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Working memory training for reward processing in university students with subsyndromal depression: The influence of baseline severity of depression

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ABSTRACT

Previous studies have tentatively suggested that working memory training (WMT) has the potential to improve reward processing, but it is not known how long this improvement lasts, whether there is a lag effect, or whether it is reflected in neurophysiological indicators. In this study, 40 university students with subsyndromal depression were randomly assigned to a training group or a control group and completed a 20-day working memory training task and a simple memory task, respectively. All participants completed the Temporal Experience of Pleasure Scale (TEPS) and a doors task with electroencephalogram (EEG) signals recorded simultaneously on a pre- and post-test and a 3-month follow-up. The reward-related positivity (RewP) amplitude, theta power, and their differences between conditions (i.e., ΔRewP and Δtheta power, respectively) in the doors task were the primary outcomes, and the score on TEPS was the secondary outcome. The results indicated no group-related effects were demonstrated in primary and secondary outcomes at post-test and 3-month follow-up. Furthermore, the differences in the pre- and post-test in Δtheta power were moderated by the baseline severity of depression. This was primarily driven by the fact that the change values in the control group increased with the severity of depression, while the change values in the training group had high homogeneity. Our findings did not provide support for the effect of WMT on reward processing across the whole sample, but without intervention, there would be high heterogeneity in the change in the cognitive control ability to loss feedback, which is detrimental to individuals with high depression severity.

1. Introduction

The mental health of the university student population is not favorable due to the pressure from various aspects such as sudden changes in life environment, new social situations, heavy academic burdens, and severe employment situations (Acharya et al., 2018; Y. Li et al., 2021). Particularly since the outbreak of the novel coronavirus disease (COVID-19), the change of study style, the increase of uncertainty in various aspects, and the decrease in employment opportunities have further aggravated the mental health problems of university students (Hou et al., 2021; Y. Li et al., 2021; Wang et al., 2020). Of all the mental health problems, the detection rate of depression is the highest (Eisenberg et al., 2013; Zeng et al., 2019). In China, the results of a recent meta-analysis showed that depression detection rates in the university student population were as high as 20.8% over the ten-year period from 2010 to 2020, with a significant upward trend (Chen et al., 2022). Given that depression not only affects students' academic performance and well-being (Awadalla et al., 2020; Kelifa et al., 2021), but also imposes a significant economic burden on society when diagnosed with major depressive disorders (MDD) (Greenberg et al., 2021), early intervention with university students who have depressive tendencies, but do not yet meet the diagnostic criteria for depression (i.e., subsyndromal depression), is of great relevance and can provide better improvements (Ebert et al., 2019; Hetrick et al., 2008; van Zoonen et al., 2014).

Anhedonia, the diminished ability to experience pleasure or a lack of response to pleasurable stimuli in daily life (Snaith, 1993), is a core symptom of MDD, one of the most important diagnostic criteria for MDD

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in the Diagnostic and Statistical Manual of Mental Disorders-5th Ed. (DSM-5) (American Psychiatric Association, 2013), and one of the most likely psychopathological endophenotypes of MDD (Hasler et al., 2004). Based on the fact that anhedonia is closely associated with altered reward processing (Padrão et al., 2013; Rzepa et al., 2017) and is associated with altered functioning of the brain's dopamine reward circuit at the neural level (Coccurello, 2019; Heshmati & Russo, 2015), the deficits of reward processing may be an important reason for anhedonia in depressed populations. Previous studies have shown that not only patients with MDD exhibit abnormalities in brain activation and functional connectivity between brain regions during reward processing (Ng et al., 2019; W.-N. Zhang et al., 2013), but those at risk who have a family history of MDD were also characterized by altered reward processing (Gotlib et al., 2010). Furthermore, the neural responses to rewarding stimuli could predict subsequent depressive symptoms (Morgan et al., 2013), onset of depression (Bress et al., 2013), and the treatment outcome for depression (Klawohn et al., 2021). Therefore, interventions of reward processing in individuals with subsyndromal depression may be an important pathway to reducing their anhedonia, as well as the severity of depression.

