absent trials, a homogenous array of distractors were presented; on target-present trials, one of the distractors (green vertical bars) was replaced by a singleton feature (pop-out) target (a red or blue vertical bar, or a green 45° left- or right-tilted bar). In the single-item conditions, the display contained only one item, either a target or a distractor. The possible targets were the same as in the multi-item conditions (all requiring a target-present response); the same was true for the single distractor (a green vertical bar, which required a target-absent response).

Display items were bars subtending approximately 0.9° of visual angle in height and 0.2° in width. Bars were oriented vertically or tilted 45° to the left or right, respectively, relative to the vertical. Display items were colored in isoluminant green (CIE x, y chromatic coordinates 0.311, 0.578; luminance 1.6 cd/m²), red (CIE 0.596, 0.358; 1.6 cd/m²) or blue (CIE 0.148, 0.065; 1.6 cd/m²) and presented on black (CIE 0.368, 0.315; 0.1 cd/m²) screen background. Display items in the multiple-item conditions were arranged on a virtual rectangular grid consisting of 7 × 7 cells, with each cell subtending 2.2° in height and width. Item positions were slightly jittered vertically and horizontally by a maximum of 0.6° of visual angle relative to the cell center. Minimum (and maximum) distance (measured as the distance between centers of gravity) between display items was 1.1° (3.3°) both horizontally and vertically. The entire display subtended between 16.0° of visual angle vertically and horizontally. In the multiple-item condition with a variable target location, target presentation was restricted to the inner 5 × 5 grid cells, in order to equate local feature contrast effects (observers were not informed about the restriction). In the multiple-item condition with a constant target location, the target appeared always in the display center. In the single-item conditions, only one stimulus – either a target or a distractor – was presented, either variably in one of the 5 × 5 grid cells (underlying multi-item displays) or constantly in the display center.

Stimulus presentation, timing, and response recording were controlled by a Pentium PC running under the Windows XP operating system and using the “Cogent 2000” toolbox (www.vislab.ucl.ac.uk/Cogent/) for MATLAB (Mathworks, Inc.). Stimuli were presented at 100 Hz on a 19” CRT monitor (Phillips Brilliance P202), at a screen resolution of 1280 × 1024 pixels. Observers viewed the display from a distance of 70 cm. Observers responded by pressing one of the control (Ctrl) keys in the lower left and right parts of a standard keyboard placed at a comfortable distance on a table in front of the observer.

Observers’ task was to indicate, as quickly and accurately as possible, whether a target item was present in the display or not. Prior to the experiment, observers were carefully informed about the identity of distractor and target items: distractors were always green vertical bars; targets were either red (vertical), blue (vertical), 45° left-tilted (green), or 45° right-tilted (green) bars. Observers were to press the right control key to indicate target presence, and the left key to indicate target absence.

2.1.3. Procedure and timing

Each trial started with the presentation of a fixation point (a circle with a diameter of approx. 0.2° of visual angle) for 570 ms; over this period, the luminance of the fixation marker increased gradually from background luminance to 1.6 cd/m² and then gradually decreased again to background luminance. The screen remained blank for a period of 200 ms after the disappearance of the fixation point, to avoid forward masking in the single-item condition. The response-relevant display consisted of the simultaneous onset of all the items in the multiple-item condition, or the presentation of an isolated item in the single-item condition. Displays remained visible until the observer had indicated whether a target was present or absent. The response was followed by an inter-trial interval with a blank screen for 400 ms. At the end of each block participants received feedback on their mean RTs and error rates.

The following four experimental conditions were completed by all participants: multiple items, variable location (MV); multiple items, constant location (MC); single item, variable location (SV); single item, constant location (SC). Both in the multiple and the single-item conditions, target locations were either constant or variable. In the constant-location conditions, the target was presented at the display center (i.e., at the location of the fixation point), on multiple-item trials, the target (in the center) was surrounded by distractors, while it was the only item on single-item trials (see Fig. 1, top left and right-hand panels). In the variable-location conditions, the target was presented at a randomly chosen location within the inner 5 × 5 cells of the virtual display grid (see Fig. 1, bottom left and right-hand panels).

The order of conditions was counterbalanced across the twelve observers. Half of them began the experiment with the multiple-item; the other half with the single-item condition. Of the six participants with multi-items as the first condition(s), three started with the constant-, the remaining three with the variable-location condition, and likewise for the six participants who with a single item as the first condition(s).

Each of the four conditions comprised of 10 blocks of 94 trials, giving a total of 3760 experimental trials. Targets were presented in 60% of trials (target-present trials); in the remaining 40%, no target was presented (target-absent trials). The definition of the target type (color: red, blue; orientation: left, right-tilted), in target-present trials, was equally probable. At the beginning of each condition, a training block of ten trials was presented to familiarize observers with the task. Before the experiment, participants were given the opportunity to become familiar with the different task by performing at least two blocks of ten trials in each condition. Observers were free to take a break between blocks. The experiment was run in two sessions, with two experimental conditions completed per session; two sessions, either the multi-item variable- and constant-location conditions, or, respectively, the single-item variable- and constant-location conditions, were run on the same day. Each of the two sessions took about 60 min to complete.

2.2. Results

RTs shorter than 200 ms and longer than 1000 ms were excluded from analysis (0.3% of all trials), as anticipatory or exceedingly slow reactions, respectively. Additionally, RTs deviating from mean RT by more than three standard deviations were excluded from analysis separately for each participant and each of the four conditions (less than 1.1% of all trials). Data were analyzed using repeated-measures analyses of variance (ANOVA); Bonferroni correction was used for multiple comparisons of condition means where necessary.

2.2.1. Errors

Mean error rates for target-absent (false alarms) and target-present trials (misses) trials were subjected to a repeated-measures ANOVA with the factors: display (multiple items, single item), target location (constant, variable location), and error type (miss, false alarm). The ANOVA revealed the main effects of display [F(1, 11) = 32.719, p < .001] and error type [F(1, 11) = 24.782, p < .001] to be significant. Target location did not affect error rate [F(1, 11) < 1, n.s.]. Error rates were significantly lower in multiple-item than in single-item conditions (5.1% vs. 6.7%), and significantly more false alarms were made than misses (7.7% vs. 4.1%).

Moreover, the interaction between display and error type was significant [F(1, 11) = 34.798, p < .001]. Miss rates did not differ be-
displays, target-present RTs were significantly faster than target-absent RTs did not differ significantly (402.3 vs. 393.6 ms; $t(11) = 1.717$, two-tailed $p = .114$).

