Increased working memory load does not modulate the attentional blink

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Research Article

Keywords: Attentional Blink, Working Memory, Cognitive Load, Dual-Task, Web-Based Experiment

Posted Date: September 12th, 2022

DOI: https://doi.org/10.21203/rs.3.rs-2034244/v1

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Abstract

The human capacity to process and encode stimuli in working memory is limited, and one way to test this capacity is the attentional blink. In this paradigm, participants are usually able to correctly identify a first target but fail to correctly identify a second target presented shortly after. In the current experiment, we combined the attentional blink paradigm with a visual working memory manipulation to examine the modulation of the target identification by reduced cognitive capacity. Bottleneck theories predict an increased attentional blink with limited resources. In contrast, the overinvestment hypothesis predicts an inverted-u shaped relationship between attentional resources and the attentional blink. In support of the former explanation, we found an increase in the attentional blink with increasing working memory load. However, we did not find an interaction between the target lag and the working memory load, which indicates that the working memory load did not modulate the attentional blink but affected the perceptual encoding of the second target.

Introduction

Humans gather and process much more information than they consciously perceive (Martens and Wyble 2010). In the selection and filtering of irrelevant from relevant information, attention plays a central role (Baddeley 2012). One approach to examine the attentional capacity to process and encode relevant stimuli in working memory is to examine the attentional blink (AB) (Raymond et al. 1992). Experiments on the AB often consist of the presentation of a stream of visual distractor stimuli (Rapid Serial Visual Perception Stream, RSVP), in which two target stimuli are embedded. The participants’ task is to identify both targets. While participants are usually able to correctly identify the first target (T1), the identification of the second target (T2) is impaired, if the two stimuli are presented in short succession (between 200ms and 500ms) (Chun and Potter 1995). Importantly, a modulation of the AB is reflected in the interaction between the T1-T2 lag and the independent variable (e.g., group or condition, MacLean and Arnell 2012). After three decades of research, different explanations coexist for this perceptual gap (Dux and Marois 2009; Petersen and Vangkilde 2022), and most theories suggest an interplay between working memory and attention allocation to explain the attentional blink (Zhou et al. 2020). As Dux & Marois (2009) state: “[…] the AB reflects the competition between targets for attentional resources, not only for working memory encoding, episodic registration, and response selection […], but also for the enhancement of target representations and the inhibition of distractors.”

Whereas most theories converge on the common idea that devoting capacity-limited attentional resources to T1 limits processing of T2, different approaches make different predictions regarding the specific mechanisms of the AB. On the one hand, bottleneck theories propose that processing T1 and the following distractor (T1+1) depletes the attentional resources so that T2 can’t be sufficiently processed (Shapiro et al. 1994; Chun and Potter 1995). More specifically, Wyble et al. (2009) argue that working memory (WM) encoding of the first target suppresses the allocation of attention to new stimuli, thereby preventing them from being integrated with the episodic memory of the first item. This results in the inability to correctly recall T2. Consequently, allocating more attentional resources to the task will support
correctly identifying T2, but at the expense of binding or order errors. On the other hand, the overinvestment hypothesis argues that too many items entering a first representational stage at the conceptual level leads to interference between items on a limited-capacity processing stage (Olivers and Nieuwenhuis 2006). Accordingly, allocating more attentional resources to the task will lead to stronger interference between items. In short, the former view of a processing bottleneck predicts a negative linear relationship between attentional resources and the AB, i.e., an increased AB with limited resources and a decreased AB with increased resources. In contrast, the latter view predicts an inverted-u shaped relationship between attentional resources and the AB, i.e., a decrease in the AB by a reduction in attentional focus.

One way of testing the different predictions from the aforementioned theories is by combining the AB with a second task. Following the model of working memory proposed by Baddeley (2012) which involves the interaction of attentional control (performed by the central executive) with the maintenance of information in working memory and episodic memory, a second task should require additional attentional control. This, in turn, should limit the attentional capacity available for the processing of the RSVP stream. In line with this idea, Olivers and Nieuwenhuis (2006) interleaved to-be-remembered patterns in between RSVP streams, and participants had to indicate whether two consecutive patterns matched. Interestingly, and in line with earlier findings (Olivers and Nieuwenhuis 2005), participants showed a reduced AB under the additional working memory task.

