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Understanding the allocation of attention when faced with varying perceptual load in partial report: A computational approach

Søren Kyllingsbæk[a,b,*], Jocelyn L. Sy[b], Barry Giesbrecht[b]

[a] Department of Psychology, University of Copenhagen, Denmark
[b] Department of Psychology, University of California, Santa Barbara, United States

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ABSTRACT

The allocation of visual processing capacity is a key topic in studies and theories of visual attention. The load theory of Lavie (1995) proposes that allocation happens in two steps where processing resources are first allocated to task-relevant stimuli and secondly remaining capacity 'spills over' to task-irrelevant distractors. In contrast, the Theory of Visual Attention (TVA) proposed by Bundesen (1990) assumes that allocation happens in a single step where processing capacity is allocated to all stimuli, both task-relevant and task-irrelevant, in proportion to their relative attentional weight. Here we present data from two partial report experiments where we varied the number and discriminability of the task-irrelevant stimuli (Experiment 1) and perceptual load (Experiment 2). The TVA fitted the data of the two experiments well thus favoring the simple explanation with a single step of capacity allocation. We also show that the effects of varying perceptual load can only be explained by a combined effect of allocation of processing capacity as well as limits in visual working memory. Finally, we link the results to processing capacity understood at the neural level based on the neural theory of visual attention by Bundesen et al. (2005).

1. Introduction

Investigating the nature of visual processing capacity and how it is allocated to objects relevant to our current behavioral goals is crucial for understanding visual cognition in general and visual attention in particular. Load theory (LT) first proposed by Lavie and Tsal (1994; see also Lavie, 1995) has provided an influential account of this important component of visual processing.

1.1. Load theory

According to LT, perception is capacity-limited and all stimuli are processed in an automatic fashion until this capacity is exhausted (e.g. Lavie, 2005, p. 75; see also Lavie, 1995; Lavie & Cox, 1997; Lavie, Lin, Zokai, & Thoma, 2009). Further, allocation of visual processing capacity happens in two steps: (1) initial allocation of resources to task-relevant stimuli, followed by (2) automatic allocation ('spill over') of the remaining capacity to task-irrelevant stimuli. Two key predictions follow from these premises. First, in situations of high perceptual load (e.g. when many stimuli have to be processed), full perceptual capacity will be engaged leaving no spare capacity to process task-irrelevant distractors. Second, in situations of low load (e.g. when few stimuli have to be processed and processing is easy), excess capacity not used to process task-relevant stimuli will automatically 'spill over' leading to perception of task-irrelevant distractors. A large number of studies have provided evidence consistent with these general predictions, including behavioral evidence for reduced flanker interference under conditions of high perceptual load (e.g. Lavie, 1995; Lavie, 2005; Lavie & Cox, 1997), neuroimaging evidence for modulations of distractor-related brain activity (e.g. Handy, Soltani, & Mangun, 2001; Rees, Frith, & Lavie, 1997) and has been extended to real life situations (Forster & Lavie, 2008) and mind wandering (Forster & Lavie, 2009). Moreover, beyond the empirical evidence consistent with LT, the theoretical notion that the selectivity of attention is modulated by perceptual load has been offered as a resolution to the long standing debate between proponents of early selection (e.g. Broadbent, 1958; Cherry, 1953; Treisman & Gelade, 1980) and late selection (e.g. Deutsch and Deutsch, 1963; Shiffrin & Schneider, 1977).

Recently, Benoni and Tsal (2010; Tsal & Benoni, 2010; see also Eltiti, Wallace, & Fox, 2005; Paquet & Craig, 1997) criticized LT and presented an alternative explanation to the classical effects of perceptual load in visual search (e.g. Lavie, 1995; Lavie & Tsal, 1994). In a series of experiments, Benoni and Tsal (2010) compared three different search conditions in combination with a compatible, neutral, or incompatible task-irrelevant flanker: (1) Low perceptual load with a single target search item, (2) high perceptual load with several task-relevant stimuli including the search target, and

* Corresponding author at: Center for Visual Cognition, Department of Psychology, University of Copenhagen, Øster Farimagsgade 2A, DK-1353 Copenhagen K, Denmark. Tel.: +45 3532 4861.
E-mail address: sk@psy.ku.dk (S. Kyllingsbæk).

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(3) a novel dilution condition where the task-relevant distractors in the search display were presented in a different color from the search target and the task-irrelevant flanker. Benoni and Tsal (2010) argued that LT would predict similar performance due to low perceptual load in both the classical low load condition and the new dilution condition where the difference in color enabled the participants to ignore the distractors in the search display. However, they found that the compatibility effects between the target and the task-irrelevant flanker disappeared in the dilution condition thus making it similar to the high load condition. Benoni and Tsal (2010) argue that the effect of the task-irrelevant flanker is diluted in both the classical high load condition and the new dilution condition. The reduction in the compatibility effect seen for larger set sizes is thus not due to increased perceptual load, but rather to processing of the features of the neutral task-relevant distractors in the search display diluting the effect of the task-irrelevant flanker.

As pointed out by Benoni and Tsal (2010, p. 1297), a major weakness of LT is that it only provides a very general definition of capacity allocation and perceptual load. The theoretical discussion of these important concepts would therefore benefit significantly from a more explicit and detailed account of how distribution of perceptual capacity takes place when perceptual load is varied. The theory of visual attention (TVA) by Bundesen (1990) provides such an account. In contrast to LT, TVA is a computational theory and thus provides quantitative measures of both processing capacity and allocation of attention (see also Bundesen, Habekost, & Kyllingsbæk, 2005; Bundesen & Habekost, 2008; Kyllingsbæk, 2006).

The purpose of the present paper is to compare LT and TVA. More specifically, we will test a core difference between the two theories: In LT allocation of processing resources is a two step process where resources are first allocated to task-relevant stimuli and then in the second step to task-irrelevant distractors if present. In contrast, in TVA allocation of capacity is a one step process involving both task-relevant and irrelevant stimuli. Following the theoretical derivations, we highlight three diverging predictions of LT and TVA and test these predictions in two partial report experiments in which both the number and the discriminability of the task-irrelevant distractors were manipulated (Experiment 1) and in which the perceptual load of the task was varied (Experiment 2).

1.2. A theory of visual attention

According to TVA, visual processing may be understood as a competitive race between different possible categorization of objects in the visual field (see details in Section 6; see also Bundesen, 1990). A fixed limited processing capacity is allocated to the most important objects based on an initial computation of attentional weights. The categorizations that finish the race first are encoded into a limited Visual Working Memory (VWM) store which holds categorizations of only 3–5 objects items (e.g. Cowan, 2001; Sperling, 1960; Luck & Vogel, 1997; Todd & Marois, 2004; Vogel & Machizawa, 2004). Information from other stimuli that finish processing after VWM has filled up is lost. Recently, the theory has been extended to a Neural Theory of Visual Attention (NTVA) that accounts for neurophysiological data from single units (Bundesen et al., 2005).

In TVA, allocation of processing capacity is based on attentional weights computed for both task-relevant and task-irrelevant stimuli in the visual field. Thus, TVA makes no explicit distinction between task-relevant and task-irrelevant stimuli. Consequently, there is no separation between a process of allocating perceptual capacity to task-relevant stimuli and a process of 'spilling over' of excess capacity to task-irrelevant stimuli. After attentional weights for the presented stimuli have been computed, a limited pool of processing capacity, C, is allocated according to the following ratio:

$$\frac{w_x}{\sum_{z \in S} w_z}, \tag{1}$$

where w_x and w_z are the attentional weights of stimulus x and z, respectively, and S is the set of all stimuli (both task-relevant and task-irrelevant). Any stimulus with a positive attentional weight will be allocated some perceptual processing capacity irrespective of the size of the sum of the attentional weights given by the denominator in Eq. (1). In relation to LT, the denominator of Eq. (1) may be viewed as an alternative way of expressing perceptual load.