An ANOVA of the target-present RTs, with the factors display (multiple items, single item), target location (variable, constant), and target dimension (color, orientation), revealed all three main effects to be significant. Multiple-item displays were responded to 22.9 ms faster than single-item displays (370.7 vs. 393.6 ms) ($F(1, 11) = 25.155$, $p = .002$). Target-present RTs were significantly faster with multiple-item than with single-item displays (389.7 vs. 398.0 ms) [non-significant main effect of display: $F(1, 11) = 1.298$, $p > .25$]. The main effect of trial was significant [$F(1, 11) = 25.155$, $p < .001$]; target-present RTs were overall faster than target-absent RTs (382.2 vs. 405.5 ms). The main effect of target location was also significant [$F(1, 11) = 88.705$, $p < .001$]: RTs were slower overall when target location was variable rather than fixed (402.8 vs. 384.9 ms).

Importantly, the interaction between display and trial was significant [$F(1, 11) = 15.312$, $p = .002$]. Target-present RTs were significantly faster with multiple-item than with single-item displays (370.7 vs. 393.6 ms; $t(11) = 3.417$, two-tailed $p = .006$), while target-absent RTs did not differ between the two display conditions (408.7 vs. 402.3 ms; $t(11) < 1$, n.s.). With multiple-item displays, target-present RTs were significantly faster than target-absent RTs (370.7 vs. 408.7 ms; $t(11) = 5.616$, two-tailed $p < .001$); by contrast, with single-item displays, target-present and -absent RTs did not differ significantly (402.3 vs. 393.6 ms; $t(11) = 1.298$, two-tailed $p = .114$).

A separate ANOVA of the target-absent RTs, with the factors display (multiple items, single item) and target location (variable, constant), revealed the main effect of target location to be significant [$F(1, 11) = 11.676$, $p = .006$]. Variable target location produced slower RTs than constant target location (390.5 vs. 373.9 ms) [$F(1, 11) = 58.214$, $p < .001$]. And color targets were responded to faster than orientation targets (373.9 vs. 390.4 ms) [$F(1, 11) = 30.955$, $p < .001$]. Of the interactions, only target location × dimension was reliable [$F(1, 11) = 10.932$, $p = .007$]: RTs to color targets were somewhat less affected by variability, versus constancy, of target location (379.6 vs. 368.1 ms) than RTs to orientation targets (401.3 vs. 379.6 ms). [Note, though, that the RT difference between color and orientation targets remained significant even with constant locations ($t(11) = 4.781$, $p = .001$).]

A separate ANOVA of the target-absent RTs, with the factors display (multiple items, single item) and target location (variable, constant), revealed the main effect of target location to be significant [$F(1, 11) = 69.426$, $p < .001$]: target-absent RTs were 19.2 ms slower when the target location was variable rather than constant (415.1 vs. 395.9 ms). Although multiple-item displays were responded to somewhat slower than single-item displays (408.7 vs. 402.3 ms), the main effect of display was non-significant [$F(1, 11) < 1$, n.s].

2.2.3. Inter-trial effects

Feature- and dimension-based inter-trial transition effects were analyzed separately for the four conditions (Mv, Ml, Sv, Sl) by repeated-measures ANOVAs, each with the factors inter-trial transition (same dimension same feature, sDsF; same dimension different features, sDdF; different dimensions same features, dDsF; different dimensions different features, dDdF) and trial (absent, present). The main effect of target presence was highly significant ($F(1, 11) = 92.955$, $p < .001$), the main effect of error type, this effect is mainly due to the high false-alarm rate in single-item conditions.

The four experimental conditions: multiple and single item with constant target location (top left and right-hand panels) and multiple and single item with variable target location (bottom left and right-hand panels).
different feature, sDdf; different dimension, dD) and dimension (color, orientation). See Table 1 (left-hand side) for the results.

For all analyses, both main effects were significant. In all cases, RTs were faster to color than to orientation targets [MIv: \(F(1,11) = 24.367, p < .001\); MIc: \(F(1,11) = 24.378, p < .001\); Slv: \(F(1,11) = 16.712, p = .002\); Slc: \(F(1,11) = 8.069, p = .016\)]. For conditions with variable target positions (MIv and Slv), but not those with constant target positions (MIc and Slc), the inter-trial effects were significantly influenced by target dimension [MIv: \(F(2,22) = 3.483, p = .049\); Slv: \(F(2,22) = 4.396, p = .025\), due to a change to a color target from an orientation target being somewhat easier than a change to an orientation target from a color target.

In all cases, though, the pattern of inter-trial effects was qualitatively similar between color and orientation targets. The main effect of inter-trial transition was significant for all conditions [MIv: \(F(2,22) = 12.680, p < .001\); MIc: \(F(2,22) = 44.713, p < .001\); Slv: \(F(2,22) = 62.904, p < .001\); Slc: \(F(2,22) = 58.231, p < .001\)]. Planned simple contrasts to follow up these effects in the various conditions showed that, in all conditions, there was a dimension-specific change effect: RTs were significantly slower when the target on trial \(n\) was defined in a different dimension to the target on trial \(n-1\) [comparison dD vs. sDdf: MIv: \(F(1,11) = 14.714, p = .003\); MIc: \(F(1,11) = 33.420, p < .001\); Slv: \(F(1,11) = 80.960, p < .001\); Slc: \(F(1,11) = 46.738, p < .001\)]. Although significant in all cases, the effect was smaller in multi-item conditions as compared to single-item conditions [17.2 vs. 32.9 ms; t(11) = 4.698, two-tailed \(p = .001\); more precisely, 13.2, 21.2, 30.5, and 35.3 for the MIv, MIc, Slv, and Slc conditions, respectively]. However, the four conditions differed with respect to the occurrence of feature-specific change effects (within a repeated target-defining dimension): while these were significant for both single-item conditions [comparison sDds vs. sDdf: Slv: \(F(1,11) = 13.429, p = .004\); Slc: \(F(1,11) = 20.557, p = .001\)], for the multi-item conditions, there was a significant effect only for the MIc condition [\(F(1,11) = 19.986, p = .001\)], but not for the MIv condition [\(F(1,11) = 1.19, \text{n.s.}\)]. Numerically, the effects were 1.2, 7.8, 9.4, and 16.7 ms for the MIv, MIc, Slv, and Slc conditions, respectively. Also, overall, they were smaller for multi-item displays than for single-item displays [4.5 vs. 13.1 ms, t(11) = -3.029, two-tailed \(p = .001\)]

To examine whether the effects in the multiple-item conditions – in particular, the significant, albeit small feature-specific effect in the MIc condition – are due to carry-over of strategy (e.g., Leber & Egeth, 2006) from the single-item to the multiple-item conditions in those participants who performed the former condition first, 12 additional observers (seven female; age range 21–35 years, median age 25.8 years) were recruited. Six of the 12 observers performed only the multi-item conditions (MIv and MIc, in counter-balanced order) and six the single-item conditions (Slv and Slc). By combining their data with those for the starting condition of the original observers (of who six had started with the multiple-item conditions and six with the single-item conditions), it became possible to compare the two displays conditions between subjects, uncontaminated by any carry-over effects. See Table 1 (right-hand side) for the results.