In a similar setup, Akyürek and Hommel (2006) used a working memory task with increasing memory load in the interval between RSVP streams. Whereas increased working memory load reduced the overall detection accuracy of T1, the authors did not observe an interaction with the lag between T1 and T2. Extending these findings, Akyürek et al. (2007) modified the task to include an active engagement with working memory. To this end, participants were required to compare T1 with a previously presented memory set upon detection, and report T2 after the RSVP stream. This active engagement with working memory led to an interaction between lag and working memory load with a marked increase of the AB (i.e., a decreased rate of correct T2 detections) with increasing memory load only at short lags. In summary, it appears that a small increase in working memory load can decrease the AB by drawing attentional resources away from the distractors, but a large working memory load interferes with encoding of multiple targets.

One possible confound in the combination of the AB with additional tasks is the switching between tasks. It has been shown for simple reaction time tasks, that switching between modalities can severely interfere with sensory processing (Shaw et al. 2020). Similarly, switching between goals in the reporting of the targets can increase the AB (Ferlazzo et al. 2007). Critically, by combining the reporting of the target to a single goal facilitates the interpretation of the findings as this avoids the postcompletion error (Byrne and Bovair 1997), by which the second goal (T2) is neglected after completing the first goal (T1). Therefore, it could be possible that the AB increase reported by Akyürek et al. (2007) was due to the focus on the first goal. The short lag of 300 ms could have been too short to refocus on the second goal, but the long lag of 800 ms could have provided enough time for this. Thus, in order to investigate the possible interaction
between working memory load and attentional resources without the confounding influence of a goal switch, we designed a single-goal AB experiment in combination with a linear increase in working memory load by using a visual n-back task (0-, 1-, 2-back). Following the literature summarized above, we hypothesize an interaction between working memory load and the AB. More specifically, in line with the findings by Olivers and Nieuwenhuis (2006), we hypothesize that the overinvestment hypothesis holds for small working memory loads, which should result in an AB reduction for the 1-back compared to the 0-back condition. Furthermore, in line with the idea of an encoding bottleneck due to reduced attentional resources (Shapiro et al. 1994; Chun and Potter 1995; Wyble et al. 2009), we hypothesize an AB increase for large working memory loads, i.e., an increased AB for 2-back compared to 1-back.

Methods

The goal of the current experiment was to investigate the effect of increasing working memory load, and thereby reduced attentional capacity, on the attentional blink. To this end, we designed a web-based experiment in which we combined the AB RSVP stream with an orthogonal manipulation of working memory load via a visual n-back task. All experimental materials, data, and analysis code are openly available on GitHub (https://github.com/juliankeil/attentionalblink).

3.1. Sample Size Estimation

We hypothesize a modulation of the AB by working memory load. Thus, the critical effect in the current experiment consists of an interaction between the T1-T2 lag (three levels, 200 ms, 300 ms, 400 ms) and the memory load (three levels, 0-, 1-, 2-back) on the percentage of correct T2 identification, given that T1 was correctly identified (MacLean & Arnell, 2012). In this 3x3 repeated measures design, the required sample to obtain a medium effect of $f^2 = 0.25$ at an alpha error probability of 0.05 and a power of 0.95 is n = 54 (Faul et al. 2007).

3.2. Participants

Of the 134 participants who started the demographic questionnaire (for details on the material, please see section 3.4.), 118 started the actual experiment, and 102 completed all parts. Of these, 5 participants were excluded due to being left-handed (possible confound in the response using the keys “a”, “s”, and “d”, see section 3.4.), and one was excluded to uncorrected hyperopia. Moreover, 5 participants never responded, 7 had too many errors during the RSVP streams (error rate above mean + 2 SD, M = 30.43, SD = 14.78), and 5 had too many errors during the n-back task (hit rate below mean + 2 SD, M = 58.34, SD = 22.96, correct-rejection rate below mean + 2 SD, M = 94.88, SD = 7.00). Finally, 19 participants had to be excluded, as the screen refresh rate was not set to approximately 60 Hz (see section 3.4.). This resulted in a final sample of N = 60, and an estimated power of 0.975 to detect a medium effect of $f^2 = 0.25$, with a critical F value for the 3x3 repeated measures interaction of 2.45. The final sample consisted of 41 females and 19 males (no participant reported “diverse” or “N/A”), aged between 18 and 58 years (M = 25.5, SD = 9.79), of which one reported a doctorate as the highest level of education, 14 reported a
university degree, 44 reported a high-school diploma (Abitur), and one a middle-school diploma (Realschule). Participants were recruited from the participant pool of the Institute of Psychology of the Christian-Albrechts-University Kiel and from social networks in return for partial course credit and the chance to win a 10€ voucher. All participants provided written informed consent to participate in the experiment, and the experiment was conducted in accordance with the 2008 declaration of Helsinki. The experimental protocol was evaluated and approved by the ethics committee of the Christian-Albrechts-University Kiel (ZEK-1/22).