2. Allocation of perceptual processing capacity—contrasting load theory and TVA

Prior to comparing allocation schemes in LT and TVA, it is important to define some key terms. Following the definitions used in LT (e.g. Lavie, 1995), we define *task-irrelevant distractors* as distracting stimuli at positions in the stimulus display known to the participant to contain no task relevant information. Correspondingly, *task-relevant stimuli* (task-relevant targets and task-relevant distractors) are defined as stimuli (targets or distractors) located at positions in the stimulus display that may potentially contain a target.

2.1. Load theory

Fig. 1A illustrates LT's assumptions of how processing capacity is distributed under conditions of variable load. In the figure, the gray areas indicate perceptual capacity allocated to task-relevant stimuli and the white areas indicate processing capacity that is allocated to task-irrelevant stimuli. As load is increased for example when an extra stimulus is added to the set of task-relevant stimuli in a search task (e.g. Lavie & Cox, 1997, Experiment 2), the amount of capacity allocated in the first step of allocation increases (gray area). When perceptual load is low, a large amount of excess perceptual capacity (white area) is available to automatically 'spill over' to process task-irrelevant distractors in the second step. The amount of extra capacity decreases systematically with perceptual load until all capacity resources are used to process task-relevant stimuli thus effectively preventing processing of task-irrelevant distractors.

2.2. A theory of visual attention

Fig. 1B–D illustrates how processing capacity is allocated according to TVA. Fig. 1B illustrates how perceptual capacity is allocated when a task-irrelevant flanker is presented together with 1–4 task-relevant stimuli, i.e. under increasing perceptual load. For the purposes of this example, the absolute attentional weight of a task-relevant stimulus was assumed to be equal to 3 and the attentional weight of the task-irrelevant flanker equal to 1. When only a single task-relevant stimulus is presented, the relative attentional weight of the task-irrelevant flanker is equal to $1/(1+3) = 1/4$ (cf. Eq. (1)). Thus the flanker will be allocated a relatively large proportion of the perceptual capacity or in terms of LT, 1/4 of the capacity will 'spill over' to the task-irrelevant stimulus. When the load is increased by an additional task-relevant stimulus, the proportion of allocated capacity to the flanker drops to $1/(1+2\times3) = 1/7$. For the high load condition with four task-relevant stimuli, the allocated capacity to the flanker has dropped to $1/(1+4\times3) = 1/13$. Note also that the proportion of allocated resources to each of the task-relevant stimuli also decreases when the perceptual load is increased, being equal to 3/4, 3/7, 3/10 and 3/13 in the four cases illustrated in Fig. 1B. At the same time however, the summed processing of the task-relevant stimuli increases.

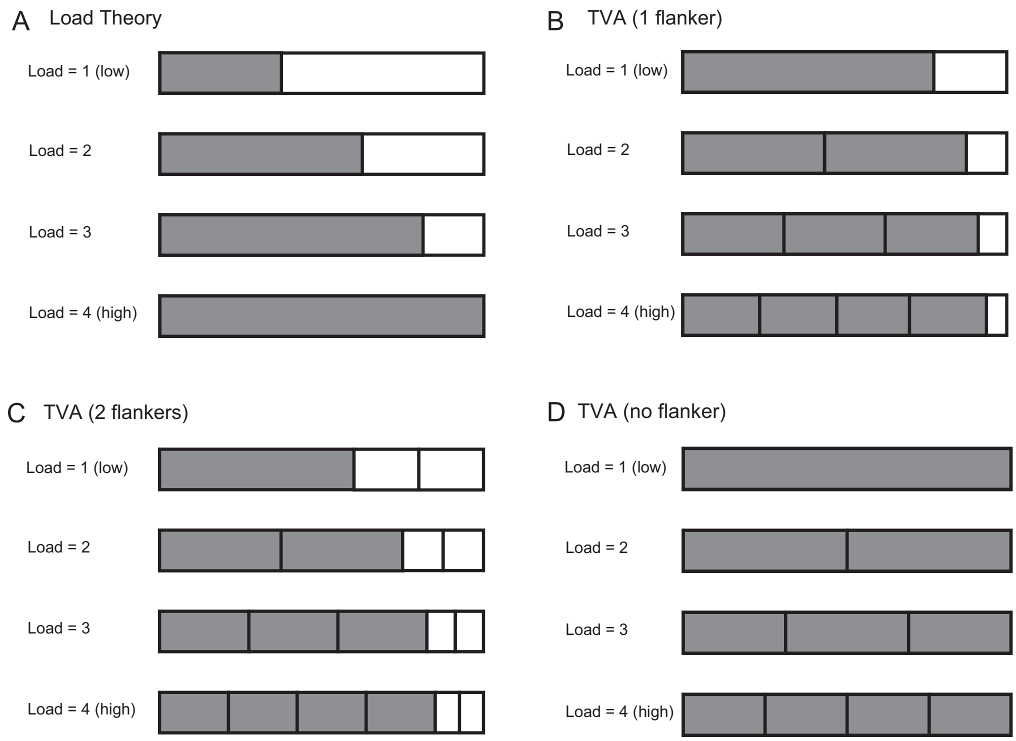

Fig. 1. Allocation of visual processing capacity according to LT and TVA when perceptual load is varied by presenting 1–4 task-relevant stimuli. Panel A: Allocation of capacity according to LT with an increasing amount of processing capacity allocated to the task-relevant stimuli (gray area) when perceptual load is increased. Panel B: Allocation of processing capacity with one task-irrelevant distractor (flanker; white area) according to TVA. Panel C: Allocation of processing capacity with two task-irrelevant distractors (flankers) according to TVA. Panel D: Allocation of processing capacity according to TVA when only task-relevant stimuli are presented.

Comparing LT illustrated in Fig. 1A with the illustration of capacity allocation in TVA in Fig. 1B, it is clear that the two models may mimic each other closely. However, there are conceptual and testable differences:

2.3. Manipulations of the discriminability of the task-irrelevant flanker

According to LT, perceptual capacity is first allocated to the task-relevant stimuli and then the remaining capacity will involuntarily 'spill over' to task-irrelevant distractors. Thus the attentional weight of task-irrelevant distractors should not influence the amount of perceptual capacity allocated to the task-relevant stimuli. In contrast, TVA assumes that perceptual capacity is allocated simultaneously for both task-relevant stimuli and task-irrelevant distractors. Thus TVA predicts that the degree to which there are reductions in the attentional weights of the task-irrelevant distractors will result in an increase of the *relative* attentional weights of the task-relevant stimuli (cf. Eq. (1)). This in turn leads to more capacity being allocated to the task-relevant stimuli when task-irrelevant flankers are easy to distinguish from the target stimuli, e.g. when task-relevant and task-irrelevant stimuli have different colors.

2.4. The effect of varying the number task-irrelevant distractors

When perceptual load is held constant, LT predicts no effect of manipulating the number of task-irrelevant distractors when these are neutral in relation to the target stimuli.[1] This is because, according to LT and as described above, capacity allocation happens separately for task-relevant and task-irrelevant stimuli. Thus the proportion of capacity allocated to the task-relevant stimuli is independent of the number of task-irrelevant stimuli.