As can be seen, the pattern of effects was very similar. More formally, the main effect of inter-trial transition was significant in all conditions [MIv: \(F(2,22) = 19.1968, p < .001\); MIc: \(F(2,22) = 45.431, p < .001\); Slv: \(F(2,22) = 68.313, p < .001\); Slc: \(F(2,22) = 65.705, p < .001\)]. Also, planned simple contrasts revealed the dimension change effect to be significant in all conditions [comparison dD vs. sDdf: MIv: \(F(1,11) = 27.956, p < .001\); MIc: \(F(1,11) = 48.389, p < .001\); Slv: \(F(1,11) = 64.727, p < .005\); Slc: \(F(1,11) = 67.315, p < .001\)] numerically, the effects were 22.6, 30.6, 34.2, and 34.9 ms for the MIv, MIc, Slv, and Slc conditions, respectively. Furthermore, while again there were significant feature-specific change effects (from one target-defining feature to another within the same dimension) for the single-item conditions [comparison sDds vs. sDdf: Slv: \(F(1,11) = 19.348, p = .001\); Slc: \(F(1,11) = 21.759, p = .001\)], for the multiple-item conditions, there was such an effect only with constant, central target location [MIc: \(F(1,11) = 15.336, p = .002\)], but not with variable target location [MIv: \(F(1,11) = 3.626, \text{n.s.}\)]. Numerically, the effects were 5.8, 10.7, 12.4, and 17.5 ms for the MIv, MIc, Slv, and Slc conditions, respectively. This replicates the findings of the within-subject anal-

### Table 1

<table>
<thead>
<tr>
<th>Experiment 1a: within-subject</th>
<th>Experiment 1b: between-subject</th>
</tr>
</thead>
<tbody>
<tr>
<td>sDds</td>
<td>sDdf</td>
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<tr>
<td>MIv</td>
<td>359.9</td>
</tr>
<tr>
<td>MIc</td>
<td>336.2</td>
</tr>
<tr>
<td>Slv</td>
<td>374.0</td>
</tr>
<tr>
<td>Slc</td>
<td>349.8</td>
</tr>
</tbody>
</table>

2 As the interpretation partially relies on the non-existence of feature-based inter-trial effects in the MIv condition, the question arises whether the tests (contrasts) performed to assess statistical significance of the difference between the SF and DF conditions had sufficient power (to guard against falsely maintaining the null hypothesis). Test power (1-beta) was calculated using the post hoc option of the G-Power program (Faul, Erdfelder, Lang, & Buchner, 2007) on the assumption that the test had the power to capture an effect of a similar magnitude as those observed in the MIc and Slv conditions, that is, an RT increase on feature change versus feature repetition trials of about 8 ms. Given that the test power was sufficient to exclude false acceptance of the null hypothesis in the MIc condition, the same comparison in the MIv condition should have captured the significance of an effect of a similar magnitude in the MIv condition. The power analyses, based on explained and residual variances, revealed an effect size \(f^2\) (as defined by Cohen (1988)) of 1.35 and a power of 0.99 for the MIc condition; the values for the Slv and Slc conditions were \(f^2 = 1.15\), power 1-beta = .99 and \(f^2 = 1.36\), 1-beta = .99, respectively. Thus, the power of the test comparing the SF and DF conditions was sufficient to detect an effect of a similar magnitude to those observed in the remaining conditions.

2 In a study designed to address contradictory findings of the effects of irrelevant singletons on visual-search performance, Leber & Egeth (2006) showed that observers do not switch to the most efficient strategy even if the task and the context would allow them to do so. Leber et al. induced observers to use either a feature search mode designed to address contradictory feature (feature group) or a singleton detection mode (singleton group) in a task in which either mode could be used to detect that target. By analyzing the effects of different types of distractor trials, they demonstrated that the feature group continued using the feature search, while the singleton group continued using the singleton search strategy on trials in which both strategies could be used. This result suggests that, contrary to the widely held assumption that observers always use the most efficient strategy available to perform a task, they tend to stick to the strategy that proved successful initially. With regard to the present study, two aspects of Leber and Egeth's (2006) study are noteworthy: First, Leber et al. tested singleton versus feature search, that is, search modes that are likely to involve response selection mechanisms comparable with to the decision processes (based on saliency vs. template matching) assumed to underlie performance in the present study. Second, Leber and Egeth (2006) presented only 24 practice trials to induce either of the two strategies, followed by 320 training trials in which the adopted strategy was consolidated. In the present experiments, observers performed three times this number of trials in the experimental conditions, making strategy carry-over to other conditions (where the strategy acquired first would work) even more likely.

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ysis, and shows that the (significant) feature-specific effect in the MIc condition is not simply due to carry-over of decision strategy from the single- to the multi-item(s) conditions.

2.3. Discussion

2.3.1. Reaction times

Overall, target-present RTs were faster with multi-item displays than with single-item displays (despite a higher false-alarm rate, suggesting a tendency to respond target-present, in the single-item conditions). While this fits with the view that target detection in multiple-item conditions is based on fast, saliency-based mechanisms, it is difficult to square with the idea that this type of task involves a time-consuming (pre-selective) search component in addition to the (post-selective) decision component that it shares with the single-item conditions.

Furthermore, the finding that, in the single-item conditions (but not the multiple-item conditions), target-present RTs are statistically as slow as target-absent RTs suggests that responding to a single-item display, whether it contains a target or a distractor, is based on the same process, which is highly likely to involve access to the featural level, that is: identification of the single-item features and comparison against a target (or distractor) template. This process of featural analysis is relatively slow: it consumes time over and above that required with multiple-item displays to establish target-presence – that is, to detect the presence of a pop-out, or saliency, signal. With multiple-item displays, a target-absent response is likely to be given as a default response unless a saliency signal emerges within a certain amount of sampling time (in which case a target-present response is triggered; Chun & Wolfe, 1996).

This would explain why target-absent decisions take longer than target-present decisions with multi-item displays. In any case, it appears that the addition of multiple non-target items to display changed the nature of the task (even when the target location was perfectly predictable), from feature discrimination to singleton detection.

Also worthy of note is that the factor target location (constant vs. variable) did not interact with display (single item vs. multiple items). This implies that, whatever the type of display, variable location added a constant amount of time – presumably required to localize the target and direct focal attention to it – to decision making and responding on a trial. (This does not mean that focal-attentional stimulus analysis is strictly necessary in the multi-item, particularly the MVl, conditions; rather, as argued by Müller and Krummenacher (2006), the same signal that triggers a spatial orienting response to the target may also be used to initiate a detection response. See also Töllner, Zehetleitner, Gramann, & Müller (in press-a).)