Working memory (WM) is the system in which individuals temporarily store and process information during the performance of cognitive tasks and is considered to be central to human cognitive activity (Baddeley, 1974, 2003). Baddeley and colleagues have proposed the existence of a hedonic detector in their new WM model, suggesting that the manipulation of hedonic information relies heavily on working memory (Baddeley, 2007; Baddeley et al., 2012). In other words, the deficits of reward processing likely reflect a difficulty in retaining pleasurable and rewarding information in WM (Kring & Barch, 2014). The relationship between working memory and reward processing was demonstrated in a series of earlier studies among individuals with schizophrenia by Heerey and colleagues. For example, Heerey et al. (2007) used a delay discounting task and found that patients with schizophrenia exhibited a preference for smaller, immediate rewards compared to healthier volunteers, and individuals with superior working memory exhibited a lesser tendency to devalue future rewards. Heerey and Gold (2007) also found a dissociation between affective experience and motivated behavior and a significant correlation between working memory and the level of concordance in patients with schizophrenia, particularly in the representational responding condition (i.e., participants were asked to press a button to indicate their preference for seeing or not seeing each slide again later, while the stimuli were not visible during their response) rather than evoked responding condition (i.e., participants were instructed to press a button to either increase or decrease the amount of time they viewed the slides while they were on the screen). Furthermore, Heerey et al. (2008) found that in comparing participants with schizophrenia to healthy participants, notable differences were observed in the evaluation of potential outcomes, during the process of selecting between competing response options, and the group differences in the use of potential outcomes during decision-making were due to the impairments in working memory ability. These early studies indicate that working memory is closely related to the maintenance of reward information and its use to guide further behavior. Recent studies showed that a higher working memory load blunted nucleus accumbens responsiveness to reward feedback (Gaillard et al., 2019) and increased discounting rates in the reward task but not in the loss task (Bailey et al., 2018). Neuroimaging findings also demonstrated decreased activation in the ventral and dorsal striatum in highly demanding tasks (Croxson et al., 2009; Kurniawan et al., 2010). Consistent with these, Yee and Braver (2018) also proposed that working memory capacity plays a critical role in reward processing. Thus, the improvement of working memory capacity might be one of the paths to improve reward processing in individuals with subsyndromal depression.

Fortunately, WM is highly plastic and can be improved by training (Zhao & Zhou, 2010). Neuroimaging studies have found that the brain regions improved by working memory training (WMT) are core brain regions for reward processing (e.g., the prefrontal cortex and caudate nucleus; Bäckman et al., 2011; Oldham et al., 2018; Salminen et al., 2016; Silverman et al., 2015). Therefore, WMT has the potential to improve reward processing for university students with subsyndromal depression. Empirical studies have shown that WMT improves response during anticipation of reward stimuli. For example, four weeks of dual N-back WMT reduces reaction time to emotional reward pictures in populations with high social anhedonia (Li, Xiao, et al., 2016) and subsyndromal depressive symptoms (Zhang et al., 2019), and increases the activation intensity of the anterior cingulate cortex, left dorsal striatum, and precuneus in anticipation of emotional rewards; and increases the activation intensity of the dorsolateral prefrontal cortex and supramarginal gyrus in anticipation of monetary rewards in populations with high social anhedonia (Li, Li, et al., 2016).

However, there are some shortcomings in the previous studies: First of all, the three studies mentioned above did not work with an effective "active" control group and thus it is not possible to fully exclude the possibility that the beneficial effects of WMT found are due to some single confounding factor; or, alternatively, multiple confounding factors, such as a "placebo effect", a "practice effect", and so on. Second, the previous studies all collected only pre- and post-test data, which makes it impossible for us to clarify how long the effects lasted or whether some lagged effects were not yet reflected in the post-test. Finally, none of the previous studies involved the examination of neurophysiological activity, which limits our ability to uncover the neural mechanisms underlying the effects of WMT on reward processing. For the first point, this study used active control and asked participants in the control group to complete a simple memory task every training day. For the second point, this study examined not only the immediate effects in the post-test but also the long-term effects of WMT in the 3-month follow-up. For the last point, a classical guessing task was used, and participants' electroencephalogram (EEG) data was simultaneously recorded during the task to examine the effect of WMT on neurophysiological activity during reward processing. In terms of neurophysiological indicators, in recent years, researchers used EEG techniques and found that the reward positivity (RewP), located in the frontocentral sites approximately 300 ms after feedback onset, can be used as a stable electrophysiological indicator of reward processing (Proudfit, 2015). Furthermore, previous studies have shown that RewP is associated with oscillations in the theta band in the medial frontal regions, with the power being higher for losses than for gains (Cohen et al., 2007; Marco-Pallares et al., 2008). The scalp distribution of theta oscillatory activity is slightly skewed to the right and distributed more towards the front than RewP (Nieuwenhuis et al., 2005). Therefore, the RewP amplitude and theta band power were used in this study as neurophysiological indicators of reward processing.

