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Adaptation facilitates change detection even when attention is directed elsewhere

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Abstract

After several seconds of adaptation to a visual array of randomly oriented Gabor patterns, observers can detect and localise a change in the orientation of one of these Gabors, even when the change is preceded by a blank inter-stimulus interval (Morgan & Solomon, 2019a). Previously, we reported that the ability to detect this changed element was unaffected by distracting observers' attention away from the adapting stimuli by making them look for rare conjunctions of shape and colour at the central fixation point. That finding is replicated in the current paper, and augmented by a demonstration of the attentionally demanding nature of the conjunction search: it significantly impairs discrimination between adapting arrays in which either many or few items briefly lose contrast. Consequently, we can be certain of adaptation's immunity to the withdrawal of attention, when assessed objectively (i.e. with a performance-based metric).

Introduction

Wohlgemuth (1911) wondered whether selective attention was needed for the motion aftereffect (MAE). In a design well ahead of its time, he adapted to a peripheral moving stimulus, while simultaneously carrying out a central task involving the rapid, serial, visual presentation (RSVP) of numbers. The central task had no effect on the MAE, leading Wohlgemuth to conclude that motion adaptation did not require scarce attentional resources.

Wohlgemuth's (1911) conclusion can be considered unsafe, because his assessment of motion adaptation was based on a rather subjective and arguably artificial metric: duration of the MAE. As noted previously (e.g. Morgan, 2011), It is hard to know when a stimulus has stopped moving, particularly when it is stationary to begin with. The desire for a more objective assessment of the MAE led us to the visual search paradigm.

Following adaptation to a spatially distributed array of Gabor patterns (hereafter "Gabors"), each of which is the product of a drifting luminance grating and a stationary, 2-D Gaussian window, an identically distributed post-adaptation array of static circles will appear to move. This is the MAE. As a measure of its strength, we used the response time for an observer to correctly identify the one circle in the post-adaptation array that actually was moving (Mogan & Solomon, 2019a) by positioning the mouse cursor over the moving stimulus and clicking.

In the aforementioned MAE search, adaptation impaired performance; it increased response times. We also adopted the visual search paradigm for a “change detection” task in which adaptation facilitated performance. In one version of this task (“the basic design,” illustrated in Figure 1), observers were required to select the one new item in a post-adaptation array of Gabors. This target Gabor was perpendicular to the adaptation array’s Gabor in that position. All the remaining, non-target Gabors were identical to the spatially corresponding Gabors in the adaptation array. High levels of performance with the basic design were found to correlate with low levels of performance (long response times) in the MAE search (Mogan & Solomon, 2019a). Thus, co-opting the visual search paradigm seems to allow not only an objective assessment of MAE strength, but an unbiased, performance-based assessment of orientation-selective adaptation as well.