3.3. Experimental Procedure

The current experiment was designed as a web-based study to be completed on the participants’ own computers, consisting of three parts. The first part was programmed in LimeSurvey (https://www.limesurvey.org/) and comprised the informed consent into the data collection including the information regarding data protection and contact information to the data security officer. After being informed about the experimental procedures, the participants themselves generated an individual code to anonymize the data. Before continuing to the demographic questionnaire, the participants had to indicate that they conducted the experiment at a computer with dedicated off-screen keyboard, as the experiment was not designed to be completed on a smartphone, tablet, or touch-screen display. The demographic questionnaire comprised questions on age (numerical value), sex (male, female, diverse, N/A), highest level of education (primary school, middle school, high school, university, doctorate, N/A), handedness (right, left, both), uncorrected hyperopia (yes, no), and information regarding recent head injuries, neurological disorders, or epilepsy (yes, no). Before continuing to the second part, the participants were shown two illustrations of the experimental design.

The second part of the study comprised the RSVP AB streams and the interleaved n-back task (please see section 3.4. for details). Participants reached the second part via a link provided at the end of the first part.

After completing the second part of the experiment, participants were automatically forwarded to another, independent, LimeSurvey questionnaire. The use of two separate questionnaires ensured the collection of independent datasets to avoid conclusions regarding the individual participants’ identities. Here, participants could provide their email addresses to obtain partial course credit or take part in the lottery to win a 10€ voucher. All email addresses were deleted after completion of the project and the final dataset does not contain any identifiable information.

3.4. N-Back Attentional Blink Experiment

The second part of the experiment represents the main part comprising the RSVP AB task and the interleaved n-back task (Figure 1A). This part was programmed in PsychoPy (Peirce et al. 2019) and hosted on Pavlovia.org for online participation (https://github.com/juliankeil/attentionalblink/01_experiment/). It comprised one practice block and 27 experimental blocks of 10 RSVP streams interleaved with the n-back task in the inter-trial interval (ITI).
The screen background was set to neutral grey (RGB [128, 128, 128]) and all stimuli were presented in white in “Open Sans” type. Instructions were presented with a letter height of 0.05 relative to the individual screen height (except for the block number, which was presented in black letters, letter height = 0.075). A black fixation cross (letter height = 0.01) was displayed in the ITI with a random duration between 750ms and 1250ms. During the practice trials, feedback (letter height = 0.1) was provided for 1 s after each RSVP stream and n-back stimulus, comprising “Wrong” in red, “Correct” in green, and “You should have pressed a/s/d” in black (in the original experiment, all feedback was in German).

One RSVP stream comprised 6 stimuli, numbers served as distractors and uppercase letters as targets. RSVP stimuli were presented for 4 screen refresh frames and separated by 2 frames. Only datasets with a screen refresh rate of approximately 60 Hz (+/- 2 Hz) were included in the analysis, resulting 66.6 ms presentation time followed by a blank screen for 33.3 ms. Similar numbers and letters were excluded from the stimulus set (e.g., 1, I, J, 5, S, 8, B, Q, O, 0), and vowels were excluded to avoid the possibility to form syllables as a mnemonic strategy (Ferlazzo et al. 2007). Distractors (2, 3, 4, 7, 9) were presented randomly, but never twice in a row. Targets (C, D, E, F, H, L, M, P, R, Y) could occur anywhere in the RSVP stream except on the last position, as it has been shown that this leads to improved T2 detection (Giesbrecht and Di Lollo 1998; Vogel and Luck 2002). Thus, T2 could be presented at lags 2, 3 and 4 (i.e., 200ms, 300ms, or 400ms after T1). Following the RSVP stream, participants had 1.5 s to respond (Figure 1B).