In stark constrast to LT, TVA predicts a significant effect of the number of task-irrelevant distractors on capacity allocation to task-relevant stimuli. This is illustrated when comparing Fig. 1B and C. The two panels illustrate capacity allocation in TVA when one and two task-irrelevant distractors are presented, respectively. As can be seen from the comparison, TVA predicts that the capacity allocated to the task-relevant stimuli will decrease significantly when the number of task-irrelevant distractors is increased. LT, on the other hand, predicts no effect on capacity allocation when increasing the number of task-irrelevant stimuli.

2.5. Allocation of capacity when task-irrelevant distractors are absent

In situations where no task-irrelevant stimuli are presented and perceptual load is varied, LT and TVA make divergent predictions. The divergence is clear when Fig. 1A (LT) are compared with Fig. 1D (TVA). Specifically, LT assumes two steps of capacity allocation: processing capacity is first allocated to task-relevant stimuli and then the remaining capacity automatically 'spills over' to task-irrelevant distractors. Starting with a low-load task, more and more total capacity will be allocated as the perceptual load of the task is increased. As a result, LT predicts that the total amount of processing capacity allocated to task-relevant stimuli should increase with perceptual load (cf. Fig. 1A). Thus when measur-

[1] This will be the case when neither target congruent nor incongruent responses are associated with the task-irrelevant distractors as in the paradigm used in the present work. Note that this will not be the case in the standard paradigms used by Lavie et al. where the effect of task-irrelevant distractors is measured by reaction time differences when target response incongruent and congruent flankers are presented.

ing the total processing capacity across task-relevant stimuli, it should increase with perceptual load, as would occur when increasing the number of letters in a whole report task. The predictions of TVA, however, are quiet different. When the task-irrelevant flankers are absent, all perceptual processing capacity is allocated to the task-relevant stimuli in accordance with Eq. (1). Thus the total processing capacity allocated to task-relevant stimuli should stay constant across variations in perceptual load. Consistent with TVA's allocation scheme, Shibuya and Bundesen (1988; see also Bundesen, 1990, pp. 529–531) found strong evidence of proportional allocation of a fixed processing capacity in both whole and partial report where the perceptual load was manipulated by varying the number of targets and distractors. It is difficult to explain these types of results using LT because in order to account for them, excess capacity that is unallocated at the first step would have to 'spill back' to the task-relevant stimuli during the second step of capacity allocation.

3. The present experiments

The preceding comparison of LT and TVA revealed three key differences between the models: (1) LT predicts no effect of similarity between the task-irrelevant distractors and the target, TVA does; (2) LT predicts no effect of the number of task-irrelevant distractors, TVA does; and (3) LT predicts no change in performance when task-irrelevant distractors are absent, TVA does. We report two partial report experiments that systematically test these three divergent predictions: In the experiments, subjects reported several target letters presented at the perimeter of an imaginary circle while ignoring task-irrelevant flankers presented to the left and/or right. The exposure duration of the displays was manipulated systematically to yield estimates of the individual processing capacity in each participant measured as number of letters processed per second. In the first experiment, the perceptual load (the number of targets) was held constant while both the number and the discriminability of the task-irrelevant flankers were varied. In the second experiment, the perceptual load was manipulated as well as the number of task-irrelevant flankers. The analyses of the behavioral data along with quantitative modeling provide clear evidence in favor of the TVA predictions. These results offer a more precise explanation of how attentional capacity may be allocated under variable load and flanker conditions.

4. Experiment 1

In Experiment 1, we tested the effect of varying the number of task-irrelevant flankers and their discriminability in a partial report task where the number of targets (perceptual load) was held constant. In each display, participants viewed four target letters presented at the perimeter of an imaginary circle centered at fixation. Outside the circle to the left or right, one or two task-irrelevant distractors (flankers) were presented. In half of the trials, the task-irrelevant distractors were presented in a different color than the targets to make it easier for the participants to ignore them.

4.1. Methods

4.1.1. Participants

Six undergraduate students (3 female) from the University of California, Santa Barbara participated in the experiment. The participants received course credits for their participation and were naïve with respect to the purpose of the experiment. All participants had normal or correct-to-normal visual acuity.

4.1.2. Stimulus material

The stimulus material consisted of uppercase letters printed in Arial font and colored in blue or red. The mean width of the letters was 1.05 degrees of visual angle (range .43–1.53) and the height was 1.03 degrees of visual angle at a viewing distance of 100 cm. A total of six relevant stimulus positions and two irrelevant flanker positions were used. The relevant stimulus positions were located at 45, 90, 135, 225, 270, and 315 degrees around the perimeter of an imaginary circled centered at fixation with a radius of 3.91 degrees of visual angle. The irrelevant flanker positions were located left and right of fixation at a distance of 5.85 degrees of visual angle from fixation. A sketch of the stimulus positions are shown in Fig. 2. Pattern masks consisting of red and blue simple geometric shapes were used to terminate stimulus processing. The width and height of the masks were 1.94 degrees of visual angle. A white fixation cross was continuously visible in the center of the screen. All stimuli were presented on a black background.

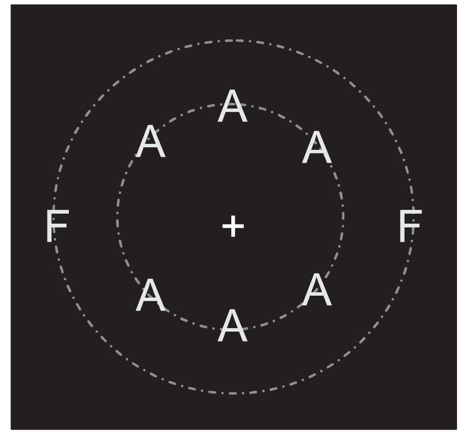

Fig. 2. The stimulus locations used in Experiment 1. Task-relevant locations are indicated by A and task-irrelevant flanker locations by F.

4.1.3. Procedure

The experiment was run on a CRT running at 75 Hz controlled by a PC. Each participant were designated a target color (red or blue) which was held constant across the experiment. The other color was only used for the flankers in conditions where the color of the flankers differed from the color of the target letters. Thus, half of the participants reported red letters and ignored blue letters and vice versa for the rest of the participants.

Each trial began with the presentation of the fixation cross in the center of the screen. When properly fixated, the participant initiated the presentation of four target letters presented at four out of the six randomly chosen relevant stimulus positions. Along with the target letters, none, one, or two task-irrelevant flanking letters were presented. The set of target letters and flanking letters were drawn from the set of upper case letters from the English alphabet without replacement. Thus, all letters presented in a given display were different from one another.

After the presentation of the stimulus letters, eight pattern masks were presented at the eight possible relevant and irrelevant stimulus positions. Four different exposure durations were used: 27, 53, 107, and 213 ms. The exposure duration of the masks was 500 ms.

The task of the participants was to report as many as possible of the four targets letters at the relevant stimulus positions while ignoring the task-irrelevant flanking letters if present in the display (partial report). After the offset of the masks, the participant typed in the identity of the remembered target letters in any order that they preferred. Participants were informed that reaction time was not recorded and that they could use as much time as they wished for responding.

4.1.4. Design

Five different conditions were used: (1) No flanking stimuli, (2) one irrelevant flanker in the target color presented either to the left of right of fixation, (3) two irrelevant flankers in the target color, (4) one irrelevant flanker in the non-target color, and (5) two irrelevant flanker in the non-target color. Each of the five conditions was run with the four different exposure durations, yielding a total of 20 different experimental conditions. The order of trials was randomized across blocks of 600 trials. A total of 120 repetitions per condition and exposure durations were run yielding a total of 2400 trials per participant. The trials were run on four separate sessions. Participants 5 and 6 ran an additional four sessions, thus a total of 4800 trials. The participants were familiarized with the stimulus procedure in two practice trial blocks.