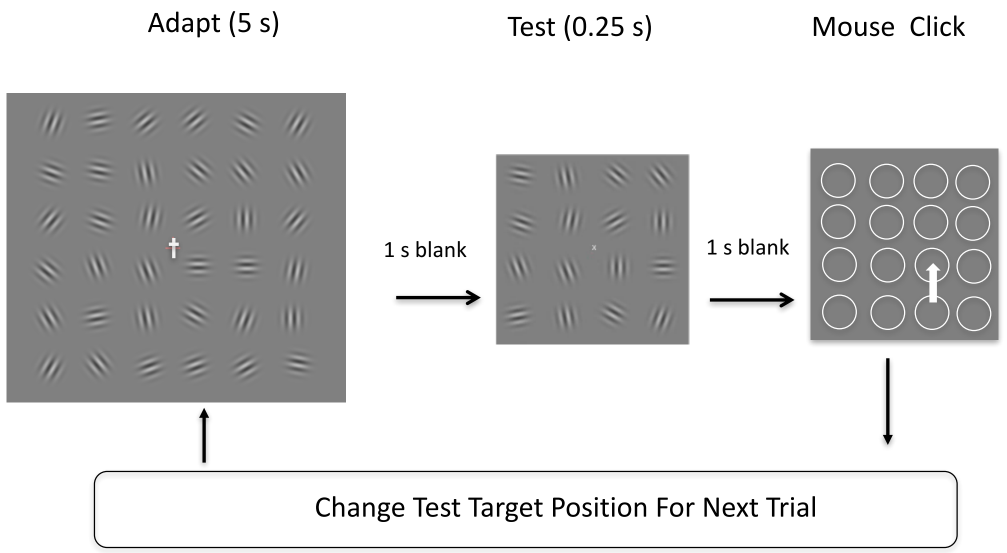


Figure 1. The basic design. The adaptation array on the left was exposed for 5 s while observers fixated on the central cross. Gabors flickered at a rate of 7.5 Hz to prevent the build-up of afterimages. During adaptation observers fixated the asymmetrical cross in the centre and reported rare conjunctions of its contrast and shape. After adaptation, the test array was presented for 0.25 s, before being replaced by a set of placeholder circles. Observers selected one of these circles by positioning the mouse cursor and clicking. The correct circle, which was in the position of the unique test Gabor that had been rotated 90 deg from its corresponding adaptor, disappeared after the click. This provided observers with feedback, enabling them to learn the task.

Like Wohlgemuth (1911) we sought to determine whether attention was needed for adaptation, and like Wohlgemuth we employed a central, RSVP task to distract attention away from adaptation. The specific task we employed was adapted from Schwartz, Vuilleumier, et al. (2005), who reported a reduction in the positive BOLD response in the peripheral areas of V1 when observers were required to detect rare conjunctions of shape and colour in central vision. Like Wohlgemuth we found no consistent effect of the central, distracting task on our measures of adaptation (Morgan & Solomon, 2019a), however (again, like Wohlgemuth) we offered no compelling evidence that our central task was actually effective at distracting attention away from the adapting stimulus.

In the current paper, we use a dual-task paradigm (Sperling & Melchner, 1978) to demonstrate the efficacy of our central task at distracting attention away from the adapting stimulus. First, in Experiment 1, we replicate and extend our previous finding. Not only does performance with the basic design remain unimpeded by execution of the central task, but performance on the central task does not improve when observers are allowed to forego subsequent visual search. Experiment 2 utilises the same stimuli as Experiment 1, but a variable number of Gabors in the adapting array simultaneously lose a fraction of their contrast. Observers are required to report whether this loss of contrast occurred in the majority of Gabors or merely a minority. Performance on this latter task is shown both to be impeded by as well as to impede concurrent execution of the central task for distracting attention.

General Methods

The basic design

The adaptation array comprised 6 x 6 equally spaced Gabors, with orientations randomly sampled from the uniform distribution between 0 and 180 deg (see Figure 1). Each Gabor was the product of a static, circular Gaussian envelope ($\sigma = 0.21$ deg) and the sum of two, oppositely drifting, sinusoidal luminance gratings (spatial frequencies: 3.75 cycles/degree, temporal frequencies: 7.5 Hz). The mean luminance and maximum Michelson contrast of each Gabor were 70 cd/m^2 and 0.2 respectively. Centre-to-centre spacing was 1.87 deg. To avoid possible edge effects, the outermost elements of the adapting array were omitted from the test array, leaving only the centre 4 x 4 elements.

Each trial began with a 5 s presentation of the adapting array. Observers were instructed to fixate a stationary point in the centre of the display, and to carry out a task based on additional stimuli presented there. The first adaptation period was followed, after 1 s, by a 0.25-s test. Change was introduced by rotating one of the Gabors 90 deg from its adapting orientation. After the test, the stimuli were replaced by a set of circular placeholders, and the observer used a mouse to click on the position of the target. To give feedback, the target's placeholder was switched off to show the target's position after the mouse click. After the mouse click, the screen went blank while the next set of Gabors was calculated (~1 s) and then the next adaptation array was presented. (In what we are calling "the basic design," orientations in the adapting array were re-sampled on every trial, cf. Experiment 1, Phase 2.)