The participants’ task was to decide whether T1 and T2 were the same (by pressing “s”) or different (by pressing “d”), or whether only one target was presented (by pressing “a”). Previous studies showed a near perfect T1 detection (Chun and Potter 1995; Martens and Wyble 2010), and that the AB is due to the inability to correctly identify T2. Using a paired response allows testing the encoding and consolidation of T1 and T2, as the three-alternative forced choice task can only be correctly answered if T1 and T2 have been correctly identified (T2|T1). In case of identical T1 and T2 (condition “S”), the correct response was pressing “s” (s|S), in case of different T1 and T2 (condition “D”), the correct response was pressing “d” (d|D), and in case only T1 was presented (condition “A”), the correct response was pressing “a” (a|A). Thus, the AB can be seen in cases in which T2 was incorrectly identified (s|D, d|S), or not encoded (a|D, a|S), and it was operationalized as the percentage correct responses to both targets. All conditions (A, S, D) were presented 10 times, resulting in (3 (load) x 3 (condition) x 3 (lag) = 27 possible combinations) 270 trials overall, split into 27 blocks. The order of lags and conditions was pseudorandomized within a block, and the order of n-back load was randomized between participants to avoid order effects of working memory load.

The orthogonal n-back task presented in the ITI was aimed to increase the working memory load during each block. Before the start of each block, participants were informed about the condition, i.e., whether they should report a target stimulus (“=”, 0-back) or a symbol repetition with respect to the last (1-back), or second-to-last stimulus (2-back) by pressing the space bar, and they had to confirm the condition by pressing the appropriate number to proceed. Within one block, 11 n-back symbols (@, <, %, !, &, ?, #, §) were presented, and each block started and ended with an n-back symbol. The symbol “=” was only used
as a target in the 0-back condition to avoid confusion with the other n-back conditions. Each n-back stimulus was presented for 500ms (white, letter height = 0.1) and a target was drawn with 33% likelihood. After the n-back stimulus, participants had 1.5s to respond. The performance in the n-back task was operationalized as the sensitivity d’, i.e., the difference between the z-transformed hit rate and the z-transformed false alarm rate (Green and Swets 1966; Hautus 1995).

3.5. Hypotheses

In general, we hypothesize a modulation of the AB by working memory load. As mentioned above, the critical effect in the current experiment consists of an interaction between the T1-T2 lag (factor Lag) and the memory load (factor nBack) on the dependent variable percentage correct target identification (T2 | T1) (MacLean and Arnell 2012).

As a manipulation check, we first aim at testing the effect of the n-back task (0-, 1-, 2-back) and the different target combination conditions (A, S, D) on the dependent variable (DV) percentage correct responses. Here the null hypothesis (H01) states no difference in the DV depending on the n-back task or target condition. Accordingly, the first alternative hypothesis (H11) assumes a difference in the DV between the three target combinations (A, S, D, main effect for the factor Target). The second alternative hypothesis (H12) assumes a difference in the DV between the three n-back conditions (main effect for the factor nBack). More specifically, we assume that small increases in working memory load should improve the target identification (1-back > 0-back, Olivers and Nieuwenhuis 2006), and large increases in working memory load should impair the target identification (1-back > 2-back, Shapiro et al. 1994; Chun and Potter 1995; Wyble et al. 2009). Further hypotheses originate from significant H11 and H12: If we accept H11, we need to examine the effect of the factor nBack separately for the three target combinations. Specifically, the condition A, in which only T1 is presented, should capture the basic perceptual ability of the participants, as T1 is usually identified correctly, and sufficient attentional resources should be available. Accordingly, we assume no difference in the DV depending on the factor nBack (H13). Importantly, the factor Lag does not exist in the single target condition A. In contrast, for the two-target conditions (factor Target, S and D), we can examine the combined effects of the factors Lag (200ms, 300ms, 400ms) and nBack (0-, 1-, 2-back) in a three-way repeated-measures ANOVA, and we assume (H14) that the working memory load will have different effects at short versus long lags (MacLean and Arnell 2012).

Finally, we hypothesize that the effect of working memory load on the DV is not uniform across participants, but that those who are most affected by the n-back task should also show the strongest attentional blink (H15).

3.6. Statistical Analyses

All statistical analyses were performed in R (R Core Team 2011), and the analysis code is available at https://github.com/juliankeil/attentionalblink/03_analysis/.
The Mauchly test was used to verify the assumption of sphericity and the Greenhouse-Geisser correction was applied when necessary to correct for non-sphericity. For these cases, the corrected degrees of freedom and p-values are reported.