4.2. Results

4.2.1. Mean scores

For each trial we calculated the number of correctly report targets. From these, the mean number of reported letters (mean score) in each of the 20 experimental conditions was calculated. Fig. 3 shows the mean score as a function of exposure duration and

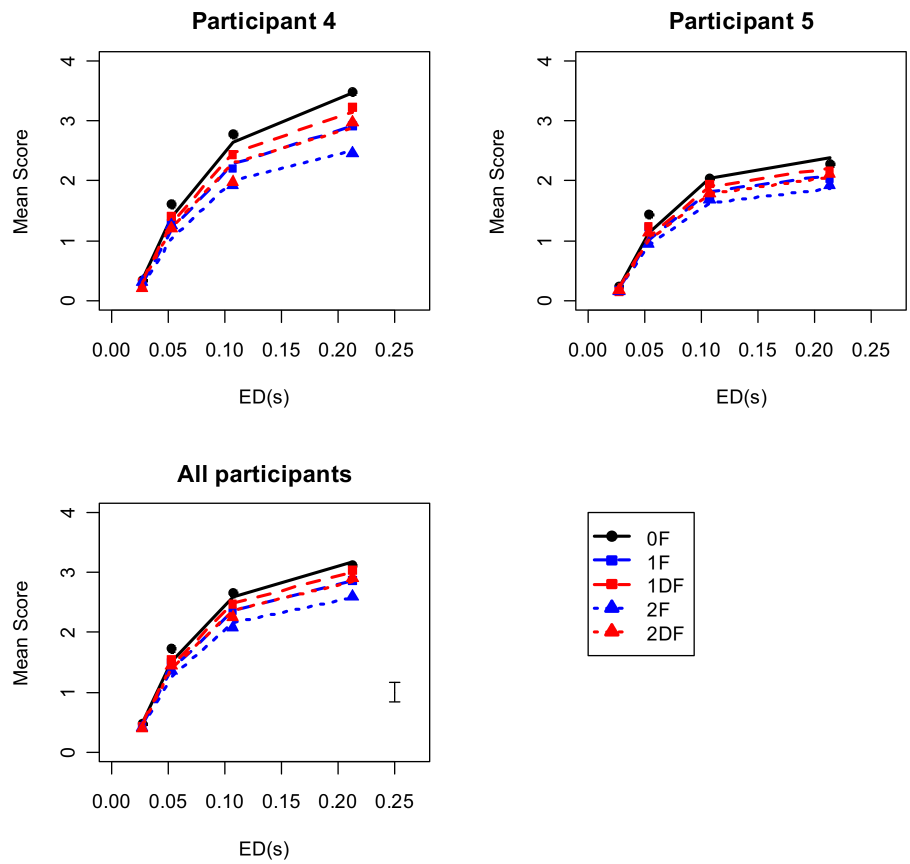

Fig. 3. The means scores as a function of exposure duration and the number and color of the task-irrelevant flankers in Experiment 1. Symbols indicate observed values and lines indicate predicted values derived from TVA. Black filled circles and black solid lines represent trials with out any flankers present. Blue symbols and lines represent trials where the task-irrelevant flankers were presented in the same color as the targets. Red symbols and lines represent trials where the flankers were presented in a different color from the targets. Filled squares and dashed lines represent trials with only one flanker. Filled triangles and dotted lines represent trials with two flankers present. The error bar in the lower right corner of the plot representing all participants indicates the average standard error of the observed mean scores across participants. (For interpretation of the references to color in text, the reader is referred to the web version of the article.)

the number and type of task-irrelevant flankers. The results are shown for two representative participants as well as the average across all six participants. Similar to previous results (e.g. Shibuya & Bundesen, 1988), mean scores were close to zero for the shortest exposure duration and rose quickly towards an asymptote corresponding the VWM capacity of the participant around 200 ms ($F(3,15) = 64.26$, $p < .0001$).

A clear reduction in the mean number of reported targets was found when the central four targets were accompanied by flanking letters ($F(2,10) = 32.67$, $p < .0001$). Moreover, a clear effect of varying the number of task-irrelevant flankers systematically reduced the mean score as the number of flankers was increased from one to two ($F(1,5) = 21.70$, $p < .01$). This effect was modulated when the flankers were presented in a different color from the task-relevant target letters, thus enabling the participants to ignore the flankers more efficiently ($F(1,5) = 47.19$, $p < .001$).

Specifically, when looking at the results from trials with the longest exposure duration of 213 ms, all six participants showed a decrease in mean score when the number of flankers was increased from zero to one and two flankers, yielding a significant negative trend as a function of number of flankers ($t(11) = -6.38$, $p < .001$). The mean scores across the three conditions were 3.12, 2.87, and 2.59 letters when the number of flankers, were zero, one, and two, respectively. A similar pattern of results was found for trials with an exposure duration of 107 ms.

We also measured the effect of the color of the task-irrelevant flankers. Again, we found a systematical effect in all six participants, where the mean score increased when the discriminability between task-irrelevant flankers and task-relevant target letters were increased thus helping participants to ignore the flankers. Across the six participants, the mean score increased from 2.87 to 3.03 letters for displays with a single flanker presented at 213 ms ($t(5) = 5.32$, $p < .005$) and from 2.59 to 2.91 letters for displays with two flankers presented ($t(5) = 6.11$, $p < .005$). A similar pattern of results was found for trials with an exposure duration of 107 ms.

4.2.2. Errors

The mean number of error reports of the task-irrelevant flankers was .082 (SD = .16) and the mean number of error reports of letters not shown in the display was .16 (.084).

4.2.3. Data fitting

To test the hypothesis of how processing capacity is allocated according to TVA, we fitted a five parameter version of the model to the data of each participant (cf. Kyllingsbæk, 2006; Shibuya & Bundesen, 1988). The fitted parameters were: C, the fixed total processing capacity measured in letters/second, K, the storage capacity of VWM, w_F, the attentional weight of a task-irrelevant flanker, α, the proportional reduction in attention weight of a task-irrelevant flanker when presented in a different color from the target letters, and finally, t_0, the smallest ineffective exposure duration.

The maximum likelihood estimates for the five parameters for each of the six participants are listed in Table 1. The model fitted the data well for all six participants yielding correlations between observed and predicted mean scores in the range of .986 and .998. Thus, the model was able to account for well above 97% of the vari-

Table 1
Estimates for the five TVA parameters for each participant in Experiment 1.

Participant	C	K	w_F	α	t_0
1	51.9	3.60	0.525	.610	.013
2	49.2	2.34	0.311	.448	.009
3	67.3	4.96	0.721	.376	.025
4	51.7	3.71	0.855	.423	.020
5	45.3	2.43	0.510	.546	.022
6	65.5	3.77	0.245	.236	.013

ance in all participants (range 97–99.5%). The parameter estimates correspond well to similar estimates found previously both regarding processing capacity C at about 25–60 Hz, VWM capacity K of 3–5 letters, and the smallest ineffective exposure duration, t_0, at about 20 ms (e.g. Bundesen, 1990; Finke et al., 2005; Kyllingsbæk, 2006; Shibuya & Bundesen, 1988).