RTs to color targets were somewhat less affected by variability, as compared to constancy, of target location than RTs to orientation targets, suggesting that color targets were somewhat more potent in summoning and/or engaging focal attention than orientation targets.

2.3.2. Inter-trial effects

The inter-trial effects were overall smaller under MI conditions than under SI conditions. This alone would argue against the same decision mechanism (generating inter-trial effects) being involved in both types of task. In particular, as predicted, there was no (significant) feature-specific effect in the MVl condition (only a dimension-specific effect), suggesting that this task is solved via response decisions being (largely) based on the detection of an above-threshold supra-dimensional saliency signal. By contrast, there are feature-specific effects, in addition to dimension-specific effects, in the single-item conditions, indicating that (post-selective) feature analysis is required to solve the task with only a single item in the display. The pattern of effects suggests that the features of the single item presented are serially compared with a set of (target) memory templates, where comparisons within the same dimension (as that which was target-defining on the preceding trial) are given priority over comparisons involving a dimensional change in the template. This would explain why there are dimension-specific change effects over and above feature-specific effects.

On a serial model, where, following an unsuccessful match with an intra-dimension template, one of the two templates in the other dimensions is selected first for the comparison and only then, in case of a further mismatch, the other template in the changed dimension, one would expect the dimension-specific effect to be, on average, 1.5 times the size of feature-specific effect in single-item conditions. Actually, however, the dimension-specific effect is larger, that is, about 2 times the feature-specific effect (2.2 [Experiment 1a] to 2.3 [Experiment 1b] times). This would suggest that either all alternative features in the changed dimension are checked exhaustively, or that there is an additional time overhead for loading the templates for the changed dimension into working memory. Of further interest in this context is that, in single-item conditions, target-absent RTs were as fast as target-present RTs in the dD condition, 402.3 versus 407.8 ms (t(1) = 1.031, n.s.) (whereas they were much slower in multi-item conditions, 408.7 vs. 369.7 ms, (t(1) = 5.943, 2-tailed p < .001). This could mean that, if the second comparison in the changed dimension provides a mismatch, a negative decision is made as rapidly as the positive decision if this comparison provides a match (consistent with exhaustive checking).

Furthermore, while there are significant feature-specific effects in both SI conditions, under MI conditions, such effects are overall smaller and significant only with targets appearing consistently in the display center. The feature-specific effect in the latter condition (MIc) would appear to be inconsistent with the notion that in multi-item conditions, responding is generally based on (overall-) saliency signals. Note, however, that RTs are overall faster in the MIc condition compared to the Slc condition (381.2 vs. 388.6 ms), despite the fact that no search was necessary in either condition because focal attention could be deployed to the (invariable) target location in both conditions. Interestingly also, target-absent RTs were still slower than dD target-present RTs in the MIc condition (400.1 vs. 365.2 ms), whereas they were equally fast in the Slc condition, which suggests a difference in the decision process between the two conditions. This difference is difficult to account for by the mechanisms envisaged by Mortier et al. (2005), unless one admits that response decisions are influenced (expedited) by some second source of information not available in the Slc condition, namely: a fast-operating (pre-attentive) saliency-based target individuation process, in addition to a slower-operating (focal-attentional) target discrimination process. Although the latter process was not strictly necessary to perform the task, it appears that observers engage in it to some extent (the inter-trial effects appeared less marked in the MIc condition compared to the Slc condition), even if they had not performed any SI conditions beforehand (a feature-specific

4 Interestingly, observers appear to be using such a strategy of matching stimulus features against target templates, even though a theoretically more efficient alternative would be to compare the stimulus presented against the distractor template. In such a scheme, the stimulus must be a distractor if neither a color nor an orientation check provides a mismatch, in which case a negative decision can be made; and it must be a target, requiring a positive decision if one comparison provides a mismatch, which statistically would require 1.5 checks. Accordingly, target-present responses should be faster than -absent responses – an effect that was not significant in Experiment 1; furthermore, assuming that checking on trial n starts with the dimension checked last on trial n – 1, there should be a dimension-specific inter-trial effect, but no feature-specific effect – which is also at variance with the findings. Thus, it appears that observers use a confirmatory strategy, rather than a disconfirmatory one, perhaps because focally attended stimuli are automatically processed for feature identity.
effect in the Mlc condition was obtained in the between-subject Experiment 1b, as well as the within-subject Experiment 1a). One possible account for this may be derived from the ‘perceptual-load theory’ proposed by Lavie and her colleagues (e.g., Lavie, 1995, 2005). In the Mlc condition, focal attention can be allocated in advance to the fixed, central target location. Consequently, the central display element is processed attentionally as soon as it appears, involving an (automatic) element of feature analysis (even though this would not be necessary to perform the task). This outcome of this feature analysis process would to some extent influence the response decision, which is, however, mainly based on the (fast) saliency-based target individuation process that operates in parallel. This would give rise not only to a feature-specific inter-trial effect in the Mlc condition, but also (relative to the Mlv condition) enhanced feature- and dimension-based inter-trial effects – because a post-selective source of inter-trial effects would add to a pre-attentive source. This second source plays no role in the Mlv condition, in which there is very little analysis of target features following selection (see also Töllner, Zehetleitner, Gramann, et al., in press-a).

In summary, then, the pattern of general RT and inter-trial effects revealed in Experiment 1 suggests a fundamental difference in the way the task is solved with multi-item displays (where responses are largely saliency-based and – dimension-specific – inter-trial effects arise from a pre-selective coding stage) and single-item displays (where responses involve focal-attentional feature analysis, producing feature-specific inter-trial effects).

3. Experiment 2

Experiment 2 was designed to examine another prediction deriving from the account of Mortier et al. (2005) with respect to so-called ‘redundant-signals effect’, by comparing processing of targets differing from distractors on one (color or orientation, single targets) or on two dimensions (color and orientation, dual [redundant] targets) between multiple- and single-item(s) conditions. Using redundantly defined targets allows for the identification of the mechanism (serial, parallel race, parallel co-active) underlying the processing of redundant dimensional target signals (Krummenacher et al., 2001; Krummenacher, Müller, & Heller, 2002; Miller, 1982; Zehetleitner, Müller, & Krummenacher, 2009).