The first two hypotheses (H1₁ and H₁₂) were tested in a repeated-measures ANOVA with the factors nBack (3 levels: 0-, 1-, 2-back) and Target (3 levels: A, S, D). The third hypothesis (H₁₃) assumes no difference in the DV depending on the factor nBack for the single target condition (A) and was tested with an equivalence test for paired samples with a smallest raw effect size of interest of +/-7%, i.e., approximately half of the difference between paired and unpaired target reports across experiments in (Ferlazzo et al. 2007). The fourth hypothesis (H₁₄) was tested in a repeated-measures ANOVA with the factors Lag (3 levels: 200ms, 300ms, 400ms), nBack (3 levels: 0-, 1-, 2-back) and Target (2 levels: S, D). For the fifth hypothesis, the relationship between perceptual sensitivity (d') in the n-back task and the percentage correct responses in the RSVP stream across target conditions was examined using a linear mixed effects model. In the computation of perceptual sensitivity (d'), extreme values were corrected (Hautus 1995).

The alpha level was set to 0.05 in all tests and corrected for the number of comparisons in all post-hoc paired t-tests using a Tukey correction.

**Results**

The current data analysis focused on the potential influence of increasing working memory load on visual perception capacity as assessed with an attentional blink experiment. Behavioral data from 60 participants entered the final data analysis, and the data are available at https://github.com/juliankeil/attentionalblink/02_data/.

4.1. The target detection between different target types

The first hypothesis was aimed at testing an influence of increasing working memory load on general visual target detection. This hypothesis was tested as a main effect for the factor Target in a repeated-measures ANOVA with the factors nBack (3 levels: 0-, 1-, 2-back) and Target (3 levels: A, S, D), and we found a significant effect (F(1.52, 89.89) = 28.20, p < 0.001, h² = 0.165). Paired post-hoc tests revealed a difference in percentage correct detection between single (A) and two identical targets (S) (t(59) = -3.94, p < 0.001), between single (A) and two different targets (D) (t(59) = -6.77, p < 0.001), and between identical (S) and different (D) targets (t(59) = -4.30, p < 0.001).

4.2. The influence of the n-back task on target detection

The second hypothesis was tested as a main effect for the factor nBack in the aforementioned ANOVA, and we found a significant effect (F(1.99, 117.70) = 4.80, p = 0.01, h² = 0.005). Paired post-hoc tests revealed a difference in percentage correct detection between 0-back and 2-back conditions (t(59) = 2.78, p = 0.02), and between 1-back and 2-back conditions (t(59) = 2.49, p = 0.04), but not between 0-back and
1-back ($t(59) = 0.35, \ p = 0.93$). This indicates that large increases in working memory load impair the target identification, but small increases in load are not beneficial. The interaction between the factors Target and nBack was not significant ($F(3.58, 211.33) = 0.91, \ p = 0.449, \ h^2_G = 0.002$), and to further examine the effect of the factor Lag, the target conditions were split between single (A) and double (S, D) target conditions.

### 4.3. Detection of a single target

The third hypothesis concerned the target identification in the single (A) target condition. Here, we hypothesized no difference between n-back tasks, as the basic perceptual ability should be unaffected by manipulations of working memory load. Indeed, in the one-factorial ANOVA for the effect of the factor nBack (3 levels: 0-, 1-, 2-back), we did not find a significant effect ($F(1.97, 116.49) = 0.82, \ p = 0.442, \ h^2_G = 0.002$). TOST equivalence tests with raw equivalence bounds of +/-7% indicated equivalence between 0-back and 1-back ($t(59) = -2.69, \ p = 0.004$), 0-back and 2-back ($t(59) = -2.85, \ p = 0.003$), and 1-back and 2-back conditions ($t(59) = -4.08, \ p < 0.001$).

### 4.4. The influence of the n-back task on target detection at different lags

The fourth hypothesis concerned the critical influence of the working memory manipulation at different T1-T2 lags, and it was tested in a repeated-measures ANOVA with the factors Lag (3 levels: 200ms, 300ms, 400ms), nBack (3 levels: 0-, 1-, 2-back) and Target (2 levels: S, D), as detailed in tables 1 and 2. As before, we found main effects for the factors Target ($F(1, 59) = 18.56, \ p < 0.001, \ h^2_G = 0.032$) and nBack ($F(1.99, 117.19) = 5.65, \ p = 0.005, \ h^2_G = 0.006$). Moreover, we also found a main effect for the factor Lag ($F(1.78, 105.24) = 82.04, \ p < 0.00, \ h^2_G = 0.117$). However, we found no significant interactions between the factors nBack and Lag (see table 1 for details), indicating that the manipulation of working memory load was identical across the different lags (Figure 2).