The estimates of the relative attentional weight of a flanker compared to a target letter, w_F, and the proportional reduction of the flanker effect, α, are of particular interest to the present study. We found a mean attentional weight of .528 indicating that on average the flanker captured about 50% of the processing capacity that was allocated to each of the four target letters. There were, however, substantial individual differences: The most efficient participant only allocated about 25% of the capacity of a target to each flanker. At the other extreme, the least efficient participant allocated 86% of the capacity of a target to each flanker, i.e. nearly the same amount of attention was devoted to a flanker compared to the task-relevant letters by this participant.

The mean value of α was estimated to .440 across the six participants (range .236–.610). This value indicates that the participants were able to reduce the effect of the task-irrelevant flankers substantially when given an extra cue (i.e., color) to distinguish task-relevant from task-irrelevant stimuli. Notably, the most efficient participant measured by the value of w_F was also the participant with the lowest estimated value of α. The attentional weight of a flanker with a different color was reduced to $w_F \times \alpha = .245 \times .236 = .058$. In other words, this participant was able to reduce the effect of the task-irrelevant flankers to only 6% compared to the task-relevant letters when the flankers were presented in a different color than the targets.

4.3. Discussion

In Experiment 1, we held perceptual load constant by presenting four target letters in a partial report task with a varying number of task-irrelevant flankers. The number of flankers varied between zero, one, and two and the color of the flankers was either identical to or different from the target letters. We found clear effects in terms of reduced mean number of reported targets when the number of flankers was increased from zero, to one or two flankers. Further, the effect of the number of task-irrelevant flankers was strongly modulated by the discriminability between targets and flankers. When the flankers were presented in a different color, the mean number of letters reported increased significantly.

The results of Experiment 1 are in clear support of the predictions of TVA. We found strong correlations between the predicted performance of a five-parameter version of TVA and the observed data in Experiment 1. Further, the effects of varying the number of task-irrelevant flankers and their color was straightforwardly explained by two parameters of the model, the relative attentional weight allocated to each task-irrelevant flanker and the relative reduction of this effect when the flankers differed in color from the target letters. Further, fitting the TVA model to the data gave direct estimates of processing capacity in terms of number of letters processed per second, VWM capacity, and least effective exposure duration (perceptual threshold).

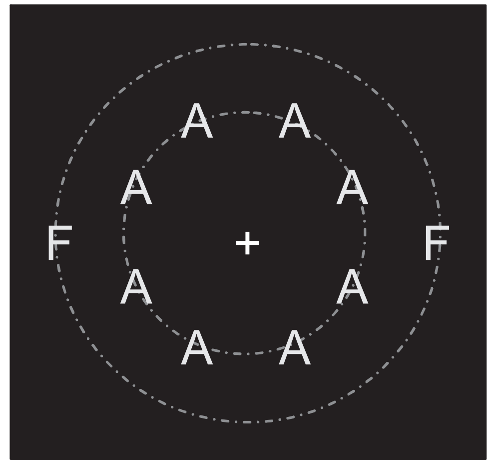

Fig. 4. The stimulus locations used in Experiment 2. Task-relevant locations are indicated by A and task-irrelevant flanker locations by F.

The results however are difficult to reconcile with LT because of the assumption of two steps of capacity allocation. In the present experiment, because perceptual load was held constant, the capacity allocated to the four targets should be constant across the various flanker conditions. Further, the allocation of processing capacity in the second step where unused capacity 'spills over' to task-irrelevant flankers should not effect allocation of capacity to the target letters which, according to LT, is done prior to the capacity spill-over step. Thus, our manipulations of the number of flankers and their discriminability should have little effect on the mean number of reported targets according to LT. However, we found a clear effect when (1) we compared performance where flankers were absent or present and (2) a modulation of this effect when the discriminability of the flankers was varied. Both effects were predicted by TVA, but not LT.

5. Experiment 2

In Experiment 2, we varied the perceptual load in the partial report task by presenting between two and eight letters to be reported. Again, one or two task-irrelevant flankers were presented to the left and/or right of the task-relevant stimuli. We were thus able to investigate the joined effect of varying perceptual load and the impact of the number of task-irrelevant distractors in partial report.

5.1. Methods

5.1.1. Participants

Six undergraduate students (four female) from the University of California, Santa Barbara participated in the experiment. The participants received course credit for their participation and were naïve with respect to the purpose of the experiment. All participants had normal or correct-to-normal visual acuity.

5.1.2. Stimulus material

The stimulus material was similar to the one used in Experiment 1. A total of eight relevant stimulus positions and two irrelevant flanker positions were used. The relevant stimulus positions were located equally spaced around the perimeter of an imaginary circled centered at fixation with a radius of 3.91 degrees of visual angle. The irrelevant flanker positions were located left and right of fixation at a distance of 5.85 degrees of visual angle from fixation. A sketch of the stimulus positions are shown in Fig. 4. The mask, fixation cross, and background of the stimulus displays were similar to Experiment 1.

5.1.3. Procedure

The color of both the task-relevant target letters and the task-irrelevant flankers were the same for each participant. Half of the participants saw red letters and the other half blue letters.

Each trial began with the presentation of the fixation cross in the center of the screen. When properly fixated, the participant initiated the presentation of between