The results of Experiment 1 suggest that, in the multiple-item condition, responses are based more or less directly on an overall-saliency representation of the display. The location-specific integration mechanisms in the overall-saliency map integrate dimension-specific feature contrast signals in a weighted manner – giving rise to a pattern of dimension-specific, but not feature-specific inter-trial effects. Krummenacher and colleagues (2001, 2002) have shown that, in singleton feature search, RTs to targets redundantly defined in two dimensions (e.g., a red right-tilted bar amongst green vertical bars) are faster than RTs to targets defined in just one dimension (e.g., a red vertical or a right-tilted bar amongst green vertical bars). However, to understand the processing architecture (parallel co-active, parallel race, serial) that generates such redundancy gains, further analyses of the entire RT distributions are required. Using one such analysis, namely testing for violations of Miller’s (1982) ‘race model inequality’ (RMI), Krummenacher et al. (2001, 2002) were able to demonstrate that dimensional signals are indeed processed in a parallel co-active fashion. Adapted to the present task conditions, Miller’s (1982) RMI states that, for the assumption of a parallel race between signals to hold, the probability of having responded to a redundantly defined target at a given point in time t after display onset $[P(RT < t|C&O)]$ must be smaller or equal to the probability of having responded to a color target at time $t [P(RT < t|C)]$ plus the probability of having responded to an orientation target at time $t [P(RT < t|O)]$. Formally:

$$P(RT < t|C&O) \leq P(RT < t|C) + P(RT < t|O)$$

Violations of this inequality [i.e. if $P(RT < t|C&O) > P(RT < t|C) + P(RT < t|O)$] falsify the assumption of a parallel race between dimensional signals and provide evidence for parallel co-active signal integration. Finding such violations, Krummenacher et al. (2001, 2002) concluded that redundant target signals are integrated at some processing stage to drive (or co-activate) the required detection response. Going beyond this, Krummenacher et al. (2001) identified this integration stage in singleton feature search with the (pre-selective) overall-saliency map, rather than some post-selective stimulus analysis and stimulus-to-response mapping stage. In support of this, Krummenacher et al. (2002) showed that, with dual targets (presented at separate, but nearby locations), violations of the RMI (indicative of signal integration) are only observed if the critical target features are defined in different dimensions (but not when they are defined within the same dimension) – consistent with theories of saliency computation that assume that the saliency map integrates dimension-specific feature contrast signals. Furthermore, when presenting dual redundant targets (i.e., one differing from distractors by color, the other by orientation; Krummenacher et al., 2002, Experiment 2), RMI violations are observed only when the redundant target signals are spatially coincident or relatively close (but not when they are distant) – consistent with the hypothesis of saliency models that assume that overall-saliency map units integrate the incoming information in a spatially scaled manner. Finally, when focal attention is directed to a (symbolically) pre-ued display location, a target redundantly defined in two dimensions produces violations of the RMI even if it occurs outside the focus of attention – consistent with the assumption of saliency models that the signal integration occurs pre-attentively (Krummenacher et al., 2002, Experiment 3). On this basis, co-activation effects by dimensionally redundant singleton feature targets were expected in the multi-item condition of Experiment 2, reflecting signal integration at a pre-selective processing stage.

By contrast, with regard to the single-item condition, the results of Experiment 1 suggest that making a response decision requires access to the feature level in a post-selective (stimulus analysis) process. That is, the target attributes are compared serially to the templates for possible targets held in working memory. Comparison starts with the feature template that provided a match on the previous trial; if there is a mismatch on the current trial, the next comparison will be with the alternative feature template within the same dimension, and only then with the templates in the alternative dimension – giving rise to a pattern of feature-specific as well as dimension-specific inter-trial effects.

The critical question therefore is whether co-activation effects (as demonstrated with multi-item displays) would also be found in single-item conditions, when the single target exhibits two response-critical features in two dimensions (e.g., being both red and right-tilted), compared to just one (e.g., the feature red alone or right-tilted alone, each of which would also require a target-present response). With single-item displays, the pre-selective coding stages contribute little to responding (because perceptually, the single target item is – by virtue of being the only display item – always defined in multiple dimensions). Thus, the question is whether two post-selectively analyzed target features (that are to be discriminated from non-target features) can simultaneously activate the target-present response; restated, whether multiple features can be compared simultaneously with the target description held in working memory. If not – that is, if there is co-activation only in multi-item displays, but not single-item displays) –,
then this would lend further support to the assumption that the critical processing stages in the non-search (discrimination) task of Mortier et al. (2005) and the singleton feature search (detection) tasks examined by Müller and colleagues are different.

Although there are studies that have reported co-activation effects in discrimination tasks (e.g., Mordkoff & Yantis, 1993), it is not a priori clear whether these findings would extend to the non-search task of Mortier et al. (2005) – for which the results of Experiment 1 suggest that it involves a post-selective comparison process that checks only one feature at a time. If it is indeed not possible to compare multiple (dimensional) features simultaneously with the target description(s) held in working memory (as also predicted by Huang & Pashler’s, 2007, BMT), then no co-activation effect would be expected when the single display item (in the non-search task) possesses two target-defining features (in separate dimensions).

The assumption that processing of dimensionally redundant target signals in single-item conditions operates serially, rather than in a parallel or parallel co-active fashion, can be tested by examining the RT distributions for violations of the so-called Grice inequality (Grice, Canham, & Gwynne, 1984; see also Townsend & Nozawa, 1995; Van Zandt, 2002). The Grice inequality (which is closely related to the RMI) states that, if redundant signals are processed in a parallel-race architecture, the larger of the two probabilities of having responded to a dimensionally singly defined target at a given time \( t \) after display onset \( \max\{P(\text{RT} < t|C), P(\text{RT} < t|O)\} \) must be smaller or equal to the probability of having responded to a redundant target at time \( t \) \( \max\{P(\text{RT} < t|C\&O)\} \). Formally: \( \max\{P(\text{RT} < t|C), P(\text{RT} < t|O)\} < P(\text{RT} < t|C\&O) \)

Violations of this inequality [i.e., \( \max\{P(\text{RT} < t|C), P(\text{RT} < t|O)\} > P(\text{RT} < t|C\&O) \)] rule out parallel-race models and provide evidence for serial processing of dimensional signals. Thus, if processing of redundant targets in the single-item conditions of Experiment 2 requires serial comparison with target templates in working memory, violations of the Grice inequality would be expected – rather than violations of the RMI, which, according to Krummenacher et al. (2001, 2002) would reflect signal integration at an early processing stage in cross-dimensional singleton search. Conversely, in multiple-item conditions, violations of the RMI, but no violations of the Grice inequality are expected. Finding such a double dissociation would provide strong evidence that the underlying processes are different in multiple-item search tasks and single-item non-search tasks (parallel co-active processing in multiple-item conditions vs. serial processing in single-item trials), so that the two types of task cannot be directly compared.