Furthermore, several empirical studies have shown that training duration and sessions affect training as well as transfer effect. For example, Jaeggi et al. (2008) allocated participants of training group into four different training settings, whose crucial difference was the number of training sessions between pre- and posttests, ranging from 8 to 19 sessions (i.e., 8 days, 12 days, 17 days, and 19 days). They found that the training group revealed significant differences of gains in fluid intelligence between the following groups: 8 vs. 17 days; 8 vs. 19 days; and 12 vs. 19 days. In conclusion, they found a significant growth in far transfer throughout the sessions (from 8 to 19 sessions). Stepankova et al. (2014) assigned healthy older adults to train on a verbal N-back task over the course of a month for either 10 or 20 sessions and found a positive relationship between training frequency and the gain in visuospatial skills. A recent meta-analysis also showed the effects of working memory training were moderated by the training length and duration (Teixeira-Santos et al., 2019). Thus, the setting of working memory training is an important but not yet fully studied issue. Looking back at previous studies, the number of sessions ranged from 3 (Borella et al., 2010) to over 100 (Schmiedek et al.,2010), and the duration of a single session also ranged from only 10 min (Owen et al., 2010) to

30–45 min (Olesen et al., 2004). Given that most of the published studies used 20 sessions, each lasting about 30 min (see Von Bastian & Oberauer, 2014), and several training programs directly related to this study were also set in this way (e.g., Li, Li, et al., 2016; Li, Xiao, et al., 2016), this study adopted the same settings.

In summary, referring to previous studies (Chen et al., 2018; Wei et al., 2022), this study asked participants in the training group to complete the adaptive running working memory task five days per week (once a day, in an available time slot), for a duration of one month, and asked participants in the control group to complete a simple memory task five days per week (once a day, in an available time slot), for a duration of one month. In the pre- and post-tests and the 3-month follow-up test, these data were analyzed: (1) RewP amplitude, theta power and their differences between conditions (i.e., ΔRewP and Δtheta power, respectively) in completing the guessing task (i.e., doors task) as the primary outcomes; and (2) self-reported experiential pleasure as the secondary outcome. Also, participants' WM capacity was investigated at the pre-, post-, and 3-month follow-up tests. Overall, it was hypothesized that the training group would have significantly higher gains in these outcomes than the control group at both post-test and 3-month follow-up. Furthermore, as previous studies have shown differences in improvements after WMT between depressed and healthy groups (Zhang et al., 2019) and individual differences at baseline can affect the effects of WMT (Studer-Luethi et al., 2012, 2016; Wiemers et al., 2019), another goal was to explore whether baseline severity of depression would moderate the effects of WMT on primary and secondary outcomes and hypothesized that participants with higher baseline severity of depression would benefit more from the WMT.

2. Methods

2.1. Participants

All of the procedures involving human participants were performed in accordance with the ethical standards of the institutional or national research committee, and the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. This study was approved by the Ethical Evaluation of Research Projects of the Department of Psychology in the School for Social and Behavioral Sciences at Nanjing University. All participants provided informed written consent.

Based on Li, Xiao, et al. (2016), an effect of $f = 0.34$ was assumed for the sample size calculation of our primary and secondary outcomes at post-test. Using G*Power, an α of 0.05 and a β of 0.80 suggested 14 participants (i.e., 7 participants per group) would be needed to detect an interaction effect in the 2 (*Group*: training group vs. control group) × 2 (*Condition*: losses vs. gains) × 2 (*Time*: pre-test vs. post-test) analysis. In addition, since none of the related previous studies conducted follow-up tests, referring to previous intervention studies (Wen et al., 2021), an attrition rate of 20% was assumed and used a medium effect size ($f = 0.25$) for the calculation at 3-month follow-up. The results suggested that 30 participants (i.e., 15 participants per group) would be needed to detect an interaction effect in the 2 (*Group*: training group vs. control group) × 2 (*Condition*: losses vs. gains) × 2 (*Time*: pre-test vs. 3-month follow-up) analysis.