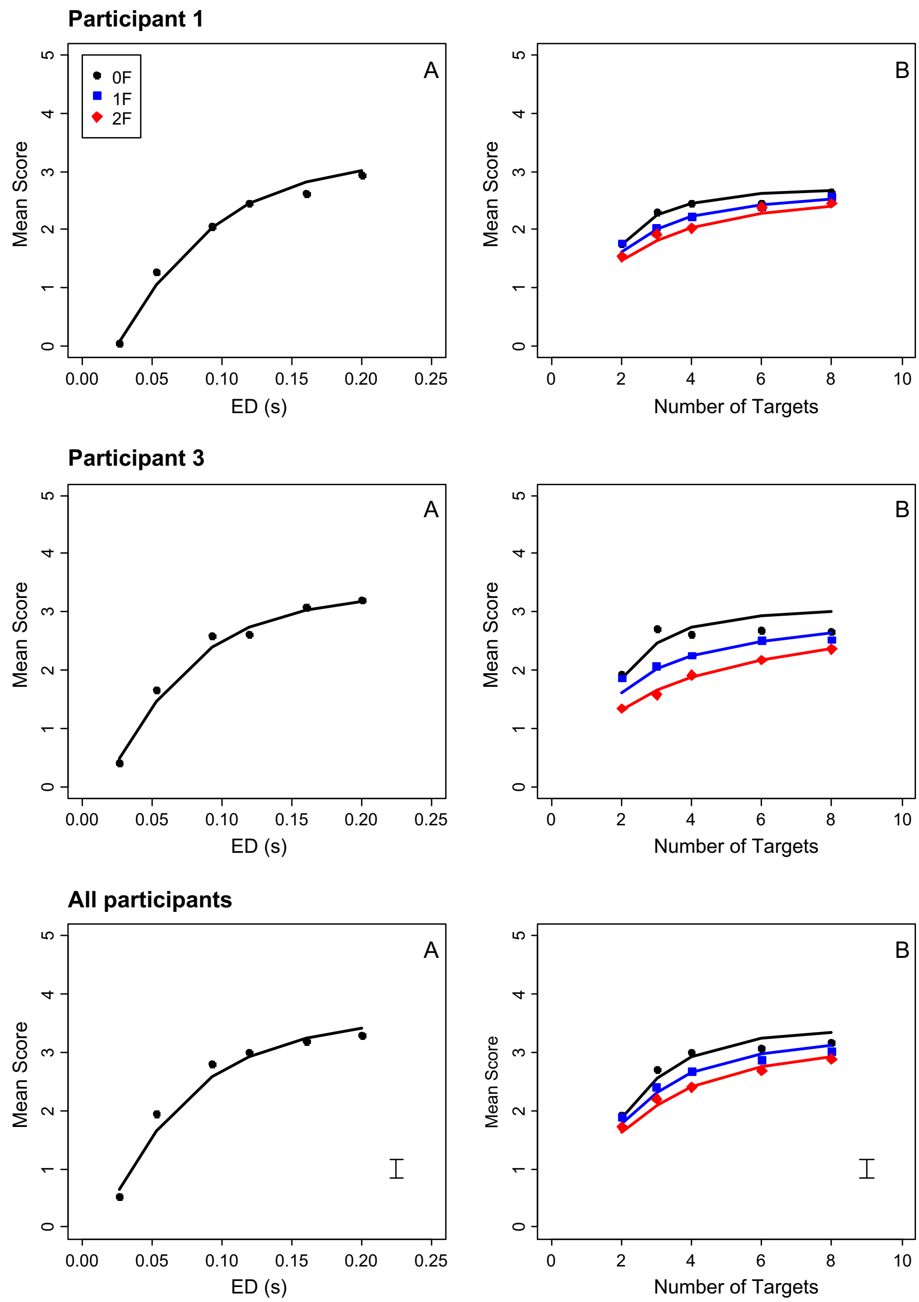

Fig. 5. The mean score as a function of exposure duration (Panels A) and number of targets to be reported (Panels B). Panels A: solid black circles represent observed values and solid lines represent predicted values of TVA. Panels B: black circles represent trials with no flankers presented, blue squares represent trials with a single flanker present, and red diamonds represent trials with two flankers in the display. Solid lines represent predicted values derived from TVA. The error bars in the lower right corners of the plots representing all participants indicate the average standard error of the observed mean scores across participants. (For interpretation of the references to color in text, the reader is referred to the web version of the article.)

two and eight target letters presented in a random subset of the eight relevant stimulus positions. Along with the target letters, none, one, or two irrelevant flanking letters were presented. After the presentation of the stimulus letters, 10 pattern masks were presented at the eight relevant and two irrelevant stimulus positions. The exposure duration of the stimulus letters varied between 27 and 200 ms. The exposure duration of the masks was 500 ms. Again the participants reported as many of the targets letters as possible at the relevant stimulus positions ignoring the flanking letters if present in the display (partial report).

5.1.4. Design

Three different flanker conditions were used: (1) no flanking stimuli, (2) one irrelevant flanker presented either to the left of right of fixation, (3) two irrelevant flankers one to the left and one to the right. Each of the three conditions was run with five different variations of the number of relevant target stimuli, 2, 3, 4, 6, or 8 targets. In all these conditions the exposure duration of the stimulus letters was fixed at 120 ms. In addition, the condition with no flankers and four targets were run while the exposure duration was varied at 27, 53, 93, 160, and 200 ms. The order of trials was randomized across blocks of 600 trials. A total of 240 repetitions of the resulting 20 different trial types yielding a total of 4800 trials per participant. The trials were run on eight separate sessions. The participants were familiarized with the stimulus procedure in two practice trial blocks.

5.2. Results

5.2.1. Mean scores

As in Experiment 1, we calculated the number of correctly reported target letters in each trial and from these the mean number of correctly reported targets (mean score) for each of the 20 different trial types. Panels A in Fig. 5 show the mean score as

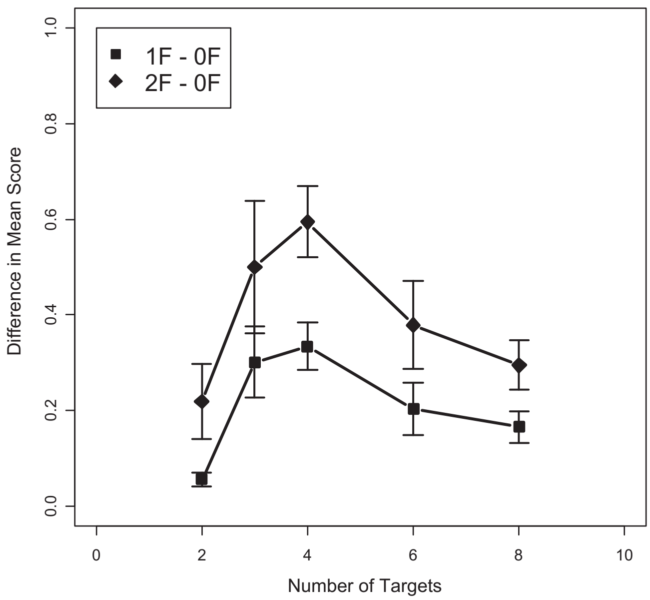

Fig. 6. The difference in mean number of reported targets (means score) between trials with one flanker in the display and trials where no flankers were presented (squares) and between trials with two flankers in the display and trials where no flanker were presented (diamonds). Error bars indicate standard error of means.

a function of exposure duration for the experimental conditions where four targets were shown without any flankers. Panels B in Fig. 5 show the mean score as a function of number of task-relevant letters (perceptual load) in the conditions where the number of targets was varied while the exposure duration was held constant at 120 ms.

Similar to Experiment 1, the mean score rose as a function of exposure duration (see Panels A) and asymptoted at the VWM capacity by the longest exposure duration. A clear and distinct pattern results was found when varying perceptual load (see Fig. 5, Panels B). As perceptual load increase, mean score increased ($F(4,70) = 69.16$, $p < .0001$). Further, a clear effect of the number of flankers was found, lowering the mean score with each additional flanker ($F(2,70) = 21.11$, $p < .0001$). In all participants the difference between the three conditions with none, one, or two flanking letters showed a consistent pattern (see Fig. 6): At a low perceptual load (2 target letters) the difference in performance between the three conditions was small. At intermediate perceptual load (3–4 target letters) the difference was largest indicating the strongest interference from the task-irrelevant flankers. Finally, at high perceptual load (6–8 target letters) the difference in performance decreased again. This interpretation was confirmed by a significant quadratic trend in the mean score as a function of perceptual load for both displays with a single flanker ($F(1,22) = 10.24$, $p < .005$) and two flankers ($F(1,22) = 9.61$, $p < .01$).

5.2.2. Errors

The mean number of error reports of the task-irrelevant flankers was .13 (SD = .10) and the mean number of error reports of letters not shown in the display was .20 (.081).

5.2.3. Data fitting

We fitted the results of Experiment 2 with a four parameter version of TVA for each participant. Because the discriminability of the task-irrelevant flankers was not manipulated in Experiment 2, the α parameter was not needed to fit the data of this experiment. The fitted parameters were: C, the fixed total processing capacity measured in letters/second, K, the storage capacity of VWM, w_F, the relative attentional weight of a task-irrelevant flanker, and finally, t_0, the smallest ineffective exposure duration. The maximum likelihood estimates for the parameters for each of the six participants are listed in Table 2. Again, the model fitted well yielding correlations between observed and predicted mean scores in the range of .948 and .991, thus accounting for 90–98% of the variance in the observed mean scores. As in Experiment 1, the parameter estimates of processing capacity, C, VWM capacity, K, and the smallest ineffective exposure duration, t_0, corresponded well with previous findings.

Table 2
Estimates for the four TVA parameters for each participant in Experiment 2.