Change detection is a somewhat unusual visual search task, because the target Gabor doesn't appear to have any discernibly different property such as more or less contrast than the other Gabors (Morgan & Solomon, 2019b), and we cannot discount the possibility that some observers may require training for successful change detection. Accordingly, we augmented target salience by delaying its onset with respect to that of the other 15 Gabors in the post-adaptation array. Within each block of 64 trials, 4 target delays were randomly interleaved: 0, 1, 2, and 4 video frames (0, 0.016, 0.032, and 0.066 s). The 0-delay condition allowed measurement of pure change detection.

The central RSVP task for distracting attention

To take attention away from the adapting stimulus during adaptation, and to prevent active memorisation of the stimuli, observers carried out an attentionally demanding task, based on stimuli appearing at fixation. In the centre of the adaptation array, superimposed on the white fixation point, a series of asymmetrical crosses were presented for the first 3.32 s of each 5 s adapt period at a frequency of 1.5 Hz, allowing 5 crosses per trial. The purpose of the (1.68 s) cross-free period at the end of adaptation was to ensure that the observer would not be required to make a response during the test stimulus. The crosses were either upright (as in Figure 1) or inverted, and could be either high contrast white, high contrast black, low contrast white, or low contrast white. (We chose contrast rather than colour as a cue because one of the observers was colour anomalous.) Each cross was selected independently from the probability mass function described by the numbers in Table 1. At the end of the adaptation period, a low frequency tone was presented if the observer either failed to indicate the presence of a rare conjunction or if the observer indicated a rare conjunction when none had been presented. A high frequency tone was given for a "hit."

Observers were instructed to press a key as soon as they saw one of the rarer conjunctions of contrast and orientation (e.g. a low contrast white, upright cross, see Table 1).

	High contrast black	Low contrast black	Low contrast white	High contrast white
Upright	0.225	0.025	0.025	0.225
Inverted	0.025	0.225	0.225	0.025

Table 1. Probabilities for each conjunction.

Experiment 1: Change detection shares no resources with the central RSVP task

Methods

Experiment 1 was run in two phases. In Phase 1, there were three different conditions: Dual Task, Search Only, and No Change. In the Dual Task and No Change conditions, observers were required to perform the central RSVP task for distracting attention. In the Search Only condition, observers could simply ignore the crosses. In the No Change condition, the target Gabor did *not* rotate 90 deg from its adapting orientation, leaving only temporal delay as a cue to target identity. The number of 64-trial blocks completed by each observer in each condition is given in Table 2. Within each phase of the experiment, different conditions were run in a pseudo-randomised sequence. However, Phase 1 was completed before Phase 2 was initiated.

Experiment	Phase	Condition	MM	JS	PL	RS
1	1	Search Only	5	5	5	5
1	1	Dual Task	5	5	5	5
1	1	No Change	5	5	5	5
1	2	Search Only	3	6	1	5
1	2	Dual Task	3	6	1	5
2		RSVP Only	8	4	6	4
2		Dual Task	6	4	5	4

2		Contrast Only	4	4	4	5

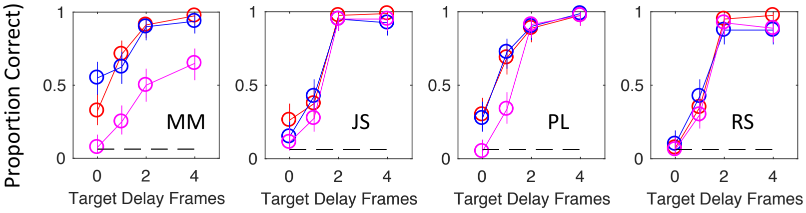
Table 2. Number of 64-trial blocks performed by authors MM and JS and naïve observers PL and RS in each Condition, Phase, and Experiment.

The Dual Task and Search Only conditions in Phase 2 were identical to those in Phase 1, except we decided *not* to re-sample the adapting orientations on every trial. This allowed adaptation to build up between trials, an effect previously documented to facilitate change-detection with shorter periods of adaptation (Morgan & Solomon, 2019a).