University students aged 18–25 years were recruited through the Internet and posters at Nanjing University. Volunteer university students were screened according to the Beck Depression Inventory—Second Edition—Chinese (BDI-II-C), and participants with severe anxiety were excluded using the Beck Anxiety Inventory (BAI). The inclusion criteria were delineated according to previous studies (Beck et al., 1996; Yang & Xiong, 2016), as follows: BDI-II-C score ≥ 14, and BAI score < 45. The exclusion of high anxiety symptoms is due to the high co-occurrence of anxiety and depression from adolescence to midlife (see Lallukka et al., 2019), and the high prevalence of anxiety among college students (see Li et al., 2022). In addition, they were also required to meet the following criteria: right-handedness, normal visual acuity or corrected visual acuity, self-reported absence of any psychiatric disorders, non-smoker, non-drinker, and not be taking any psychostimulant drugs. Upon arriving at the laboratory, all participants completed the Chinese version of the Mini International Neuropsychiatric Interview, based on the Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition (DSM-IV) and the International Statistical Classification of Mental Disorders (ICD-10) (Si et al., 2009) to exclude 16 kinds of Axis I psychiatric disorders and antisocial personality disorder.

Finally, 43 participants met the above requirements were recruited and randomly assigned to the training and control groups (as shown in Fig. 1). Due to dropouts (some participants failed to complete the training task or post-test on time), 40 participants comprised the final sample. There were 20 in the training group (mean age: 22.35 ± 1.65 years, 13 females) and 20 in the control group (mean age: 22.40 ± 2.24 years, 11 females). There were no significant differences in age ($t\,[38] = -0.08$, $p = 0.94$) and sex ratio ($\chi^2\,[1] = 0.42$, $p = 0.52$) between the two groups.

Finally, all participants received a cash payment at the end of the experiment.

2.2. Measures

2.2.1. Participants screening scales

The Chinese Version of the Beck Depression Inventory—II—Chinese (BDI-II-C), developed by Beck et al. (1996), was used to assess participants' severity of depression. The scale contains twenty-one items, with each item comprising four ordinal categories (from 0 through 3). The absence of a depressive symptom in each item is scored as "0" and presence of the symptom is scored between 1 and 3, with higher scores indicating more intense symptom severity. According to the threshold values defined in the revision of the questionnaire, a total score of 0–13 indicates no depression, 14–19 indicates mild depression, 20–28 indicates moderate depression, and 29–63 indicates severe depression. After the revision of the Chinese version, the scale has good reliability in the university student population with an alpha coefficient of 0.85 (Yang et al., 2012).