To examine for such a double dissociation between search and non-search tasks, observers in Experiment 2 were presented with either multi-item or single-item displays, with targets either defined singly in one dimension or redundantly in two dimensions, and asked to indicate whether the display contained a target item (target-present response) or (a) distractor item(s) only (target-absent response). As in Experiment 1, distractors were vertical green bars, targets were vertical red or blue bars, left- or right-tilted green bars (single targets), and different from Experiment 1, red or blue bars tilted to the left- or the right (redundant targets).

Note that only variable-location conditions (Mlv and Slv) were tested in Experiment 2. The reason for examining for serial processing the Sl condition derives from Huang and Pashler’s (2007) BMT, according to which the generation of conscious visual representations – which are hypothesized to be necessary for the decision whether a single item is a target or a non-target – requires that visual features are indexed by location. Presentation of targets at variable, rather than constant, positions in the Sl condition would force this indexing of features by location, while also making this condition more similar to the multiple-item conditions.

Further, as it was assumed that the strategy that observers had to adopt to solve the SI condition (performed first) would be carried to the MI condition (performed second), even though the latter condition would allow for a different, saliency-based strategy. To examine for such strategy carry-over effects, half of the observers completed the MI condition followed by the SI condition, and vice versa for the other half.

### 3.1. Method

#### 3.1.1. Participants

Twenty-four observers (twelve female; age range 20–29 years, median age 23.4 years) participated in Experiment 2. All had normal or corrected-to-normal vision, all reported normal color vision, and all were right-handed. Participants were paid at a rate of CHF 10 (approximately $9) per hour or received course credits. Four of the observers had participated in Experiment 1. All observers were naïve as to the purpose of the experiment; the majority of them had no previous experience with visual search task.

#### 3.1.2. Apparatus, stimuli, task

The apparatus was the same as in Experiment 1. Stimuli were also the same as in Experiment 1, except that, in addition to targets defined in one dimension (i.e., in either color or orientation) only (singly-defined targets), there were also targets defined in two dimensions (i.e., in both color and orientation: redundant targets). Distractors were vertical green bars. Singly defined color targets were red or blue vertical bars, and singly defined orientation targets were left- or right-tilted green bars. Redundant targets differed from distractors in two dimensions: they were red and left-tilted, red and right-tilted, blue and left-tilted, or blue and right-tilted.

#### 3.1.3. Procedure and timing

Procedure and timing were the same as in Experiment 1. However, only the multiple items variable target location (MI) and the single item variable target location (SI) conditions were tested in Experiment 2. The sequence of conditions was counterbalanced across participants: Half of the observers started with the multiple-item condition, the other half with the single-item condition.

Each of the two conditions comprised of 960 trials, completed in one session of ten blocks of 96 trials. There were 576 target-present and 384 target-absent trials (ratio of 60–40%). Each of the eight possible target types (four singly and four redundantly defined targets) were presented with the same probability, in randomized order. Prior to each experimental condition, observers completed one block of practice trials to become familiar with the task. One session took about 30 min to complete; the two sessions of the experiment were run on two consecutive days.

### 3.2. Results

RTs faster than 200 ms and slower than 1000 ms were excluded from analysis (0.4% of all trials) as anticipations or exceedingly slow reactions. Additionally, RTs exceeding mean RT by more than three standard deviations were excluded from analysis, separately for each participant and each of the two conditions (less than 1.3% of all trials). As the focus of Experiment 2 was on redundancy gain effects, (for reasons of brevity) only these results, along with an analysis of the inter-trial effects, will be reported below. All other effects were generally similar to Experiment 1, as far as the two experiments are comparable design-wise.

#### 3.2.1. Inter-trial effects

Importantly, the inter-trial effects (transitions between trials with singly-defined targets) replicated the pattern observed in Experiment 1. In the MI condition, mean RTs were 396.3, 395.5,
and 416.5 ms for sDsF, sDdF, and dD trials, respectively [main effect of inter-trial transition, F(2, 46) = 7.381, p < .002]; that is, there was no significant cost for a feature change within a repeated dimension [sDsF vs. sDdF, −0.9 ms, F(1, 23) < 1, n.s.], while there was a cost for changing the dimension [sDdF vs. dD, 21.1 ms, F(1, 23) = 13.017, p = .002].

By contrast, in the SI condition, RTs were 384.1, 397.8, and 430.6 ms for sDsF, sDdF, and dD trials, respectively [F(2, 46) = 36.620, p < .001]; that is, there was a significant feature-change effect [sDsF vs. sDdF, 13.7 ms, F(1, 23) = 6.997, p = .028] as well as a significant dimension change effect [sDdF vs. dD, 32.8 ms, F(1, 23) = 45.496, p < .001].

In line with Experiment 1, this pattern of feature-specific effects, in addition to a dimensional effect in the SI, but not the MI, condition suggests that decision making involves serial feature checking in single-item, but not multiple-item conditions.5

3.2.2. Mean RT redundancy gains

Mean RTs of the three types of target-present trials were examined, separately for the MI and SI conditions, by one-way repeated-measures ANOVAs with the factor target type (single color, single orientation, redundant color and orientation). The target type effect was significant for both experimental conditions [MI: F(2, 46) = 81.240; SI: F(2, 46) = 84.454; both ps < .001]. In particular, mean RTs to redundant targets were faster than those to single orientation and color targets, in both conditions (see below).6

Table 2 presents the mean RTs for singly defined color and orientation targets and redundantly defined color plus orientation targets. Also shown are the mean RT redundancy gains relative to the faster of the two singly defined dimensions (Miller & Lopes, 1988) as well as the F-values of the corresponding, planned comparisons. As can be seen, the RTs to redundant targets were significantly faster than those to the fastest singly-defined targets in both experimental conditions of Experiment 2. However, while there are significant mean RT redundancy gains in all conditions, the present analysis (mean RT) leaves it open how these gains were generated — whether by a parallel race of the two target-defining dimensions, by co-active integration of the two redundant-target signals (as expected for MI conditions), or by serial checking of the two possible target-defining dimensions (as expected for SI conditions). Note that even serial checking would predict a mean RT redundancy gain because, with redundantly defined targets, a target signal is found ‘immediately’, whatever dimension is checked first; by contrast, with singly-defined targets, finding a target-signal would require 1.5 dimensional checks, on average.

3.2.2.1. RT distribution analyses — race model inequality

To examine how the mean RT redundancy gains are generated in the two conditions of Experiment 2, the distribution of redundant-target RTs, as compared to the single-target RTs, was tested for violations of Miller’s (1982) race model inequality, P(RT < t(C)) ≤ P(RT < t(C) + P(RT < t(O)), separately for the MI and SI conditions, for the entire sample of 24 observers. As can be seen from Table 3, the distribution analyses did not reveal any significant violations of the RMI in either of the two conditions. Note, however, that P(RT < t(C) did not differ significantly from P(RT < t(C) + P(RT < t(O)) for the first three quantiles of the RT distributions in the MI condition; by contrast, P(RT < t(O) was significantly smaller than P(RT < t(C) + P(RT < t(O)) already at the first three quantiles in the SI condition. That is, performance in the SI condition was further away from violations of the RMI than performance in the MI condition.