Participant	C	K	w_F	t_0
1	44.2	3.24	0.482	.025
2	74.6	4.53	0.439	.017
3	50.7	3.37	1.151	.017
4	53.3	3.58	0.743	.009
5	58.0	4.34	0.521	.005
6	51.0	3.41	0.266	.010

In Experiment 2, the parameter of most interest was the relative attentional weight of the task-irrelevant flankers, w_F. Compared to the estimates in Experiment 1, we found a larger variation ranging from .266 to 1.151. Thus the most efficient participant allocated only 27% processing resources to each task-irrelevant flanker relative to a target, similar to the most efficient participant in the first experiment. On the other hand, the least efficient participant in Experiment 2, allocated 15% *more* processing resources to each flanker compared to the task-relevant targets—leading to a dramatic effect of the number of flanking task-irrelevant stimuli (see Fig. 5).

5.3. Discussion

The results of Experiment 2 supported and extended the findings of the first experiment. We varied the perceptual load by systematically varying the number of target letters to be reported from 2 to 8 letters. Orthogonal to this, we varied the number of task-irrelevant flanking stimuli between zero, one, and two. We found that the mean number of reported letters (the mean score) increased with perceptual load and asymptoted close to the VWM capacity of the participants when no flankers were present. The effect of the flankers was to reduce the mean score systematically when the number of flankers was increased from zero to two. Strikingly, the decrease in performance was strongest for *intermediate* perceptual load (3–4 target letters) and weaker for low perceptual load (2 target letters) and for high perceptual load (6–8 target letters).

As with the results of Experiment 1, the results of Experiment 2 are difficult to explain using LT. Specifically, LT predicts little or no effect of varying the number of flanking stimuli on the processing capacity distributed to the task-relevant stimuli in the first step of allocation. Contrary to these predictions, we found consistent and strong modulation of the mean number of correctly reported items as a function of the number of presented flankers. Also, LT provides no obvious explanation that the strongest interference from the task-irrelevant flankers was found at intermediate perceptual load rather than in conditions with low perceptual load.

The results were readily explained by a four parameter version of TVA. Here the central parameter was the relative attentional weight on the task-irrelevant flankers. This parameter explains the variation in processing capacity allocated to the task-irrelevant stimuli and the resulting decrease in the mean number of reported targets. The strongest interference from the task-irrelevant flankers found at intermediate perceptual load may also be explained by TVA. When the perceptual load is at an intermediate level close to VWM capacity two combined forces interacts resulting in the stronger effect on the mean score: (1) the relative attention weight of the flankers, w_F, and the capacity of VWM, K. When perceptual load is at an intermediate level, the processing capacity allocated to the task-irrelevant flankers will be relatively high (cf. Eq. (1)). Thus the processing speed of the flankers will also be high. Consequently, the probability that a flanker will finish processing before VWM is filled up by task-relevant letters will also be high. Correspondingly, the probability that a task-relevant stimulus will be blocked from entering VWM by one or more flankers already encoded into VWM will be relatively high leading to the stronger effect seen in conditions with intermediate perceptual load (3–4 targets).

At low perceptual load (2 targets) the processing capacity allocated to task-irrelevant flankers will also be high, as LT also predicts. Here however, the limit of VWM capacity is not preventing task-relevant items from entering when task-irrelevant flankers are already encoded. The effect of presenting either one or two task-irrelevant flankers will be minimal if there are enough resources to processes the task-relevant stimuli. Important is also that we used neutral task-irrelevant flankers which interfered minimally with report of task-relevant letters once encoded into VWM.

At high perceptual load (6–8 targets) processing resources allocated to the flankers will be relatively small due to the increase in the number of task-relevant items leading to a larger denominator in Eq. (1). This argument is similar to the decrease in interference from incompatible flankers predicted at high load by LT. However in the present paradigm the VWM capacity is also critical because the effect on mean score performance is dependent not only on processing capacity, but also on whether one or more flankers enter VWM before it is filled by task-relevant stimuli.

6. General discussion

In two partial report experiments we tested key assumptions of how visual processing capacity is allocated according to both LT and TVA. In the first experiment we manipulated the number of neutral task-irrelevant distractors and their discriminability from the target stimuli while holding perceptual load constant. Since LT assumes two steps of processing, the first for task-relevant and the second for task irrelevant stimuli, the number and discriminability of task-irrelevant distractors should have little effect on allocation of attention to the task-relevant stimuli in the first step. However, we found a consistent effect on the mean number of reported targets of both the number of task-irrelevant distractors and their discriminability from the targets.

In the second experiment, we further investigated the effect of varying the number of task-irrelevant distractors, but unlike Experiment 1, perceptual load was manipulated systematically by varying the number of targets to be reported from 2 to 8 letters. Again, we found consistent effects of the number of task-irrelevant distractors on the number of reported targets (mean score). Further, the effect was strongest at *intermediate* levels of perceptual load (3–4 letters). This modulation of the effect on mean score seemed to be the result of a combined effect of perceptual load and VWM capacity indicating that a complete explanation of perceptual load has to encompass both mechanisms of capacity allocation and limits in VWM capacity.

Though the issue of capacity allocation is central to LT, it does not provide a detailed computational account of the basic constituting mechanisms. The Theory of Visual Attention (TVA; Bundesen, 1990, 1998) provides such a detailed computational account of how capacity allocation is accomplished in relation to the task demands of the person. Further, the theory explains the complex interaction between visual processing capacity and visual working memory (VWM) which we will elaborate below.

In TVA, visual processing capacity is allocated to possible categorizations of objects in the visual field in a single step. Formally, the rate of processing for each such categorization, defined as "object x has feature i", is given by the following *rate equation*:

$$v(x, i) = \eta(x, i)\beta_i \frac{w_x}{\sum_{z \in S} w_z}. \tag{2}$$

The first term, $\eta(x, i)$, is the strength of the sensory evidence that x belongs to category i. The second term, β_i, is a perceptual decision bias associated with category i ($0 \le \beta_i \le 1$). The third term is the relative attention weight of object x—that is, the weight of object x, w_x, divided by the sum of weights across all objects in the visual field, S.

Attentional weights are defined in the *weight equation*:

$$w_x = \sum_{j \in R} \eta(x, j)\pi_j, \tag{3}$$

where R is the set of all visual categories, $\eta(x, j)$ is the strength of the sensory evidence that object x belongs to category j, and π_j is the pertinence of category j. By Eq. (3), the attention weight of an object is a weighted sum of pertinence values. The pertinence of a given category enters the sum with a weight equal to the strength of the sensory evidence that the object belongs to the category.

Processing capacity, C, is simply defined as the sum of all the rates of processing across all objects and all categories:

$$C = \sum_{x \in S} \sum_{i \in R} v(x, i), \tag{4}$$

where S is the set of all objects in the visual field, and R is the set of all visual categories. Thus in TVA, processing capacity has an explicit and quantitative definition.

6.1. The interaction of perceptual load and VWM capacity

According to TVA, the likelihood that a task-relevant object in the visual field becomes available for conscious report is dependent on several factors. Here, we will focus on the interplay between attentional weights, processing capacity, and VWM capacity. Consider specifically, letters in a partial report task similar to the one used in the present experiments. Task-relevant letters given a high attentional weight will be allocated a larger proportion of the processing capacity, thus the rate of processing of categorizations from these objects will be high (cf. Eq. (2)) and the relevant letters will be more likely to enter VWM. Thus both the attentional weight and the total amount of processing capacity determine the likelihood that a target letter is available for report.

When the perceptual load is increased by increasing the number of task-relevant elements, the denominator in the ratio of attentional weight in Eq. (2) becomes larger. This in turn leads to lower processing rates of both individual task-relevant and task-irrelevant stimuli. However, if the number of task-irrelevant distractors is held constant while the number of task relevant increases (i.e. the perceptual load) the summed capacity allocated to task-relevant items will increase and the capacity allocated to task-irrelevant distractors will decrease (see Fig. 1B). Consequently, the effect of increasing perceptual load is to reduce the influence of task-irrelevant distractors also predicted by LT.