#### Table 1

*Results for the repeated-measures ANOVA with the factors Lag (3 levels: 200ms, 300ms, 400ms), nBack (3 levels: 0-, 1-, 2-back) and Target (2 levels: S, D). * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$.**
Table 2

Results for the post-hoc t-tests for the interaction between the factors Lag (3 levels: 200ms, 300ms, 400ms) and Target (2 levels: S, D). * = p < 0.05, ** = p < 0.01, *** = p < 0.001.

<table>
<thead>
<tr>
<th>Contrast</th>
<th>Estimate (SE)</th>
<th>t(59)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>D lag 2 vs. D lag 3</td>
<td>-0.082 (0.015)</td>
<td>-5.39</td>
<td>&lt; 0.001 ***</td>
</tr>
<tr>
<td>D lag 2 vs. D lag 4</td>
<td>-0.140 (0.017)</td>
<td>-8.16</td>
<td>&lt; 0.001 ***</td>
</tr>
<tr>
<td>D lag 3 vs. D lag 4</td>
<td>-0.057 (0.013)</td>
<td>-4.29</td>
<td>&lt; 0.001 ***</td>
</tr>
<tr>
<td>S lag 2 vs. S lag 3</td>
<td>-0.139 (0.019)</td>
<td>-7.05</td>
<td>&lt; 0.001 ***</td>
</tr>
<tr>
<td>S lag 2 vs. S lag 4</td>
<td>-0.197 (0.021)</td>
<td>-9.34</td>
<td>&lt; 0.001 ***</td>
</tr>
<tr>
<td>S lag 3 vs. S lag 4</td>
<td>-0.058 (0.015)</td>
<td>-3.96</td>
<td>0.003 ***</td>
</tr>
<tr>
<td>D lag 2 vs. S lag 2</td>
<td>-0.108 (0.025)</td>
<td>4.33</td>
<td>&lt; 0.001 ***</td>
</tr>
<tr>
<td>D lag 3 vs. S lag 3</td>
<td>0.052 (0.016)</td>
<td>3.12</td>
<td>0.031 *</td>
</tr>
<tr>
<td>D lag 4 vs. S lag 4</td>
<td>0.051 (0.019)</td>
<td>2.69</td>
<td>0.092</td>
</tr>
</tbody>
</table>

4.5. The correlation between n-back performance and target detection

In order to examine whether the effect of working memory load on the percentage correct responses is uniform across participants, or whether those who are most affected by the n-back task should also show the strongest attentional blink, we performed a random-intercept linear mixed-effects analysis with d' as the dependent variable and the percentage correct responses and n-back condition as predictors. The model showed that – as expected – the n-back condition had a significant effect on the d' (b = -1.44, SE = 0.29, p < 0.001). Moreover, we found an interaction between the percentage correct responses and the n-back condition (b = 1.39, SE = 0.40, p < 0.001), indicating that the relationship between d' and attentional
blink is not uniform across n-back conditions (Table 3). To examine this effect in more detail, we compared the correlations between d’ and AB across the different n-back conditions (Figure 3 and Table 4). The correlation was only significant in the 2-back condition (r = 0.43, t(58) = 3.67, p < 0.001), and the correlation in the 2-back condition was significantly larger than in the 0-back condition (z = -2.66, p = 0.007).

Table 3

Results for the linear mixed-effects analysis with d’ as the dependent variable and the percentage correct responses and n-back condition as predictors. * = p < 0.05, ** = p < 0.01, *** = p < 0.001.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Estimate (SE)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>2.941 (0.540)</td>
<td>&lt; 0.001 ***</td>
</tr>
<tr>
<td>Percent correct</td>
<td>-0.454 (0.737)</td>
<td>0.538</td>
</tr>
<tr>
<td>nBack</td>
<td>-1.440 (0.292)</td>
<td>&lt; 0.001 ***</td>
</tr>
<tr>
<td>Percent correct * nBack</td>
<td>1.391 (0.407)</td>
<td>&lt; 0.001 ***</td>
</tr>
</tbody>
</table>

Table 4

Results for the post-hoc correlation between d’ and percentage correct responses following the interaction between working memory load and percentage correct responses on d’. * = p < 0.05, ** = p < 0.01, *** = p < 0.001.

