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ORIGINAL ARTICLE

Training the attentional blink: subclinical depression decreases learning potential

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Abstract
The attentional blink (AB) reflects a temporal restriction of selective attention and is generally regarded as a very robust phenomenon. However, previous studies have found large individual differences in AB performance, and under some training conditions the AB can be reduced significantly. One factor that may account for individual differences in AB magnitude is the ability to accurately time attention. In the current study, we focus on the sensitivity for temporal information on the ability to control attention. Following a visual AB task, a time estimation task was presented in either the visual or auditory modality, followed by another visual AB task. It was found that the time estimation training in both the auditory and visual modality reduced AB magnitude. Although a reduction in AB magnitude was also observed when individuals were trained on a control task (either an auditory frequency or visual line length estimation task), the effect was significantly larger following the time estimation tasks. In addition, it was found that individuals who showed most improvement on the visual time estimation task, also showed the largest reduction in AB magnitude, which was not the case for individuals who were trained on the control tasks. Finally, a negative correlation was observed between depression scores (tested by Beck Depression Inventory-Short Form (BDI-SF) scores and the improvement in the AB and time estimation tasks. Our findings demonstrate clear links between timing ability and mechanisms to control attention and emotion.

Introduction

The attentional blink (AB) paradigm has been a pivotal task to measure the time course of attention for more than 25 years. At first, the AB seemed to be a robust and universal limitation of attentional capacity to report the second of two targets when it occurs 200–500 ms after the first (Raymond et al., 1992). Interestingly, additional training on the task seemed to have little or no effect, suggesting that the AB is a structural limitation when processing sequential stimuli and reflects a fundamental feature of cognitive processing (Bowman & Wyble, 2007; Braun, 1998; Chun & Potter, 1995; Dale & Arnell, 2013a; Dale et al., 2013; Jolicœur & Dell'Acqua, 1998; Maki & Padmanabhan, 1994; Raymond et al., 1995; Wyble et al., 2009). Later on, several studies found that the AB can be attenuated and sometimes even eliminated using laboratory training tasks. Subsequently, the theoretical landscape shifted toward explaining the phenomenon as a limitation to time attention (Choi et al., 2012; Martens & Wyble, 2010; Oei & Patterson, 2013; Taatgen et al., 2009; Tang et al., 2014; Willems et al., 2015a, 2015b).

One study (Choi et al., 2012) trained participants with an adapted version of the task in which the target was very

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salient. According to the authors, it enhanced participants' temporal resolution such that it allowed them to consistently overcome the AB. A subsequent study acknowledged that this result was obtained by the use of the salient target, which may have helped to build up temporal expectations about when the targets were to appear (Tang et al., 2014).

Note however, that also in the absence of such training, large individual differences in AB performance have been observed, with some individuals (approximately 5% of the participants) showing no AB whatsoever (Martens et al., 2006; Willems & Martens, 2016). It appears that such 'non-blinkers' are less affected by irrelevant information (Martens & Valchev, 2009). Behavioral, EEG, and pupil dilation studies provided additional evidence that these non-blinkers might be better able to time attention, showing that they responded to the first target at an earlier time point than 'blinkers' did (Martens et al., 2006; Willems et al., 2013, 2015a, 2015b). Others have also suggested that there might be a link between timing and attention. Using transcranial magnetic stimulation (TMS), it was found that the AB increased when the right cerebellum was stimulated (Arasanz et al., 2012), presumably because the cerebellum processes temporal information (Kraus et al., 2013; MacDonald et al., 2013; Mangels et al., 1998).

In the current study, we focus on the role of time perception and the temporal dynamics of attention in more detail. More specifically, we hypothesized that individuals who are better at estimating time intervals would also show a smaller AB. Second, we wanted to address the question whether performance in an AB task could be improved by training them to estimate time durations, thus enhancing their sensitivity to timing. Thirdly, we investigated whether any training effects would be modality specific, or whether it would cross sensory modalities, thus testing the generalizability of the training. That is, would it matter whether the stimulus modality (i.e., visual or auditory) would be the same for the timing task and the AB task?

The interaction between time perception and memory has recently gained increasing interest in cognitive neuroscience (for reviews, see Matthews & Meck; Teki et al., 2017, Van Rijn, 2016). When something in the environment happens regularly, it can be very helpful to use this regularity to not only predict what will happen, but also when it will happen. Time perception does not appear to be accomplished by an isolated internal clock, but involves a distributed network of brain areas, depending on the particular task at hand (Paton & Buonomano, 2018). Through a process called interval timing, humans are able to estimate and predict how long something lasts by using clues from the environment as well as previous experiences, allowing expectations to guide attention to relevant events (Nobre & Van Ede, 2018). Time estimation tasks can be divided into time reproduction tasks and time discrimination tasks. In our study, we use a reproduction task to train the participants to be more accurate on reproducing a specific time interval during which the AB is often found to be largest: 300 ms. We hypothesized that an increased sensitivity to this interval would optimize attention and lead to a reduced AB. Prior studies that used a similar time estimation task on a millisecond level are for instance (Merchant et al., 2008; Rammsayer & Lima, 1991).

A fourth and final research question concerned whether any improvement in AB task and time estimation performance is modulated by depression. Depression is one of the most frequent mental disorders, and has been studied for many decades (Cuijpers & Smit, 2004; Davidson et al., 2002; Slavich & Irwin, 2014). It is well known that depression can affect cognitive processes such as attention (Ellis, 1990; Farrin et al., 2003; Sackeim & Steif, 1988), working memory (Ellis et al., 1984; Hartlage et al., 1993; Hertel & Hardin, 1990; Hertel & Rude, 1991; Seibert & Ellis, 1991), and executive function (Fossati et al., 1999; Stordal et al., 2004). Previous studies have shown that current affective states can modulate the magnitude of the AB (Vermeulen, 2010) and evidence from a number of studies has shown that compared to healthy participants, participants with an emotional disorder such as depression, anxiety or dysphoria show impaired performance in the AB task (Arend & Botella, 2002; de Jong et al., 2009; Koster et al., 2009; Mildgers et al., 2016; Rokke et al., 2002).

It is currently less clear whether depression can influence the performance on a time estimation task. Some studies have found a negative effect of depression (Bschor et al., 2004; Dilling & Rabin, 1967; Kuhs et al., 1989, 1991; Wyrick & Wyrick, 1977) while others found no difference between depression and control groups (Bech, 1975; Kitamura & Kumar, 1983; Mezey & Cohen, 1961). It has been suggested though that the (potential) poorer performance of depressed people in timing and AB task may be caused by a deficit in their learning ability (Chen et al., 2015). In the current study, we used the Beck Depression Inventory-Short Form (BDI-SF) to test whether individuals who score relatively high on depression indeed show a decrement in performance and learning potential in both the time estimation training task and the AB task. To the best of our knowledge, no studies have directly looked at the relation between AB task performance, time estimation ability, and depression.

Two experiments were set up to investigate whether the AB can be attenuated by a time training task relative to training on a control task (a frequency estimation training task). We expected that the time training task would optimize the distribution of attention when T2 occurs 300 ms after T1, leading to an increased identification performance in the AB task, whereas the control task would not. In Experiment 2, we investigated whether it is important to present the training tasks and the AB task in the same, visual modality. We expected that any improvement in time sensitivity would correlate with individual improvements in AB task performance. Given presumed links between the ability to control attention and emotion (Joormann & Gotlib, 2007; Joormann & Quinn, 2014), we predicted that depressed participants would show reduced performance in both the training tasks as well as the AB tasks.