However, VWM capacity also plays a role in determining the consequences of perceptual load according to TVA. The reason is that task-relevant items may be blocked from entering VWM if slots in VWM are already occupied by task-irrelevant stimuli. Thus if task-irrelevant distractors are allocated enough processing resources to win the processing race towards VWM and enter before VWM is filled up by task-relevant stimuli, other task-relevant stimuli will be blocked from being encoded. The likelihood that a task-irrelevant distractor enters VWM before it is filled by task-relevant stimuli is highest when perceptual load is low. However, when perceptual load is very low, and the total number of stimuli (both task-relevant and task-irrelevant) is below VWM capacity, all stimuli may enter VWM if they finish processing. Thus at very low load, TVA predicts a reduced influence of the task-irrelevant distractors. On the other hand, TVA predicts that the effect should be largest at *intermediate* perceptual load where processing capacity allocated to task-irrelevant distractors is relatively high and VWM slots are likely to be blocked by task-irrelevant flankers entering VWM before it is filled up by task-relevant stimuli. Exactly this pattern of results was found in Experiment 2 when perceptual load was varied between 2 and 8 items.

Lavie, Hirst, De Fockert, and Viding (2004) proposed an extension of LT to include the domain of cognitive control. Contrary to high perceptual load, which may help prevent interference from task-irrelevant distractors, high cognitive load introduced by increased working memory (WM) demands or adding a second task increases interference from task-irrelevant distractors. When cognitive load is low on the other hand, these resources may alleviate interference from task-irrelevant distractors. Note however that the effects of cognitive load assumed in the extension of LT are different from the effects of VWM capacity derived from TVA that we outlined above. The effects that TVA predicts are related to how task-irrelevant distractors may block task-relevant stimuli from entering VWM or themselves being blocked from entering VWM. In contrast LT assumes that cognitive load effects performance when task-irrelevant distractors have already entered WM and are competing for response selection.

6.2. The effect of dilution and perceptual load

In the Introduction, we described the results of Benoni and Tsal (2010; Tsal & Benoni, 2010) showing that dilution may account for the effects of flanker interference rather than perceptual load. We believe that the results of Benoni and Tsal as well as the classical compatibility effects on RT in visual search paradigms explained by LT may be accounted for within the general framework of TVA. Similar to our interpretation of the present results, the effects may be explained for by a combination of target–distractor discriminability, which influences the efficiency of attentional resource allocation, as well as the effect of limits in processing capacity and VWM capacity represented by parameters C and K in TVA. For instance, if one assumes that the response time modulations occur because both the target and the task-irrelevant flanker enter VWM, but that on incompatible trials they compete for response and on compatible trials they collaborate then the classical interaction of perceptual load and flanker congruency predicted by LT may also be predicted by TVA. Specifically, when load is low because only a few stimuli are presented in the visual field (e.g. when only the flanker and the target are presented), a relatively large proportion of processing capacity will be allocated to the flanker and access to VWM will be easy. Thus the flanker will finish processing quickly and have a high probability of entering VWM. Consequently, the flanker will have ample opportunity to compete or collaborate with the target for responding. When the perceptual load is high, less processing resources will be allocated to the flanker because resources are now also allocated to the neutral task-relevant distractors in the search array. Also, access to VWM will be much more limited due to the likelihood of task-relevant distractors entering along with the target thus filling up VWM. The combined effect is that the flanker will be blocked from entering VWM and is thus not able to compete with the target for response. Because a large proportion of the processing capacity will be allocated to the neutral distractors the capacity allocated to both the target and the flanker will be lower than the processing capacity allocated in the low load conditions, thus reaction time will be generally slower when perceptual load is high.

How may TVA account for the effect of dilution found by Benoni and Tsal (2010)? In this instance, the neutral task-relevant distractors in the search display are presented in a different color than the target and the flanker. According to TVA, attentional weights may then be set differentially for the neutral distractors, the target, and the flanker by adjusting the relevant pertinence values in the weight equation (cf. Eq. (3)). To minimize interference from the flanker and minimize reaction time, the attentional weight of the target should be set high and the attentional weight of the flanker as low as possible. Further, by adjusting the attentional weight of the neutral distractors to an intermediate level between the weight of the flanker and the target, the subject should be able to (1) encode the target quickly in to VWM leading to fast reaction times and just as important (2) encode enough neutral distractors to fill up VWM thus blocking the flanker from being encoded. The result of this strategy will be a combination of fast reaction times to the target, but without the negative effect of the flanker entering VWM seen in condition of low load. We plan to explore this conjecture in the future by extending our TVA analyses to modeling compatibility effects on RTs in visual search paradigms similar to those of Lavie (1995) and Benoni and Tsal (2010).

Finally, we also note that the dilution hypothesis cannot completely account for the results found in Experiment 2 of the present paper. As shown in Fig. 6, we found an increase followed by a decrease of the interference effect from the task-irrelevant flankers as a function of display size. Similar to the effect of perceptual load predicted by LT, the effect of dilution should be monotonically increasing with display size resulting in a corresponding monotonically decreasing effect of the task-irrelevant flankers.

6.3. Processing capacity and receptive field sizes of visual neurons

TVA has recently been extended in a neural theory of visual attention (NTVA) to account for data from single cell recordings using the same basic equations. Thus the theory now bridges the gap between psychology and neurophysiology (Bundesen et al., 2005; see also Bundesen, Habekost, & Kyllingsbæk, present issue). At the neural level, filtering is implemented as a mechanism that allocate neurons in the visual system to process information from attended objects, so that the probability of a particular neuron being allocated to process object x is equal to the ratio given in Eq. (1). As described above, TVA defines processing capacity, C, as the summed processing rates across all objects and categories. Correspondingly, processing capacity is defined as the summed activity of all visual neurons in NTVA. Thus NTVA also, gives an explicit and quantifiable definition of visual processing capacity, but now at the neural level. Interestingly the new definition of visual processing capacity in NTVA links visual receptive field sizes closely to visual processing capacity. Thus at the highest level of the visual system where the receptive field cover most of the visual field most visual objects are competing for the same processing resources (i.e. neurons). However, at lower levels of the visual system where receptive fields are small, competition for processing resources/neurons is local because it is confined to only objects that are within the receptive field of the neurons. Thus at lower visual areas, processing capacity may be seen as distributed. At the lowest level, receptive fields may be so small that often few or even only a single stimulus is within the classic receptive field of each neuron. When this is the case processing capacity may be viewed as close to unlimited at that particular level (see also Kyllingsbæk, Valla, Vanrie, & Bundesen, 2007; Torralbo & Beck, 2008).

7. Conclusions

We have shown that allocation of processing capacity is most likely a one step process where processing resources are distributed across both task-relevant and task-irrelevant stimuli in the visual field. This mode of operation is in clear contrast to one of the core conjectures of load theory of Lavie (1995) that assumes that allocation of processing capacity is a two step process where capacity is first allocated to task-relevant stimuli and only afterwards to task-irrelevant distractors. In contrast to this, the theory of visual attention by Bundesen (1990) assumes a single step of capacity allocation and further makes quantitative predictions of the interaction of visual processing capacity and visual working memory capacity. Furthermore, the neural extension of Bundesen's theory, NTVA, explains how processing capacity is implemented at the neurophysiological level (see Bundesen et al., 2005; Kyllingsbæk et al., 2007).

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