Nevertheless, the lack of evidence for co-active processing, in particular in the MI condition, is at variance with several reports of parallel co-active processing of color and orientation signals in search for singleton feature targets (Krummenacher et al., 2001, 2002; see also Zehetleitner et al., 2009), for a evidence of parallel co-active processing of orientation and luminance signals.

Leber & Egeth’s (2006) finding (see Footnote 3) that observers consistently used the (singleton or, respectively, feature search) strategy they had adopted in a first (training) phase of an experiment in the subsequent (test) phase, despite the fact that the carried-over strategy did not yield optimum performance, suggests that potential evidence of parallel co-active processing may have been obscured by strategy carry-over effects from the condition performed first to that performed second (see also Experiment 1). In more detail, parallel co-active signal integration is not necessarily expected to occur if the decision on target presence requires (post-selective) access to feature representations (SI condition), rather than dimensionally integrated overall-saliency values (MI condition). On the assumption that the processing strategy

5 Further analyses of the inter-trial effects separately for observers who performed the MI condition first and the SI condition second, and vice versa, revealed the effect to be significant in all cases, but MI 2nd [MI 1st: F(2, 22) = 10.906, p = .001; MI 2nd: F(2, 22) = 0.904, p = .420; SI 1st: F(2, 22) = 16.422, p < .001; SI 2nd: F(2, 22) = 20.362, p < .001]. While there was no differential order-of-performance effect between the SI condition [SI 1st: 384.9, 437.2, and 381.2 ms; SI 2nd: 387.5, 436.1, and 375.2 ms], for the MI conditions, the inter-trial, in particular the dimension change effects, were less robust for observers who had performed the SI condition first (400.6, 405.1, and 412.6 ms for sDsF, sDdF, and dD transitions, respectively) than for observers who had started with the MI condition (MI 1st: 392.1, 385.8, and 420.4 ms).

6 This pattern was unaffected by whether observers had performed the MI condition first and the SI condition second, or vice versa: MI 1st: F(2, 22) = 49.713; MI 2nd: F(2, 22) = 32.673; SI 1st: F(2, 22) = 38.772; SI 2nd: F(2, 22) = 61.742; all ps < .001.
adopted in the single-item condition is maintained in the multiple-item condition, the lack of co-active processing in the MI condition might well be due to a carry-over effect displayed by observers who performed the MI condition after the SI condition. 7 In order to address the possibility that carry-over of processing mode affected signal integration, violations of the RMI were tested for subsets of (each 12) observers who had started Experiment 2 with either the MI or the SI condition.

As can be seen from Table 4, the RMI was significantly violated at the 5%, 10% and 15% quantiles of the cumulative RT distributions in the MI condition provided that observers had not performed the SI condition beforehand. For all other observer groups and conditions, there was no evidence of RMI violations.

### 3.2.2.2. RT distribution analysis – Grice inequality

Violations of the race model inequality revealed that in the MI condition of Experiment 2, redundant signals are integrated, in parallel, to co-activate the required detection responses. However, as such, the fact that no RMI were observed in the SI condition does not tell us whether responding is based on a parallel-race of redundant-target signals or serial template matching. However, testing for violations of the Grice inequality, max{\(|RT<\theta(C)|, P(RT<\theta(O)) \leq P(RT<\theta(C\&O))\)}, permits this question to be decided (Grice et al., 1984; Townsend & Nozawa, 1995). The assumption of a parallel race underlying processing is violated if the largest probability of a response to a singly-defined target having occurred at time  is significantly larger than the probability of a response to a redundant target having occurred at time . Testing for violations of the Grice inequality was carried out only for the SI condition (as the RMI is violated in the MI condition). Concurrent violations of the Grice inequality are logically impossible, for the entire sample of observers and separately for observers who completed the SI condition followed by the MI condition and vice versa. As can bee seen from Table 3 (right-hand panel), for the entire sample, although the largest single target probabilities \(\max(p_c(p_o))\) were tested for subsets of (each 12) observers who had started Experiment 2 with the MI condition beforehand. For all other observer groups and conditions, there was no evidence of RMI violations.

### 3.3. Discussion

The fact that co-activation effects are demonstrable in the MI condition is consistent with Krummenacher et al. (2001, 2002) and Zehetleitner et al. (2009), who provided evidence that these effects arise at a pre-selective stage, namely, the computation of cross-dimensional, overall-saliency signals. This is consistent with Töllner, Zehetleitner, Krummenacher, and Müller (in press-b), who recently showed an enhanced N2pc component for redundantly, relative to singly-defined targets. As the N2pc is a marker of the event-related (difference) potential that is commonly assumed to reflect processes of attentional allocation (e.g., Eimer, 1996), the results of Töllner et al. provide electrophysiological support for an early, pre-selective effect of redundant-target coding. Furthermore, Krummenacher et al. (2001) showed that cross-dimensional signal integration in singleton detection tasks is modulated by inter-trial history: violations of the RMI were more marked if a redundantly defined target followed a redundantly defined target, rather than a singly defined target. That is, if the integration stage is pre-selective, then the inter-trial effects in this type of task must logically also be operating at a pre-selective processing stage.

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7 While the MI condition can be performed perfectly in a (feature) processing mode necessary to solve the task in the SI condition, a carry-over effect in the opposite direction is unlikely, as responding does not logically require feature identity analysis in the MI condition, but does so in the SI condition (i.e., observers would have to change mode from the MI to the SI condition).

8 Due to insufficient numbers of trials, a similar analysis was not feasible for the MI data of Experiment 2.
By contrast, the finding that there are no co-activation effects in the SI condition is consistent with the idea that the task demands in single-item conditions are entirely different (from those in multi-item conditions), involving post-selective feature checking. At least under the conditions of the present task, this appears to involve serial comparisons of the focally attended stimulus against the target memory templates, that is, it is not possible to make more than one such comparison at a time. Apart from the lack of RMI violations in the SI condition of Experiment 2, evidence for serial checking is provided by the violations of the Grice inequality, as well as the pattern of feature-specific, in addition to dimension-dependent, inter-trial effects in both Experiments 1 and 2.