Experiment 1

Materials and methods

Participants

Eighty-five volunteers from Shenzhen University, ages 18–26 years (mean age = 23.5 years), 41 female, participated in the experiment after giving their written consent. They received monetary compensation for their participation. The experiment was approved by the local ethical committee. All participants had normal or corrected-to-normal vision. All of them were assessed for depression level using the 13-item short form Beck Depression Inventory-Short Form [BDI-SF;(Beck & Beck, 1972)]. Two of the participants were excluded from the analysis because they did not attend the second session of the experiment. Fifty-one participants were trained with a time estimation task, while the remaining 32 participants were trained with a frequency task. Unfortunately, the AB task proved to be too easy for 32 participants, with performance at ceiling in the AB task (100% accuracy for T2|T1). Because this ceiling effect obscured the results, data from these participants were excluded, leaving 30 participants who were trained on the time estimation task (16 females, mean age = 21.8) and 21 on the control (frequency) task.

Procedure

The participants were invited to the laboratory at the same time on two consecutive days. On the first day, all participants performed the AB task. On the second day, participants either received the time estimation task or the frequency task, followed by a second session of the original AB task. There were no significant differences in depression level between the two groups, as measured by the BDI-SF, $p = 0.84$. The presentation of all tasks and collection of responses was done using the software Presentation (Neurobehavioral Systems, Inc.).

Time estimation task

In this time estimation task, participants were instructed to estimate the duration of a 300-ms time interval as accurately as possible. This specific interval was chosen, because the AB phenomenon is often observed to be at maximum when the onset time between the two presented targets is about 300 ms. The participants were seated comfortably at about 70 cm in front of a 19-inch CRT monitor. As illustrated in Fig. 1, at the beginning of each trial, an auditory cue (1500 Hz, 65 dB) was presented for 10 ms, indicating the start of the time estimation. Participants were asked to press the space key on the keyboard when they thought exactly 300 ms had elapsed following the onset of the cue. Subsequently, a blank screen was presented for 600 ms, followed by feedback. When participants responded within 250–350 ms, the feedback would be ‘correct’; when the reaction time was either shorter than 200 ms or longer than 400 ms, the feedback was ‘too fast’ or ‘too slow’, respectively. The feedback would be presented for 1000 ms. The inter-trial interval was either 1400, 1500, or 1600 ms with equal probability. The task consisted of 300 trials with 15 additional practice trials and took approximately 20 min to complete.

Frequency estimation task

As a control task that had little to do with timing, a frequency estimation task was given to the control group. According

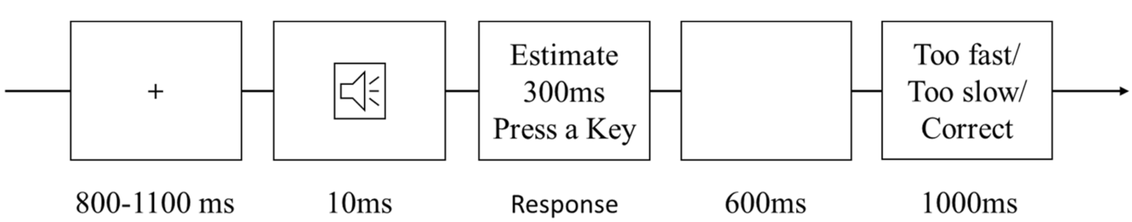

Fig. 1 The procedure of time estimation task. Participants were asked to press the space key on the keyboard exactly 300 ms after the presentation of an auditory cue

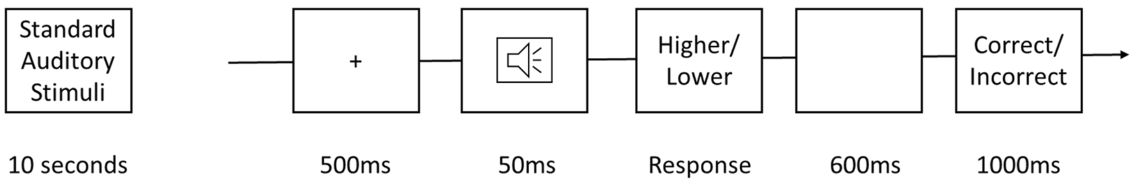

Fig. 2 The procedure of frequency estimation task. Participants were first presented with the pitch of a standard stimulus, and were then asked to indicate whether the pitch of subsequent stimuli was higher or lower than the standard stimulus

to Fechner's law of logarithm, 21 tones were created which are exponentially varied on the base of ten (794 Hz, 813 Hz, 832 Hz, 851 Hz, 871 Hz, 891 Hz, 912 Hz, 933 Hz, 955 Hz, 977 Hz, 1000 Hz, 1023 Hz, 1047 Hz, 1072 Hz, 1096 Hz, 1122 Hz, 1148 Hz, 1175 Hz, 1202 Hz, 1230 Hz, 1259 Hz) using the software Matlab^{2013}. As depicted in Fig. 2, we set 1000 Hz as the standard stimulus. At the beginning of the task, the 1000 Hz tone was played for 10 s which participants were required to memorize. In addition, they were told that they would not hear the same tone again during the rest of the task. At the beginning of each trial, a tone was randomly selected (with equal probability) and played for 50 ms. Participants were required to judge whether this tone was either higher or lower than the standard tone. When considered to be higher, they were to press the 'H' on the keyboard, whereas they pressed 'L' when it was considered to be lower. Following a 600 ms blank screen, the participants would receive a 1000 ms feedback regarding their response. The task consisted of 300 trials with 20 additional practice trials and took approximately 20 min to complete.

Attentional blink task

The participants were seated individually in a darkened room 70 cm in front of a 100-Hz CRT monitor, with their head stabilized in a chin rest. The stimuli (0.8° × 0.8°) were digits (0–9) and uppercase letters (excluding 'I' and 'O'), presented in black on a gray background. As depicted in Fig. 3, the participants were asked to identify two letters presented in a sequential stream of digits. Each trial started with a 2-s fixation, followed by the stimulus stream in which each item was presented for 100 ms. The first target (T1) was always presented as the third item in the stream and the second target (T2) was always presented as the fifth item. In between the two targets, a single distractor was presented. The duration of the distractor randomly varied between 100–650 ms in steps of 10 ms, with an equal distribution of trials for each duration. The duration of the complete stream varied depending on the duration of the fixation and the distractor interval between T1 and T2. Trials in which T2 appeared within 200–300 ms after the onset of T1 were classified as short lag trials, whereas an appearance within

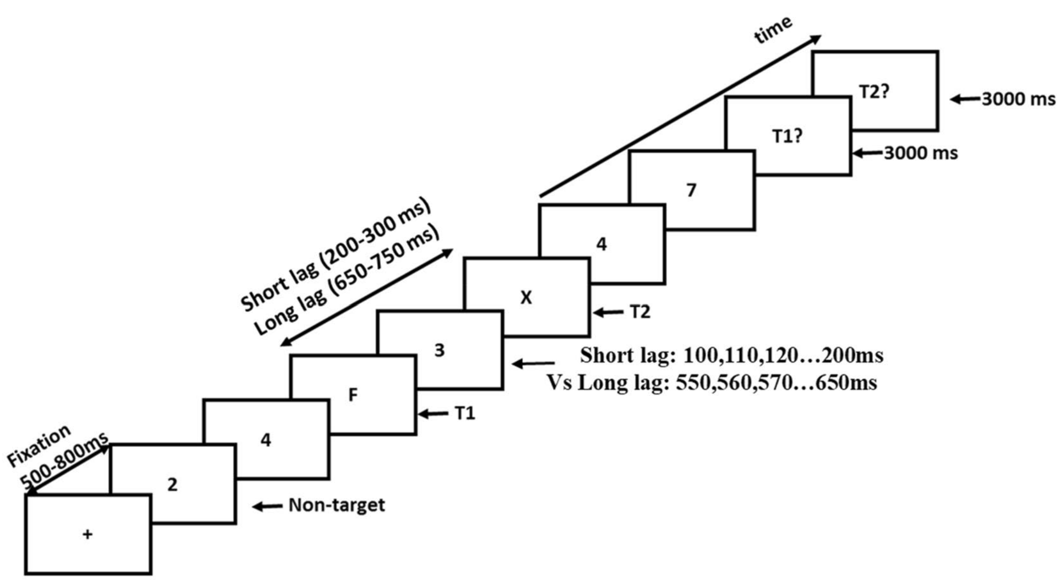

Fig. 3 The procedure of the AB task. The participants were asked to identify the two letters presented in a stream of digits. Each item was presented for 100 ms, except for the distractor between the two targets, which varied in duration between 100 and 650 ms