Results

Spatial search performances (proportions correct) are illustrated in Figure 2. First consider the leftmost symbols in each panel. These illustrate performances when there was zero delay between the target and the distractors. In Phase 1, even though adaptation was not allowed to build up between trials, three of our four observers (MM, JS, and PL) were able to perform at levels significantly above chance in both the Dual-Task and Search-Only conditions [in all cases, $\chi^2(1) > 6.7$, $p < 0.01$]. These proportions correct (i.e. for MM, JS, and PL) have been transformed into d-prime values (Green & Swets, 1966) for the attention operating characteristics (AOCs; Sperling & Melchner, 1978) in Figure 3. In Phase 2, all four observers were able to perform at levels significantly above chance in both of these conditions [again, in all cases, $\chi^2(1) > 6.7$, $p < 0.01$]. This confirms that target rotation ("relative novelty," as per Morgan & Solomon, 2019b) by itself can be a sufficient cue for detection. As RS did not perform significantly above chance with zero delay in Phase 1, we have used his Phase-2 data for the AOCs in Figure 3.

Phase 1 (Resampled Adaptors)



Phase 2 (Fixed Adaptors)

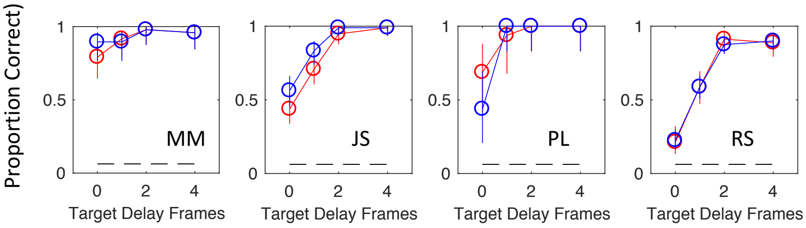


Figure 2. Spatial search results from Experiment 1. Red and blue symbols show proportions of correct response (vertical axis) in the Dual Task and Search Only conditions, respectively. Magenta symbols show data from the No Change condition. Error bars are Binomial 95% confidence intervals. Horizontal dashed lines indicate chance performance (6.25% correct).

Delay by itself was also a sufficient cue, as is evident from the magenta symbols, illustrating performance in the No Change condition. Nonetheless, in many cases (MM and PL in Phase 1 and all observers in Phase 2), target rotation significantly improved detection rates for at least one of the non-zero target delays. [When Dual Task and Search Only data are combined: $\chi^2(1) > 12.3$, $p < 0.002$ *after* Bonferroni correction.] On average (unweighted across all observers and both phases, but excluding target delays with which performance was perfect and thus d-prime infinite), target rotation produced an average increase in d-prime of 0.95. When weighted by number of trials, the average was 0.89.

The central RSVP task for distracting attention does not appear to have had any significant effect on spatial search. For each observer and each phase of Experiment 1, we compared spatial search results in the Dual Task and Search Only conditions in two ways. First, we collapsed the data across target delay to compare overall accuracies. This analysis suggests no significant effects (Chi-square and *p*-values appear in Table 3). Second, we tested the search results for each target delay separately. In all cases, $\chi^2(1) < 2.0$, $p > 1.6$ *before* Bonferroni correction. On average (unweighted across all observers and both phases, but excluding target delays with which performance was perfect), d-primes in the Dual Task were just 0.08 greater than d-primes in the Search Only condition. When weighted by number of trials, the average was 0.06.

	MM	JS	PL	RS
Phase 1	1.54 (0.21)	1.23 (0.27)	1.93 (0.16)	1.78 (0.18)
Phase 2	1.25 (0.26)	0.09 (0.76)	1.42 (0.23)	0.68 (0.41)

Table 3. Chi-square (twice the natural log llikelihood ratio) and *p*-values (in parentheses) in the likelihood-ratio test for a difference between search accuracies in the Dual Task and Search Only conditions.

To test whether preparation for spatial search may have affected performance in the central RSVP task, we compared performance in the Dual Task condition to performance in Experiment 2's RSVP Only condition, described below. These performances are illustrated in the top row of Figure 3. In this figure, error bars contain at least the notional equivalent of two standard errors. [Specifically, they contain 68% confidence intervals calculated using Efron and Tibshirani's (1993) BCα bootstrap.] Thus, any overlap between error bars can be interpreted as no significant difference (at the α = 0.05 level) between estimates of (d-prime) sensitivity. Using this criterion, no significant differences were found for observer JS, PL, and RS. This criterion does suggest a significant difference for MM, but note that he performed *better* in the Dual Task condition than in Experiment 2's RSVP Only condition. Thus, preparation for spatial search did not significantly impair any of our observers' serial, sequential searches for rare conjunctions of cross shape and contrast.