Note that this is not to say that no conditions where a given stimulus can be compared in parallel to multiple target templates. For instance, Mordkoff and Yantis (1993) reported RMI violations in a task where observers were presented with one item only, a colored letter; there were three possible shapes (e.g., X, O, H) and three colors (e.g., red, green, blue), with one particular shape and color (e.g., X and red) being target-defining and the other two shape and color alternatives being non-target features. Observers were instructed, in the example, to respond positively if the stimulus presented was an X (whatever its color) or red (whatever its shape). That is, the stimulus had to be checked only against two target templates. Perhaps this can be done in a parallel co-active fashion, given that the number of target alternatives to be kept in working memory is two. By contrast, parallel co-active processing may no longer be possible when the number of possible alternatives is higher (four in the present experiments). This possibility requires further exploration. Whatever the answer, the number of possible alternatives had no effect in the MI condition (despite the fact that alternatives were exactly the same as in the SI condition), supporting the view that co-activation in this condition involves a different (namely: pre-selective) processing stage to the decision making stage in the SI condition.

Interestingly, observers who learnt to use a feature checking strategy to solve the first-performed, SI task showed no co-activation effects when they were later presented with the MI task. While this is consistent with the idea that the multi-item task can be performed using a (feature analysis) processing mode adopted to solve the single-item task (but not vice versa), one might ask why there were no co-activation effects for this observer group at all – assuming that there is signal integration at the first, pre-selective stage of processing. Restated, post-selective feature checking effects should be additive with pre-selective co-activation effects. However, variance created at the post-selective stage may have swamped effects at the pre-selective stage. Alternatively, or additionally, serial checking of features at the secondary stage might have impacted, in top-down manner, on the way pre-selective signals are integrated (see also Müller et al., 2004, and Pan, Xu, and Soto, 2009, who showed an influence of post-selective working memory demands on pop-out target detection).

4. General discussion

In summary, the present experiments revealed that the pattern of inter-trial effects (indicative of the memory-based mechanisms of task performance) differs between multiple-item (search) tasks, in which responding can be based on simple target detection, and single-item (non-search) tasks, in which responding requires stimulus analysis beyond detection. The fact that there was no feature-specific inter-trial effect in the standard pop-out search tasks (with multiple items and variable target location) is consistent with saliency-based processing accounts (e.g., Itti & Koch, 2000, 2001; Müller et al., 1995; Wolfe, 1994), according to which visual selection and response decisions are based (more or less directly) on supra-dimensional saliency signals that do not (or no longer) carry information about the specific features that give rise to them (see Müller & Krummenacher, 2006). By contrast, the fact that there are feature-specific effects in the single-item, non-search task is consistent with the idea this task requires post-selective (focal-attentional) feature analysis. The present data suggest that the latter process involves a serial component, of comparing the stimulus against a set of target templates held in working memory. Consistent with this, there was no evidence of co-active processing of dimensionally redundant target features in the single-item task; also, a parallel race of such features could be ruled out by the violations of the Grice inequality in Experiment 2, which leaves only the alternative of serial processing. Note that this is the very pattern that would also be expected on the Boolean Map Theory recently proposed by Huang and Pashler (2007). Conversely, in the multi-item task, redundant target (i.e., feature contrast) signals are integrated across dimensions, giving rise to violations of the race model inequality.

This pattern of effects argues that there are two relatively independent sources of inter-trial effects in the two tasks: one located on a pre-selective processing stage, where signals are coded in a feature-unspecific, but (across dimensions) parallel co-active processing architecture; and the other on a post-selective stage, where signals are processed in terms of precise feature information, in a serial fashion (with intra-dimensional feature switches given priority over cross-dimensional switches).

Accordingly, with regard to the question posed in the Introduction, the assumption that there is only one weighting system involved in the two types of task (as proposed by Mortier et al. (2005)) is not tenable. Rather, there are multiple weighting systems operating at different levels. This is consistent with the Dimension-Weighting Account developed by Müller and his colleagues (e.g., Found & Müller, 1996; Müller et al., 1995, 2003). While this account, thus far, has only focused on the pre-selective weighting mechanism, it admits the possibility of other short-term memory mechanisms operating at later stages in the processing hierarchy. In contrast, the single-mechanism account of Mortier et al. (2005) admits only the possibility of post-selective memory buffering, and would thus be unable to explain the existence of any inter-trial effects arising from earlier processing stages.

Apart from the results revealed by the present experiments, there are a number of behavioral and brain-imaging studies that support the notion of pre-selective weighting. In particular, Zehetleitner, Krummenacher, Geyer, and Müller (submitted for publication) have recently shown cross-dimensional inter-trial transition to affect perceptual sensitivity in a pop-out localization task, indicative of an effect originating at an early level of (saliency) coding: sensitivity was reduced for a target defined in a changed dimension, as compared to a repeated dimension (see also Müller and O’Grady, 2000, who found costs in terms of sensitivity when observers had to judge dual object attributes in different dimensions, rather than in the same dimension).

Furthermore, neuro-imaging investigations of dimension-based inter-trial effects in pop-out search tasks (Pollmann, Weidner, Müller, & von Cramon, 2000, 2006) have revealed significant BOLD signal increases in visual sensory areas (V4 and hMT+) contingent on the repetition versus change of the target-defining dimension (color and motion, respectively) across consecutive trials. Sensitivity of sensory visual areas to repetitions of the relevant dimensions

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* Although the pattern of inter-trial RT effects is consistent with serial checking, one might argue that the rate of checking – some 10–20 ms per feature – is too fast to be consistent with a genuinely serial process. But it may be that multiple feature alternatives are processed simultaneously at the focal-attention stage, while however there is a serial order in which they enter this stage (along the lines of the ‘car wash’ analogy suggested by Wolfe (2003).
argues in favor of an early, perceptual locus of dimensional weighting. That this (perceptual) locus is indeed pre-selective is supported by a study of Töllner et al. (2008), who investigated ERP correlates of dimension-based inter-trial effects using a compound-search task (Bravo & Nakayama, 1992; Duncan, 1985), where the target- and the response-defining features were dissociated: participants had to respond to the orientation of a grating within a form or a color target. Analysis of the N2pc component revealed significant dimensional inter-trial effects in N2pc peak latencies (as well as amplitudes): the N2pc peaked earlier (and its amplitude was larger) with dimension repetitions rather than changes. This adds support to the notion that dimensional weighting modules (pre-selective) signal coding processes that form the basis for the allocation of focal attention.

In summary, we contend that the inter-trial effects in pop-out search (multi-item) and non-search (single-item) tasks are dissociable, reflecting different underlying memory mechanisms. Although dissociable, there may also be possible interactions between the two mechanisms, as evidenced, for instance, by the lack of co-active processing in a MI task following performance of an SI task. The present results suggest that, when the system is set for feature analysis; this impacts (perhaps in a top-down manner) on the weight distribution at the pre-selective level, which in turn determines the ability of multi-dimensional target signals to co-activate the required (detection) response. Further work is necessary to characterize these interactions in detail.

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