650–750 ms after the onset of T1 was defined as a long lag trial. Both short and long lags consisted of 100 trials each. The presentation of the distractor with variable duration was meant to create time-resolved behavioral data (Fiebelkorn et al., 2013; Huang et al., 2015; Jia et al., 2017; Landau & Fries, 2012; Song et al., 2014), the results of which will be reported elsewhere. T2 was always followed by two additional non-targets. Following the presentation of the complete stream, participants would be asked to type the two letters they had seen. They had three seconds to make a response, and they were encouraged to avoid typing errors as much as possible. T2 accuracy given that T1 was correctly identified was measured (T2|T1), which was the case on 98% of the trials in Experiment 1 and 82% in Experiment 2. AB magnitude was calculated by the following formula: AB = (T2|T1LongLag—T2|T1ShortLag)/T2|T1LongLag) × 100 (Martens et al., 2015; Willems et al., 2015b, 2016), reflecting the decrement in T2 performance on short lags, relative to T2 performance on long lags.

During the first session, the AB task contained a practice block of 30 trials and an experimental block of 560 trials. The participants received a short break every 100 trials. The task took approximately 40 min to complete. On the second day, the same AB task was presented, except for the lack of a practice block.

Questionnaire

We used BDI-SF to measure the depression level for the participants. BDI-SF is a depression inventory with 13 questions, which is a valid instrument with high validity and reliability in measure depression level. The range of possible scores is 0–39; participants with scores lower or equal to 9 are regarded as non-depressed participants and those with a score higher or equal to 10 are regarded as sub-clinically depressed participants (Beck & Beck, 1972; Furlanetto et al., 2005.

Results and discussion

First, we calculated the accuracy of the training tasks, which was 42% (SEM = 2.4%) for the time training task and 87% (SEM = 2.9%) for the frequency estimation task. Because the accuracy is not directly comparable between two tasks, to know the tendency of accuracy across timing and control tasks, we normalized the accuracy to a *Z* score. We split the training tasks into five quintiles, with the first quintile containing the first 20% of the trials and the fifth quintile containing the last 20% of the trials. Figure 4 shows the normalized accuracy of each quintile. A one-way ANOVA test with quintile as factor was applied on the time training accuracy and the frequency training accuracy respectively. For the time training task, the results showed a significant main effect of quintile, F (4, 116) = 12.86, $p = 0.001$, $\eta^2 = 0.31$. Specifically, accuracy in the first quintile was significantly lower than the last quintile $p = 0.001$, while no significant difference between the last two quintiles was found. These results indicate that performance gradually improved during the training and remained stable in the last two quintiles of the time training task. For the frequency training task, the main effect of quintile was not significant, $p = 0.08$.

To test how T1 and T2|T1 accuracy varied as a function of lag, we defined five time intervals: 200–300 ms; 300–400 ms; 400–500 ms; 500–600 ms and 650–750 ms. The T1 and T2|T1 accuracy of each time interval is depicted in Fig. 5. To analyze how T1 and T2|T1 accuracy changed over lag, we performed three-way ANOVAs with lag and session as within-subject factor and group as between-subjects factor for T1 and T2, respectively.

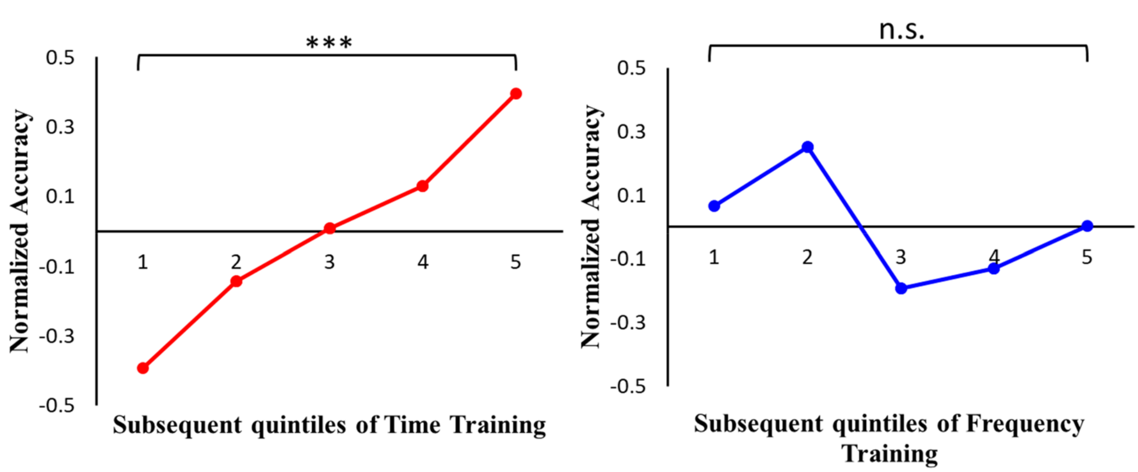

Fig. 4 The accuracy of time estimation task (left) and frequency estimation task (right) over subsequent trials, divided over five subsequent quintiles. ***Means $p < 0.0001$; n.s. means no significant difference

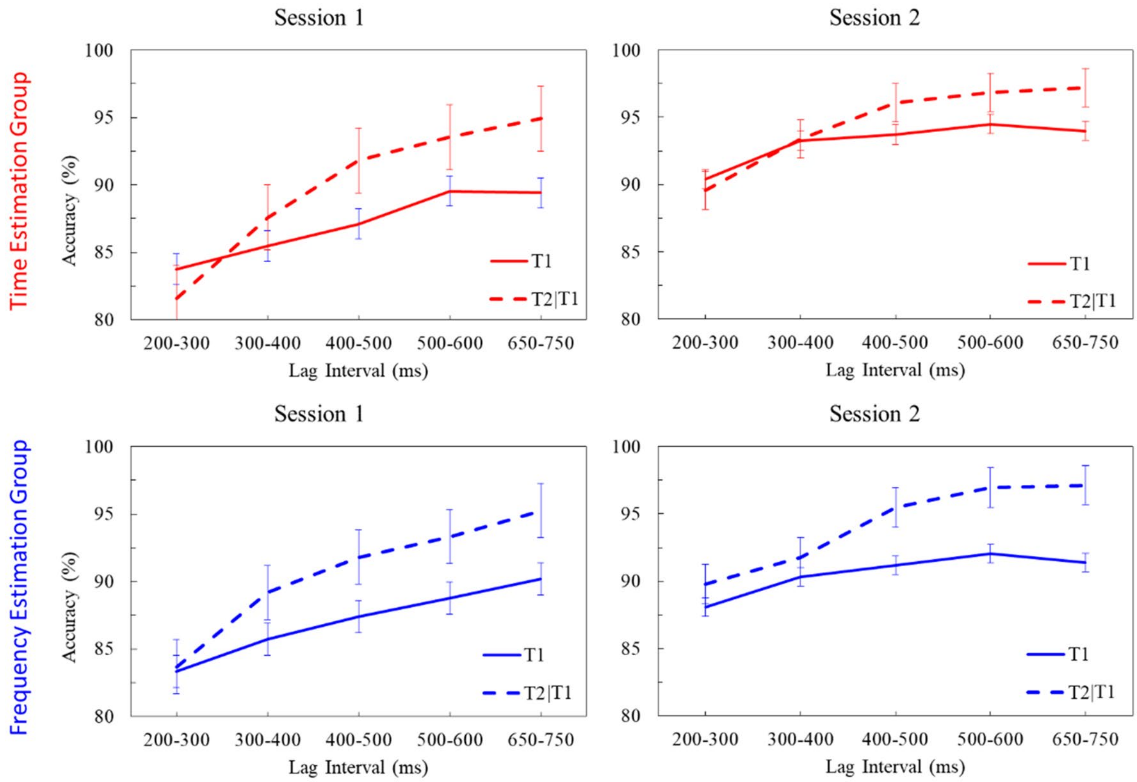

Fig. 5 The accuracy of T1 and T2|T1 accuracy over lag intervals for each session and group