<table>
<thead>
<tr>
<th>Condition</th>
<th>r</th>
<th>t(58)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-back</td>
<td>0.043</td>
<td>0.330</td>
<td>0.742</td>
</tr>
<tr>
<td>1-back</td>
<td>0.252</td>
<td>1.984</td>
<td>0.051</td>
</tr>
<tr>
<td>2-back</td>
<td>0.434</td>
<td>3.673</td>
<td>&lt; 0.001 ***</td>
</tr>
</tbody>
</table>

Comparison

<table>
<thead>
<tr>
<th></th>
<th>z</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 vs. 1</td>
<td>-1.442</td>
<td>0.149</td>
</tr>
<tr>
<td>0 vs. 2</td>
<td>-2.663</td>
<td>0.007 ***</td>
</tr>
<tr>
<td>1 vs. 2</td>
<td>-1.695</td>
<td>0.090</td>
</tr>
</tbody>
</table>

Discussion

The human capacity to process and encode stimuli in working memory is limited, and one way to test this capacity is the attentional blink (AB) (Raymond et al. 1992). In this paradigm, participants are usually
able to correctly identify a first target (T1) but fail to correctly identify a second target (T2) presented shortly after (Chun and Potter 1995). Most theories explaining this effect note that devoting attentional resources to T1 limits processing of T2. Specifically, bottleneck theories propose that processing T1 and the following distractor (T1+1) depletes the attentional resources so that T2 can’t be sufficiently processed (Shapiro et al. 1994; Chun and Potter 1995; Wyble et al. 2009), which results in the inability to correctly recall T2. To solve this, more attentional resources can be allocated to the task. In contrast, the overinvestment hypothesis proposes that if too many items enter a first processing stage, interference between items on a subsequent processing stage occurs (Olivers and Nieuwenhuis 2006). Importantly, allocating more attentional resources to the task will lead to too many items in the first processing stage and stronger interference between items. In short, the former view of a processing bottleneck predicts a negative linear relationship between attentional resources and the AB, i.e., an increased AB with limited resources and a decreased AB with increased resources. In contrast, the latter view predicts an inverted-u shaped relationship between attentional resources and the AB, i.e., a decrease in the AB by a reduction in attentional focus. To test the different predictions regarding the influence of limited attentional resources on the AB, we combined a single-goal AB experiment with a linear increase in working memory load by using a visual n-back task (0-, 1-, 2-back). Following the findings by Olivers and Nieuwenhuis (2006), we hypothesized that small working memory loads should result in an AB reduction (1-back compared to 0-back). Furthermore, following the idea of an encoding bottleneck (Shapiro et al. 1994; Chun and Potter 1995; Wyble et al. 2009), we hypothesized that large working memory loads should result in an AB increase (2-back compared to 1-back). In short, we found an AB increase with increasing memory load, which however was independent of the T1-T2 lag.

5.1 The influence of the n-back task on target detection at different lags

As described above, we hypothesized a modulation of the AB by working memory load. Importantly, the critical effect in the current experiment consists of an interaction between the T1-T2 lag and the memory load on the dependent variable percentage correct target identification (MacLean and Arnell 2012). In contrast to this hypothesis, we only found a main effect of memory load on the AB, with significant differences between 0-back and 2-back, 1-back and 2-back, but not 0-back and 1-back. The lack of an interaction between working memory load and lag indicates that the cognitive load itself did not modulate the AB. The results clearly speak against the overinvestment hypothesis, as no decrease in the AB between 0-back and 1-back due to a reduction of attentional capacity was found. In contrast, these findings are in line with the results by Petersen and Vangkilde (2022), who argue for a perceptual bottleneck at the early encoding stage. Supporting our third hypothesis, we found no influence of working memory load on the processing of T1 alone. Thus, sufficient resources appear to be available to correctly process a single target even under high working memory load and reducing the cognitive capacity limits processing multiple targets independent of the temporal spacing of the targets. Similar results were obtained by Akyürek and Hommel (2006), who found no influence of increased short-term memory load on the AB and Akyürek et al. (2007), who found an increase of the AB only if the memory load was increased by actively engaging with the working memory content. These results are also in line with recent findings from multisensory perception, where increased working memory load impairs processing
multiple concurrent stimuli, which results in an increased likelihood of perceptual illusions (Michail and Keil 2018; Michail et al. 2021). They are also underscored by an EEG study on the interaction between emotional arousal and the AB, indicating that emotionally arousing content was easier to identify (Keil et al. 2006). Importantly, this effect was accompanied by an increase of early evoked responses to T2 for emotionally arousing stimuli. Overall, these results indicate that modulating early sensory processing by arousal or cognitive load influences encoding sensitivity: Increasing neural excitability by emotional arousal facilitates encoding but decreasing neural excitability by cognitive load impedes encoding. Future studies should therefore examine whether the current manipulation of working memory load was sufficient to modulate the AB.