In summary, this AOC analysis indicates no competition for attentional resources between adaptation-induced change-detection and our central RSVP task (Sperling & Melchner, 1978): none of our observers performed either task better (i.e. with higher sensitivity) when the other task could be ignored. This is evident from the non-obtuse (i.e. right or acute) angles formed by the two line-segments in each of the upper panels in Figure 3.

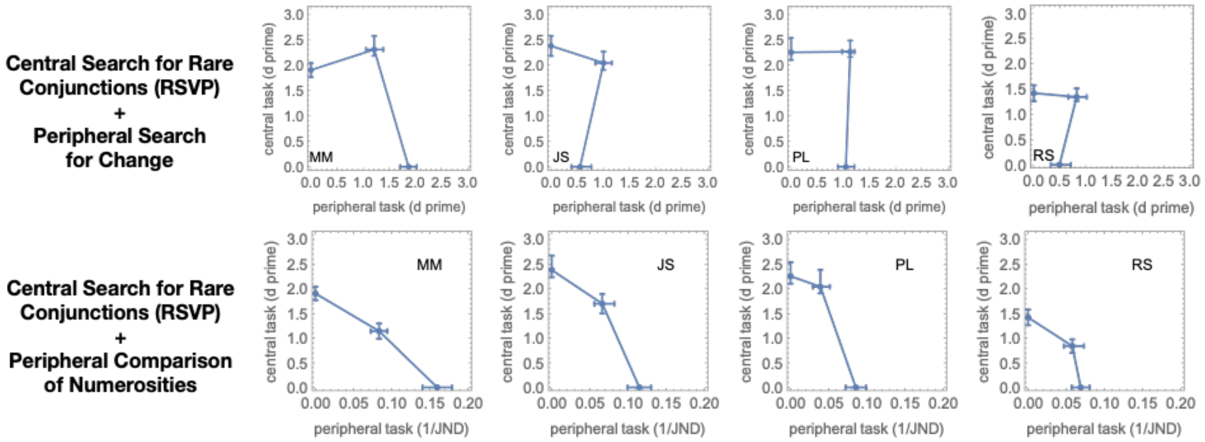


Figure 3. Attention operating characteristics. Error bars contain 68% confidence intervals.

Experiment 2: Numerosity discrimination does share resources with the central RSVP task

Method

The basic design was augmented by subtly manipulating stimulus contrast during adaptation. At a randomly selected time between 0 and 3 s after onset, half the contrast was removed from some (either 8, 13, 16, 20, 23, or 28) of the 36 adapting Gabors. Full contrast was restored to all adapting Gabors 3.32 s after onset (i.e. simultaneous with offset of the last coloured cross). At end of each adaptation period, the screen remained blank until the observer reported (by pressing the S or A key on the keyboard) whether there were more Gabors that did briefly lose contrast or whether there were more that did not. Observers received no feedback regarding the accuracy of this numerosity discrimination.

There were three different conditions: RSVP Only, Dual Task, and Contrast Only. In the RSVP Only and Dual Task conditions, observers were required to perform the central RSVP task for distracting attention. In the Contrast Only condition, observers could simply ignore the crosses. In the RSVP Only condition, observers were not required to make a numerosity discrimination. The number of 64-trial blocks completed by each observer in each condition is given in Table 2.

Results

Psychometric data (probability of reporting that the majority of Gabors briefly lost contrast vs. the number of Gabors that actually did lose contrast) from each observer and each condition (except RSVP Only) were maximum-likelihood fit with cumulative Normal distributions (not shown). We use the standard deviations of these best-fitting functions as our estimates of the just-noticeable differences (JNDs) between the numbers of Gabors that did and did not briefly lose contrast. Accordingly, we have adopted the reciprocal of JND as our index of observer sensitivity in our numerosity-discrimination task. These sensitivities are plotted in the bottom row of Figure 3.