The overall T1 accuracy for the included participants was 89.83% (SEM = 0.6%). We found a main effect of lag, F (4, 192) = 29.26, $p < 0.001$, $\eta^2 = 0.38$. Specifically, the longest lag (650–750 ms) resulted in significantly better performance than the first three lags (200–300 ms; 300–400 ms; 400–500 ms), all $ps < 0.005$, but no significant difference with the performance on the lag of 500–600 ms, $p = 0.93$. We also found a significant main effect of session, showing that session 2 (mean = 91.9%, SEM = 0.7%) had a significantly better performance than session 1 (mean = 87.1%, SEM = 1.1%), F (1, 48) = 52.05, $p < 0.001$, $\eta^2 = 0.52$. Moreover, we found a significant interaction between lag and session, F (4, 192) = 4.31, $p = 0.002$, $\eta^2 = 0.08$, but no interaction between lag, session and group, $p > 0.83$.

For the T2 accuracy, we found a main effect of lag, F (4, 192) = 93.57, $p < 0.001$, $\eta^2 = 0.66$. Specifically, the longest lag (650–750 ms) resulted in significantly better performance than all the other lags (200–300 ms; 300–400 ms; 400–500 ms, 500–600 ms), all $ps < 0.011$. We also found a significant main effect of session, such that session 2 (mean = 94.4%, SEM = 0.4%) had a significantly better performance than session 1 (mean = 90.3%, SEM = 0.7%), F (1, 48) = 1.31, $p = 0.26$, $\eta^2 = 0.03$. Moreover, we found a significant interaction between lag and session, F (4, 192) = 10.85, $p < 0.001$, $\eta^2 = 0.18$. Unfortunately, we did not find a significant effect between lag, session, and group, $p > 0.17$.

However, when we considered only the shortest lag (200–300 ms) with the longest lag (650–750 ms) in a 2 (short and long lag) × 2 (session 1 and 2) × 2 (time estimation group and frequency estimation group) ANOVA, with lag and session as within-subjects factor and group and between-subjects factor, we found a significant effect of Lag (F (1, 49) = 105.83, $p < 0.001$, $\eta^2 = 0.68$) and Session (F (1, 49) = 57.90, $p < 0.001$, $\eta^2 = 0.54$). Importantly, we found a Lag × Session × Group interaction (F (1, 49) = 5.27, $p = 0.026$, $\eta^2 = 0.10$). Pre-planned post-hoc tests were carried out to further analyze the interaction. We found that the group that received the time estimation training task, showed a significant improvement in T2|T1 performance at shortest lag following the training, $p < 0.001$ (session 1: mean = 83.9%, SEM = 0.3% vs session 2: mean = 91.7%, SEM = 0.2%). At the longest lag, there was also a significant improvement in T2|T1 accuracy after time training, $p = 0.001$ (session 1: mean = 95%, SEM = 0.8% vs session 2: mean = 97%, SEM = 0.4%). A significant but relatively smaller effect ($p = 0.001$) was found for the group that performed the frequency estimation task at the shortest lag (session 1: mean = 85.8%, SEM = 0.3% vs session 2: mean = 90.3%, SEM = 0.3%). At the longest lag, there was also a significant improvement in T2|T1 accuracy after time training, $p = 0.02$ (session 1: mean = 95.3%, SEM = 0.9% vs session 2: mean = 97.2%, SEM = 0.4%). To rule out a priori difference between the two groups, a 2 (short and long lag) × 2 (time estimation group and frequency estimation group) ANOVA was applied on the accuracy of T2|T1 in the first session, with lag as a within-subjects factor and group as a between-subjects factor. It was found that the main effect of lag was significant, F (1, 49) = 111.08, $p < 0.001$, $\eta^2 = 0.69$, but that there was no significant lag × group interaction, demonstrating that the two groups did not differ in AB magnitude before the training tasks.

In addition, using a 2 (session) × 2 (group) ANOVA, we subsequently compared AB magnitude for both sessions (within-subjects factor) and groups (between-subjects factor). Averaged AB magnitude as a function of group and session is shown in Fig. 6. A main effect of session was found, F (1, 49) = 35.86, $p < 0.001$, $\eta^2 = 0.42$, indicating that AB magnitude was significantly smaller in session 2. In addition, an interaction between session and group was found, F (1, 49) = 4.89, $p = 0.032$, $\eta^2 = 0.09$. To clarify this interaction, we used separate post-hoc tests to compare AB magnitude for both sessions for each group. The results showed that while both groups showed a reduction in AB magnitude, the reduction was larger for the time estimation group than for the frequency estimation group (time estimation group session 1: mean = 12%, SEM = 0.2%; session 2: mean = 6%, SEM = 0.1%, $p = 10^{-8}$, $\eta^2 = 0.45$.; frequency estimation group session 1: mean = 10%, SEM = 0.2%, session 2: mean = 7%, SEM = 0.2%, $p = 0.02$, $\eta^2 = 0.11$.).

To summarize, the group that received time training showed a larger improvement on the AB task during the second session than the group that received the frequency training task. It is noteworthy that though only 21 participants were left after exclusion, it was sufficient to perform the ANOVA analysis calculated by the software G-power. For a statistical power larger than 0.80, using ANOVA with main effects and interactions with significance at 0.05 level with a moderate-to-large effect size (0.4), at least 19 participants were required. (Faul et al., 2009). Unfortunately, additional analyses at the level of individuals were not possible, given that the sample size was not large enough to obtain sufficient power to allow a correlational analysis. Calculated by G-power, for a statistical power larger than 0.80 and detect a correlation significance at 0.05 level, at least 32 participants were required.

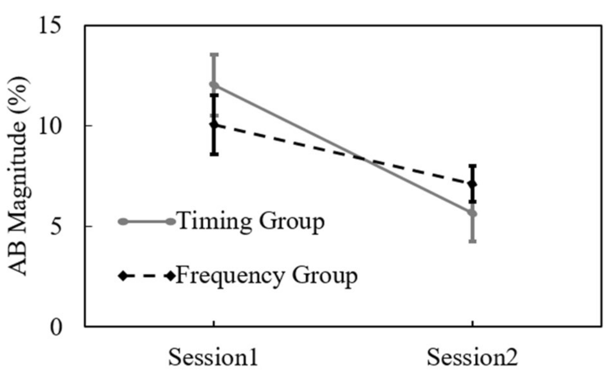

Fig. 6 The AB magnitude preceding (session 1) and following (session 2) the training task. For the group that received time estimation training, the reduction in AB magnitude was significantly larger than that for the (control) group that performed a frequency estimation training task. The error bars represent the standard error of the mean

Therefore, a second experiment was set up, targeted at finding stronger results, both at the group but also at the individual level. To that end, identification of targets in the AB task was made more demanding by reducing the presentation time and font size of each item. Also, for reasons of comparison, all tasks were to be presented in the same (i.e., visual) modality. To that end, the auditory timing and frequency training tasks were replaced by a visual time estimation task and a visual line estimation (control) task, respectively.