5.2 The relationship between perceptual sensitivity and the attentional blink

We hypothesized that the modulation of the AB by working memory load is not uniform across participants, but that those who are most affected by the increased working memory load should also show the strongest AB. To this end, we computed the perceptual sensitivity (d’) in the n-back task and examined its relationship to the AB. Overall, we did not find a relationship between the AB and the n-back d’, but the interaction between percent correct responses and the working memory load indicated that this relationship differed between the memory load levels. More specifically, we only found a significant correlation between d’ and AB in the highest memory load condition, which indicates that only this condition was sufficiently difficult to influence the AB. Here, those participants with the lowest d’ also had the strongest AB. This interindividual difference in the AB is in line with recent findings on differences in cortical structure and function underlying interindividual differences in the AB. To further examine this effect, future studies should specifically focus on increasing the task difficulty to an individually adapted working memory load.

5.3 Limitations

The present experiment comprised an online experiment. Whereas this approach allowed the collection of a large sample of participants despite COVID-19-related restrictions, it limited the controllability of the testing situation. This resulted in an exclusion rate of approximately 33% of the participants who completed the experiment. It is also possible, that those participants who were most affected by the working memory load manipulation quit the experiment. Therefore, the current results will need to be carefully replicated in a more controlled laboratory setting. Furthermore, due to the already long duration of the experiment, we neither collected a baseline-condition without the n-back task stimuli, nor the 100ms lag conditions. Thus, the variability in the AB between participants is hard to estimate, and it is not clear whether we would have found an interaction between working memory load and lag if we had included the lag-1 sparing effect. Future studies should therefore specifically focus on the large working memory load and compare it to a no-back condition, and also include the shortest lag condition.

5.4 Conclusions
In the current experiment, we combined the attentional blink paradigm with a visual working memory manipulation to examine the modulation of the AB by reduced cognitive capacity. We found an increase in the AB with increasing working memory load as predicted by bottleneck theories. However, we did not find an interaction between the T1-T2 lag and the working memory load. This lack of a change in AB across target separations indicates that the working memory load did not modulate the AB but affected the perceptual encoding of the second target.

Declarations

Acknowledgements

We thank Maria Rus for her help in the preparation of the manuscript.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Helena Skiba and Julian Keil. The first draft of the manuscript was written by Julian Keil and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Compliance with Ethical Standards

All participants provided written informed consent to participate in the experiment, and the experiment was conducted in accordance with the 2008 declaration of Helsinki. The experimental protocol was evaluated and approved by the ethics committee of the Christian-Albrechts-University Kiel (ZEK-1/22).

Competing Interests

The authors did not receive support from any organization for the submitted work. The authors have no relevant financial or non-financial interests to disclose.

Availability of data and materials

Following acceptance, all data and analysis scripts will be uploaded to osf.io. For review purposes, they are available at https://github.com/juliankeil/attentionalblink

Funding declaration

The authors received no funding or financial support to complete this work.

References


**Figures**
Figure 1

Schematic illustration of the experimental design. (A) Representation of the dual task design for the 1-back condition. Participants were presented a symbol and had to indicate by pressing the space bar, whether it matched the n-th previous trial. After the symbol presentation, the RSVP stream started, and participants had to report whether T1 and T2 were the same, different, or whether only T1 was presented. (B) Illustration of a single RSVP stream with n-back stimuli presented before and after the stream. In this case, T1 and T2 were presented at lag 2, i.e., 200ms apart and were different.
Figure 2

*Decreased percentage correct responses at short lags and high working memory load.* (A) The percentage correct target responses in conditions with two different targets for the three different working memory levels. (B) The percentage correct target responses in conditions with two identical targets for the three different working memory levels.

Figure 3
Relationship between the attentional blink and n-back $d'$: The interaction between the n-back conditions and the percentage correct responses on the n-back sensitivity ($d'$) indicates that those participants with the strongest AB were also most affected by the working memory load manipulation, but only in the high-load condition (2-back).