Likelihood-ratio tests indicate greater sensitivities to numerosity differences when observers were allowed to ignore the central RSVP task. For MM, $\chi^2(1) = 14.7$, $p = 1.2 \times 10^{-4}$; for JS, $\chi^2(1) = 6.30$, $p = 0.012$; for PL, $\chi^2(1) = 7.14$, $p = 0.0075$; but for RS, $\chi^2(1) = 0.405$, $p = 0.52$. Furthermore, the error-bar test described in Experiment 1 suggests that when observers MM, JS, and RS (but not PL) were required to simultaneously monitor the central crosses and the adapting Gabors (i.e. in the Dual Task condition), their performances in the former task suffered significantly, when compared with the RSVP Only results.

In summary, this AOC analysis indicates a competition for attentional resources between numerosity discrimination and our central RSVP task (Sperling & Melchner, 1978): all four observers performed at least one of these tasks better (i.e. with higher sensitivity) when the other task could be ignored. This is evident from the obtuse angles formed by the two line-segments in each of the lower panels in Figure 3.

Discussion

We found that the central distracting task (detecting rare conjunctions of shape and contrast) during adaptation did not significantly affect the strength of that adaption, as measured by a subsequent (to adaptation) visual search task. This negative finding is consistent with previous reports by Wohlgemuth (1911) and by Morgan (2011, 2012, 2013), and especially by Morgan & Solomon (2019a), who used the same visual search task. It is not consistent with studies reporting that a high-load task during adaptation reduces the size of the subsequent MAE (Rees, Frith & Lavie, 1997; Taya, Adams, Graf & Lavie, 2009).

The facilitating effect of target delay in our Experiment 1 can be considered a limiting case of the target-preview effect (Watson & Humphries, 1997), where the target-containing set has just one element in it. As might be expected, our facilitation effect was found with delays two orders of magnitude less than those that were found effective by Watson and Humphries, who used larger set sizes.

Is it possible that attention enhances adaptation only when adaptation is measured subjectively (in “Type 2” paradigms; Sperling, Dosher, & Landy, 1990)? We think not, because both Wohlgemuth (1911) and Morgan (2011) used the Type 2 duration method of measuring the MAE and got negative results, in contrast to Rees, Frith, & Lavie (1997), who used the same method. If we put aside Type 2 measures, including measures of bias in a 2AFC task (Taya, Adams, Graf & Lavie, 2009), as being potentially contaminated by response and expectation biases (Morgan, Dillenburger, Raphael & Solomon, 2012), we should conclude, on the basis of Type 1 measures like visual search accuracy, that adaptation requires only minimal attentional resources, if any. This conclusion is reinforced by the finding in the present paper, that the central RSVP task had little-to-no effect on adaptation, but had a profoundly detrimental effect on a concurrent numerosity-discrimination in the periphery.

We would like to be explicit about some things we are *not* claiming. We are not claiming that change detection and numerosity discrimination are comparable in any way. The logic of our study does not require any similarity between these tasks. Required for our conclusion were the findings that the central RSVP and numerosity tasks shared attentional resources, while the central RSVP task and (concurrent) adaptation did not.

The central RSVP task must have tapped into a limited pool of attentional resources because it interfered with numerosity discrimination in Experiment 2. This task, the central RSVP task, was identical in both experiments. Thus, we contend that it must have benefit from attentional resources in Experiment 1, as well. We are not claiming that the central RSVP task used all attentional resources; only that it used some. Any remaining attentional resources could have contributed to adaptation. This is why we conclude that adaptation requires “minimal” attentional resources.

This study does not and cannot show that adaptation is possible in the absence of conscious awareness of the adapting stimulus. A level of conscious awareness of the adaptor may well have been present even in the Dual-Task conditions of Experiment 1. On the other hand, the proposition that conscious awareness is not necessary for adaptation is consistent with the present findings, and with those of Morgan, Schreiber, & Solomon (2016), who showed that adaptation could occur to individually invisible motion components in an adapting stimulus.

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