Experiment 2

Materials and methods

Participants

101 volunteers (51 females) from Shenzhen University were recruited for this experiment who had not participated in the previous experiment. All participants had normal or corrected-to-normal vision and gave written consent prior to the experiment, and received monetary compensation. They were assessed for depression level using the BDI-SF. Following initial analysis, four participants were excluded because of their absence during the second session of the experiment. One additional participant was excluded due to missing data. For the remaining 96 subjects, overall T1 accuracy was 81%. Forty-seven participants were trained by the (visual) time estimation task (23 females, mean age = 21.2 years), while the other 49 participants were trained by the (time unrelated) length estimation task (28 females, mean age = 21.8 years). The experiment was approved by the local ethical committee.

Procedure

The general procedure in Experiment 2 was similar to that in Experiment 1 with the tasks being carried out on two consecutive days at the same time. As before, all participants completed an AB task on both days, while on the second day it was preceded by one of two training tasks, depending on the participants' group, as further described below. No significant group difference was observed in depression level as measured by BDI-SF prior to the experiment, $p = 0.18$.

The time estimation task

The time estimation group was asked to estimate an interval of 300 ms, using the same equipment as in Experiment 1. At the beginning of each trial, a black cross was presented. After, 1500 ms, it was replaced by the word 'GO', marking the beginning of time estimation. Participants were to press the space bar on the keyboard when they thought 300 ms had elapsed. A blank screen was then presented for 600 ms, followed by feedback. The criterion for the feedback was the same as in Experiment 1. The task consisted of 510 trials and an additional 18 practice trials, taking approximately 23 min to complete.

The length estimation task

The length estimation (control) group was asked to estimate whether a line was longer or shorter than a standard line. We used Fechner's law of logarithm and used 9 lines of different length (92, 94, 97, 99, 101, 103, 106, 108 pixels on the monitor, corresponding to 1.129°, 1.154°, 1.178°, 1.215°, 1.240°, 1.264°, 1.301°, 1.326°), varying exponentially on the base of ten. We set 100 pixels (1.228°) as the standard line. At the beginning of the task, the standard line was presented on the screen for 10 s, and the participants were told that they would see the standard line only once. If they thought the line they saw in the subsequent trials was longer than the standard line, they were instructed to press the 'L' on the keyboard; if they thought the line was shorter than the standard line, they were instructed to press the 'S' on the keyboard. After a 600-ms blank screen, participants received feedback on whether their judgment was correct. The task contained 480 trials and 20 practice trials, lasting approximately 23 min.

The attentional blink task

The task was the same as the AB task of Experiment 1, except for the following changes. Firstly, to increase the difficulty of the task, each item was presented 60 ms instead of 100 ms. Secondly, the size of the stimuli was decreased to $0.5° \times 0.5°$. The equipment and other settings were the same as in Experiment 1. The task contained 560 trials and 30 practice trials, lasting approximately 40 min.

Results and discussion

First, we calculated the accuracy of the training tasks, which was 51% (SEM = 1.9%) for the time training task and 81% (SEM = 1.1%) for the length estimation task. Because the accuracy is not directly comparable between two tasks, to know the tendency of accuracy across timing and control tasks we normalized the accuracy to a Z score. Figure 7 shows the normalized accuracy of each quintile. A one-way ANOVA test with quintile as factor was applied on the time training accuracy and the frequency training accuracy, respectively. For the time training task, the results showed a significant main effect of quintile, $F\ (4, 184) = 20.72$, $p < 0.001$, $\eta^2 = 0.31$. Specifically, accuracy in the first quintile was significantly lower than the last quintile $p < 0.001$, while no significant difference between the last two quintiles was found. These results indicate that performance gradually improved during the training and remained stable in the last two quintiles of the time training task. For the frequency

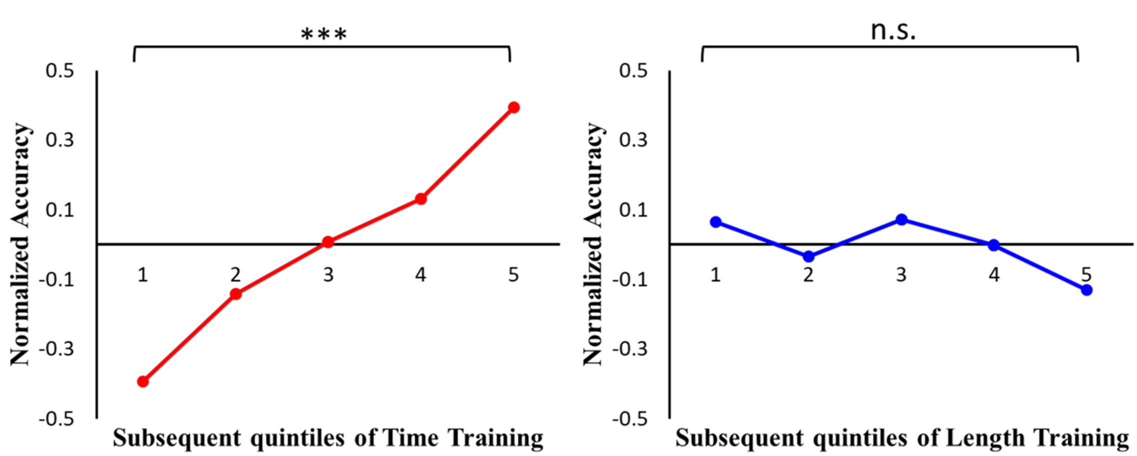

Fig. 7 The accuracy of the time estimation task (left) and length estimation task (right) over subsequent trials, divided equally into five subsequent quintiles. ***Means $p < 0.001$; n.s. means no significant difference

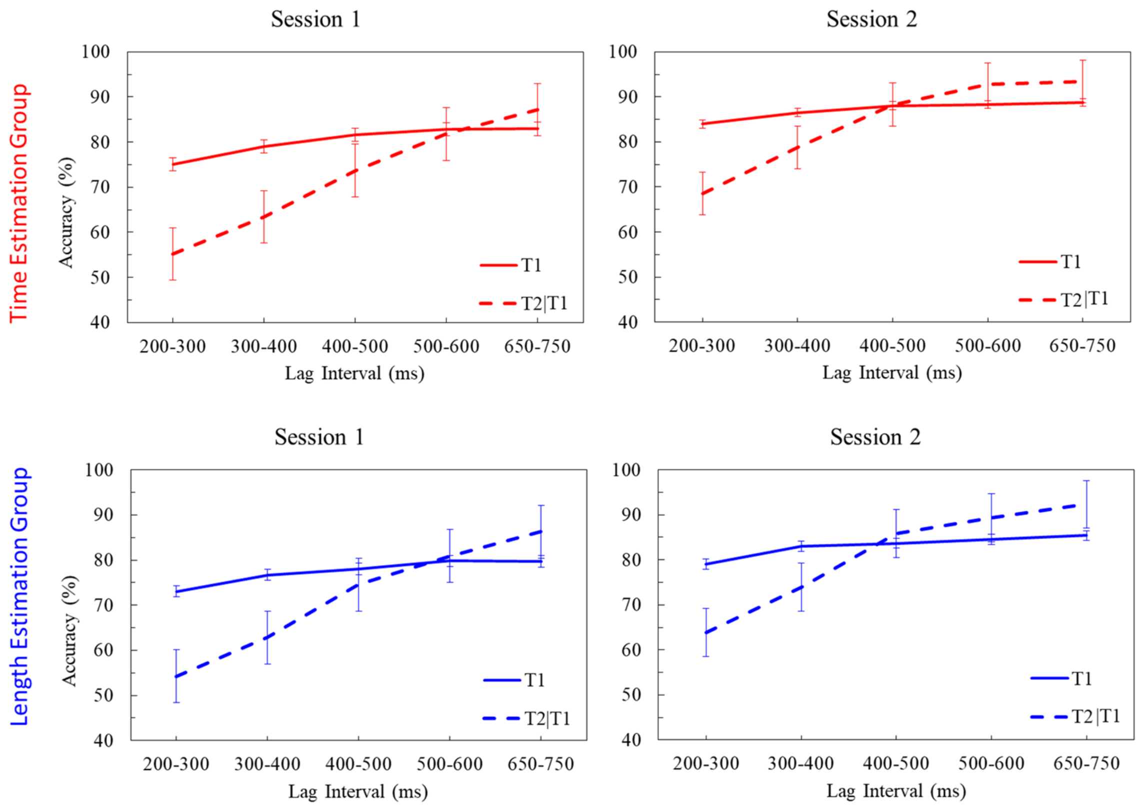

Fig. 8 The accuracy of T1 and T2|T1 accuracy over lag intervals for each session and group

training task, the main effect of quintile was not significant, $p=0.57$.

Similar to experiment 1, to test how T1 and T2|T1 accuracy varies as a function of lag, we defined five time intervals: 200–300 ms; 300–400 ms; 400–500 ms; 500–600 ms and 650–750 ms. The T1 and T2|T1 accuracy of each time interval is depicted in Fig. 8. To analyze how T1 and T2|T1 accuracy changes over lag interval, we performed three-way ANOVAs with lag and session as within-subjects factor and group as between-subjects factor for T1 and T2, respectively.

The overall T1 accuracy for the included participants was 82% (SEM = 0.1%). We found a significant main effect of session, showing that session 2 (mean = 58.7%, SEM = 2.8%) had a significantly better performance than session 1 (mean = 55.3%, SEM = 2.3%), F (1, 94) = 4.85, $p=0.03$, $\eta^2=0.05$, but no interaction between lag, session and group, $p=0.55$.

For the T2 accuracy, we found a main effect of lag, F (4, 376) = 82.04, $p<0.001$, $\eta^2=0.47$. Specifically, the longest lag (650–750 ms) resulted in significantly better performance than all the other lags (200–300 ms; 300–400 ms; 400–500 ms, 500–600 ms), all $ps<0.011$. We also found a significant main effect of session, such that session 2 (mean = 85%, SEM = 0.1%) had a significantly better performance than session 1 (mean = 77%, SEM = 0.7%), F (1, 94) = 181.11, $p<0.001$, $\eta^2=0.67$. Moreover, we found a significant interaction between lag and group, F (4, 376) = 79.14, $p<0.001$, $\eta^2=0.46$, as well as an interaction between session and group, F (1, 94) = 5.33, $p=0.02$, $\eta^2=0.05$. Unfortunately, we did not find a significant effect between lag, session, and group, $p=0.69$.

However, when we considered only the shortest lag (250–350 ms) with the longest lag (650–750 ms) in a 2 (short and long lag) × 2 (session 1 and 2) × 2 (time estimation group and length estimation group) ANOVA, with lag and session as within-subjects factor and group and between-subjects factor, we found a significant main effect of Lag, F (1, 94) = 521.25, $p<0.001$, $\eta^2=0.85$, indicating a significant AB effect. In addition, a main effect of session was found, such that T2|T1 accuracy in session 2 was significantly higher than in session 1, F (1, 94) = 225.67, $p<0.001$, $\eta^2=0.70$. An interaction between session and lag was also observed, F (1, 94) = 63.12, $p<0.001$, $\eta^2=0.40$, indicating that the AB was smaller in session 2. Importantly, the interaction between session, lag, and group was significant, F (1, 94) = 4.65, $p=0.034$, $\eta^2=0.05$. Pre-planned post hoc tests were carried out to further analyze the interaction. We found that the group that received the time estimation training task showed a significant improvement in T2|T1 performance at the shortest lag following the training,

$p = 10^{-21}$, (session 1: mean = 57.5%, SEM = 2.4% vs session 2: mean = 72.8%, SEM = 1.9%). At the longest lag, there was also a significant improvement in T2|T1 accuracy after time training, $p = 10^{-10}$ (session 1: mean = 87.2%, SEM = 1.3% vs session 2: mean = 93.5%, SEM = 0.9%). A significant but relatively smaller effect ($p = 10^{-14}$) was found for the group that performed the frequency estimation task at the shortest lag (session 1: mean = 56.9%, SEM = 2.3% vs session 2: mean = 68.3%, SEM = 1.8%). At the longest lag, there was also a significant improvement in T2|T1 accuracy after time training, $p = 10^{-10}$ (session 1: mean = 86.0%, SEM = 1.3% vs session 2: mean = 92.2%, SEM = 0.9%). Further, a 2 (short and long lag) × 2 (time estimation group and length estimation group) ANOVA was applied on the T2|T1 performance in session 1 to test whether the two groups differed in performance prior to the training tasks. A main effect of lag was found, F (1, 94) = 495.6, $p < 0.001$, $\eta^2 = 0.84$, but no other significant effects (all ps > 0.72).

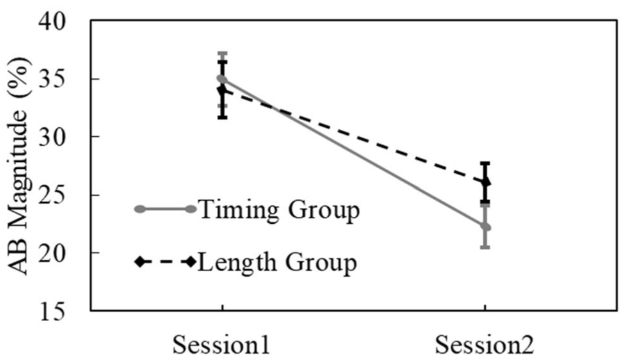

Fig. 9 The AB magnitude preceding (session 1) and following the training task (session 2). For the group that received time estimation training, the reduction in AB magnitude was substantially larger than that for the (control) group that performed a length estimation training task. The error bars represent the standard error of the mean

In addition, we also analyzed AB magnitude using a 2 (session 1 and 2) × 2 (time estimation group and length estimation group) ANOVA with session as a within-subjects factor and group as a between-subjects factor. The averaged AB magnitude as a function of session and group is shown in Fig. 9. The ANOVA revealed a main effect of session, such that AB magnitude was significantly smaller in the second session, F (1, 94) = 99.64, $p < 0.001$, $\eta^2 = 0.52$. More importantly, an interaction between session and group was found, F (1, 94) = 5.22, $p = 0.025$, $\eta^2 = 0.05$, such that the reduction in AB magnitude was largest following the time training. Further post hoc analysis confirmed that while both groups showed a reduction in AB magnitude, this reduction was substantially stronger for the group that received the time estimation task (time estimation group session 1: mean = 35%, SEM = 2%; session 2: mean = 22%, SEM = 2%, $p = 10^{-13}$, $\eta^2 = 0.44$.; length estimation group session 1: mean = 34%, SEM = 2%, session 2: mean = 27%, SEM = 2%, $p = 10^{-7}$, $\eta^2 = 0.24$.).

We thus replicated the results of Experiment 1 that a training with a time estimation task between the two AB tasks leads to a larger reduction of AB than a control task. To investigate this further at the individual level, we firstly correlated individual performance in the AB task in session 1 with performance in the training tasks. However, no significant correlation was found (for the time estimation task, $r = 0.27$, $p = 0.07$; for the length estimation task, $r = 0.14$, $p = 0.37$). To investigate whether individuals who showed most improvement in time estimation performance also showed most improvement in the subsequent AB task,

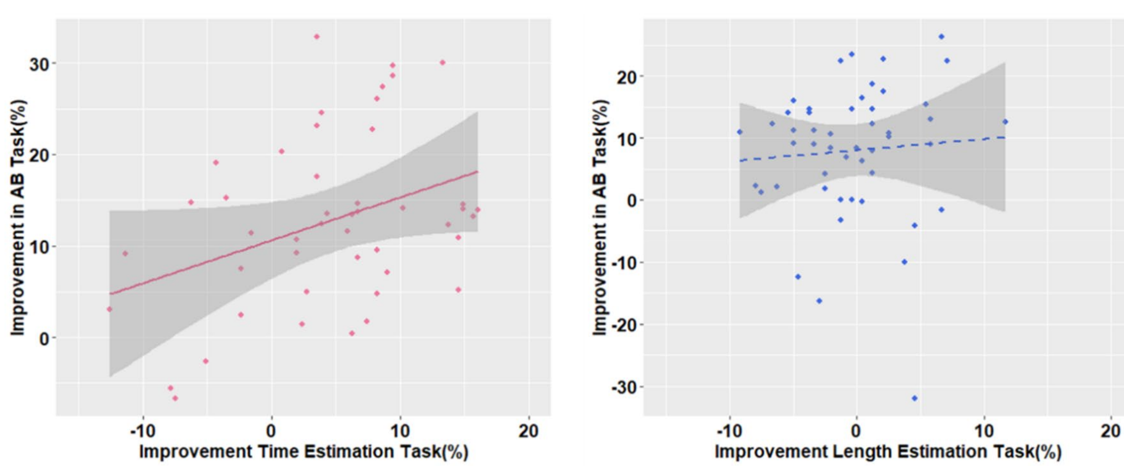

Fig. 10 The correlation between improvements in the training task vs AB task. **a** A significant correlation relationship between improvement in the time training task and the AB task in the time training group. **b** No significant correlation was found between improvement in the length training task and AB task in the length training group. The line represents the linear relationship and the shaded area represents the 99% confidence interval

Table 1 The correlations between depression scores and the (improvement) of the AB as well as the training tasks for time estimation group and the (control) length estimation group in experiment 2

		AB in session1	Training task	Improvement in AB	Improvement in training task
Depression score in time estimation group	*r*	− 0.22	0.03	0.40	0.31
	p	0.14	0.83	0.005**	0.04*
Depression score in length estimation group	*r*	− 0.07	0.01	0.34	0.22
	p	0.64	0.95	0.82	0.13

r Pearson *r* value, *p* significance value

*Correlation is significant at 0.05 level

**Correlation is significant at 0.005 level

a correlation analysis was applied on the improvement of the AB magnitude in the two sessions ($AB_{\text{session 1}} - AB_{\text{session 2}}$) and the improvement of the time estimation task (accuracy in the second half − accuracy in the first half). As shown in Fig. 10, we found that the individuals who showed improvement in the time estimation task also tended to show most progress in the AB task, $r = 0.33$, $p = 0.026$. In contrast, a similar correlational analysis for the length estimation group showed no significant correlation, $r = 0.07$, $p = 0.61$.

Subsequently, we investigated whether there was a relation between depression scores and attentional performance. The results are shown in Table 1. First, we checked for a correlation between depression scores and AB magnitude in the AB task during the first session, as well as overall performance in the training tasks in session 2 for the two groups, but we found no significant associations. However, when we compared individual depression scores with their learning ability on the different tasks, an intriguing pattern emerged. As shown in Fig. 11, we found that the depression score correlated with the reduction in AB magnitude, as well as with the improvement in the time estimation task.

In contrast, as shown in Fig. 12, individuals in the control group showed no significant correlation between the depression score and the improvements in AB ($r = -0.03$, $p = 0.82$) and length estimation tasks ($r = -0.22$, $p = 0.13$).

General discussion

In this study, we conducted two experiments to investigate whether learning to estimate time can help in learning to control attention, and whether depression modulates this interaction. In both experiments, participants performed an AB task in two sessions. Prior to the second AB task, half the participants received a time estimation task to reproduce 300 ms as accurate as possible (auditory in Experiment 1 and visual in Experiment 2), whereas the other half of participants received a control task (auditory frequency in

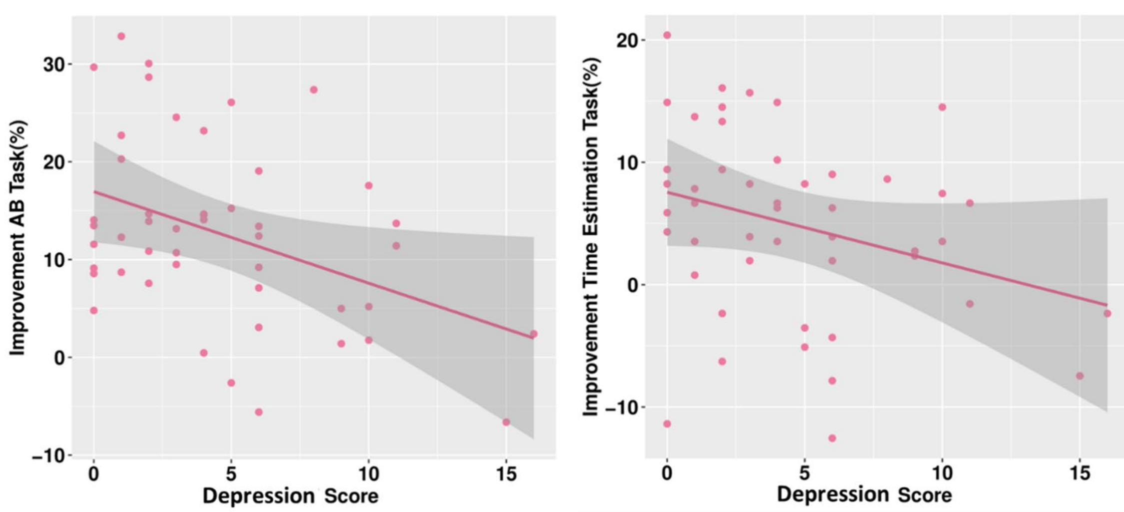

Fig. 11 The correlation between individual depression scores and the improvement in the AB task (trained by time estimation task), and the time estimation task of Experiment 2, respectively. The line represents the linear relationship and the shadow represents the 99% confidence interval

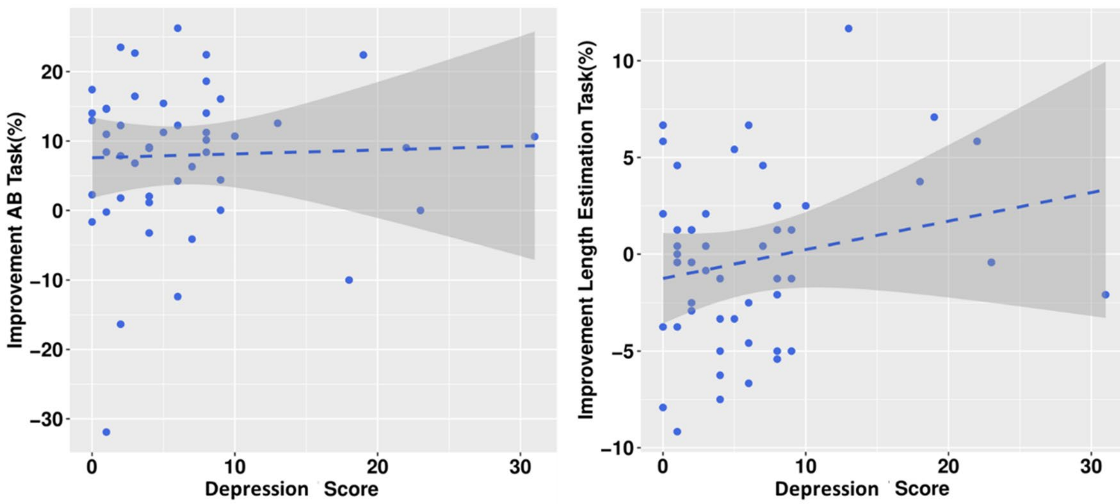

Fig. 12 The non-significant correlation between individual depression scores and improvement in the AB task (trained by length estimation task) and length estimation task in Experiment 2, respectively. The line represents the linear relationship and the shadow represents the 99% confidence interval

Experiment 1 or visual line length estimation in Experiment 2). Though AB performance improved in session 2 for both groups and in both experiments, the reduction in AB magnitude was stronger following the time estimation task. Note that the training effect in our study was nonspecific to modality, suggesting that it is the timing ability at a higher processing level that induces the improvement. Differences at the individual level were only observable when all stimuli were presented in the same visual modality and the target identification in the AB task was sufficiently demanding. This was the case in Experiment 2, where individual improvement in the time estimation task correlated with improvement in the AB task. Whereas we found no evidence that depression level directly influenced overall performance in any of the tasks, it did affect learning performance, such that individuals with higher depression scores showed less learning in the AB task and time estimation task. Interestingly though, this seems to be specific for learning to control and time attention, as the association was absent for the control group who received training with the line estimation task.

The present findings extend previous studies that demonstrated timing to play an important role in the AB. For instance, when temporal information was provided pertaining to the upcoming trial, a reduction of AB magnitude was observed (Martens & Johnson, 2005; Tang et al., 2014). Whereas we found no direct relation between performance on the time estimation task and initial (session 1) AB task performance, we did find that individuals who showed most improvement on the time estimation training task also showed the largest reduction in AB magnitude. Interestingly, this effect was specifically observed after the time estimation training while being absent following two control training tasks (frequency and line estimation). Taken together, apparently there is something specific to the time estimation training task, such that people who did well on that task also improved their performance on the subsequent AB task, a pattern that was not observed following the control training tasks. Unfortunately, it remains unclear how the time estimation training benefited subsequent AB performance in terms of an underlying mechanism or process, such as timing, processing speed, or alertness. This is beyond the scope of the current paper, but it would clearly be an interesting avenue for future research.

Our results provide converging evidence that the AB does not reflect a structural bottleneck (Dell'Acqua et al., 2012; Goodbourn et al., 2016), but rather reflects a limitation to control and time attention that can be improved with specific training (Choi et al., 2012; Taatgen et al., 2009; Willems, et al., 2015a, 2015b) over and above mere repetition of the task (Braun, 1998; Cellini et al., 2015; Dale & Arnell, 2013b; Enns et al., 2017; Maki & Padmanabhan, 1994; Nakatani et al., 2012).

Furthermore, we found evidence that there might be a link between emotional control and the learning potential to control and time attention. That is, we found that depression level can modulate the improvement of performance in the AB task following a time estimation task (Experiment 2). As suggested by the results from a meta-analysis (Rock et al., 2014), cognitive impairments such as 'difficulty in thinking' (Marazziti et al., 2010; Miller, 1975), 'quickly fatigued' and 'concentration difficulties' (Miller, 1975) as well as 'impaired ability to make decisions'(Adida et al., 2011; Clark et al., 2011) are core features of depression rather than epiphenomena. These symptoms, together with previous findings of impaired learning efficiency in depressed people (Austin et al., 1992; Brumback & Staton, 1983; Maag & Reid, 2006) are in line with our results showing impaired training improvements in temporal tasks for depressed individuals.

A number of previous studies have shown that emotional disorders such as depression, anxiety and dysphoria can lead to impairments in temporal attention reflected in a larger AB than healthy controls (Arend & Botella, 2002; Koster et al., 2009; Milders et al., 2016; Rokke et al., 2002). In contrast to these previous studies, we found no relation between depression score and general performance, perhaps because we did not select participants for having a particularly high or low depression score (Rokke et al., 2002). Instead, we studied a continuous sample from the general student population ranging from 0–31 on the BDI-SF (total score 39, mean = 5.41 SEM = 0.56), using emotionally neutral stimuli rather than emotional words (Arend & Botella, 2002; Koster et al., 2009) or emotional faces (Milders et al., 2016) to induce an AB. It is perhaps all the more interesting that we observed a link between depression and the learning potential to control and time attention, indicating that even moderate depression levels can have a negative impact on learning tasks with temporal components. Thus, the results may generalize to a larger part of the general population.

Studies on time perception can be divided along two lines. The first line of research focuses on participants' inner time experience, requiring them to judge whether an event felt relatively long or short. There is indeed evidence that that time experience is altered in depressed patients, for whom time seems to pass slower in comparison to healthy controls (Bech, 1975; Blewett, 1992). The second line of timing studies often makes use of time estimation tasks, in which the participants are asked to reproduce a certain time duration, as the time training task employed in the current study. For that type of study, the evidence for a link between depression and time estimation is less clear. That is, some of those studies fail to find evidence that depression directly influenced time estimation ability (Bech, 1975; Kitamura & Kumar, 1983; Mezey & Cohen, 1961), in line with what we found when merely looking at overall task performance. Others though did find that depression seemed to have a negative impact on performance in a time estimation task. For instance, some studies found that emotional disordered patients tended to overestimate time (Grondin, 2017; Wyrick & Wyrick, 1977), while others reported a larger error in performance (i.e., a mixture of overestimation and underestimation of time) (Dilling & Rabin, 1967; Kuhs et al., 1989, 1991). Our results are in line with the idea that depression level does not influence the ability to estimate time directly (Bech, 1975; Kitamura & Kumar, 1983; Mezey & Cohen, 1961), but instead seems to affect one's ability to improve time estimation and temporal attention.

In Experiment 1 we had some participants whose performance was at ceiling. Our solution was to remove all who had a 100% accuracy T2|T1 accuracy both in session 1 and session 2. We subsequently observed the reduction of the AB after training. Our Experiment 2 was designed to avoid the ceiling effect. Indeed, mean T1 accuracy was 81%, which in the context of the AB is often considered as an ideal level and providing a good balance between performance that is too high (at ceiling) and too low (reducing the number of T2|T1 trials too much). Moreover, to improve the validity of our study, we also performed an analysis with a stricter criterion, both in Experiment 1 and Experiment 2. Balancing both difficulty and the number of participants after exclusion, we decided to set mean T1 accuracy to be maximally 95% as the new criterion in Experiment 1, and T1 accuracy to be 85% as the new criterion in Experiment 2. We obtained similar results using these new criteria as what we reported here. An additional analysis regarding the possibility that our results were actually caused by a ceiling effect, is given in the supplementary information section, which confirmed that this was not the case.

A second limitation was that the performance level of the time training task did not match the performance level in the control tasks, which leaves the possibility that its cognitive load was higher than that of the control tasks. If the timing task required more cognitive investment, there is a possibility that this investment led to higher performance in the subsequent AB task, rather than improvement in timing ability. Note, however, that the accuracy of these different tasks cannot be directly compared. Moreover, performance level of the time training task was artificially determined by the chosen response window of 250–350 ms. A post hoc test further revealed that there was no relationship between the overall accuracy in the training task and improvement in the subsequent AB task ($p = 0.27$ in Experiment 1 and $p = 0.16$ in Experiment 2). Although it remains possible that a difference in cognitive investment between the training tasks may have been responsible for the current results, we believe it is most plausible that an improvement in the time training task led to a better ability to direct and distribute attention during the subsequent AB task as reflected in a reduced AB magnitude.

In conclusion, we found clear evidence that a task requiring participants to estimate a time interval can improve their ability to control temporal attention in a subsequent AB task. The training effect is robust as reflected in a significant reduction of the AB when the training tasks were presented in either the same (Experiment 2) or a different modality (Experiment 1). In Experiment 2, we also found that individuals who showed most improvement in the time estimation task also showed most improvement in the AB task, whereas no such relation was found when participants had performed a control training task (e.g., visual line discrimination). Finally, levels of subclinical depression may be a modulating factor, with a negative impact on individuals' learning ability of both the time estimation and the AB task.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00426-021-01603-5.

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Declarations

Conflict of interest All authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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