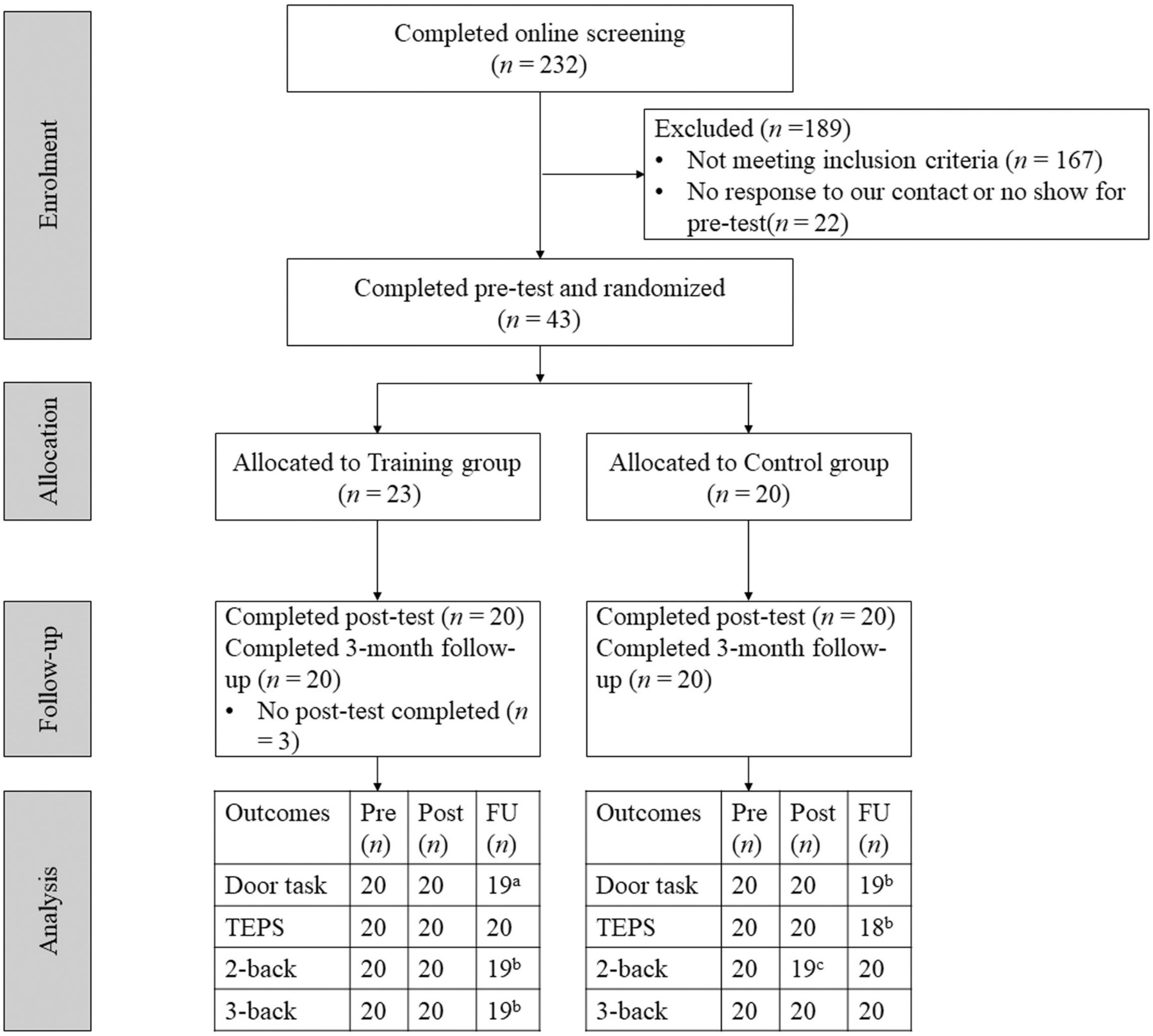
The Beck Anxiety Inventory (BAI), developed by Beck et al. (1988), was used to assess participants' severity of anxiety. The scale contains twenty-one items and is scored on a 4-point Likert scale ranging from 1 (not at all) to 4 (severely), with higher scores indicating higher levels of anxiety. A standard score (defined as int [1.19 × raw total score]) ≥ 45 is the threshold value, indicating that the individual has a high level of anxiety. After the revision of the Chinese version, the scale has a good reliability with an alpha coefficient of 0.95 (Zheng et al., 2002).

2.2.2. Primary outcomes: Doors task

The doors task shown in Fig. 2 was used to examine the neurophysiological responses of participants after receiving feedback. During each trial, participants were asked to guess two adjacent doors, with a monetary reward for a correct guess. Specifically, participants first made a choice, and a 1000-ms fixation appeared at the end of the choice, followed immediately by a feedback interface, where an upward green arrow appeared if the participant guessed correctly, indicating a ¥1 gain, and a downward red arrow appeared if the participant guessed incorrectly, indicating a ¥0.50 loss, with the feedback interface presented for 2000 ms. After the feedback, a 1500-ms fixation was followed immediately by the participant pressing a button themself to start the next trial. The gains and losses feedback were presented in a randomized manner for 20 trials each, and the experiment contained a total of 40 trials. EEG data were recorded simultaneously throughout the task, and the details of the EEG data acquisition and analysis are described below.

2.2.3. Secondary outcomes: temporal experience of pleasure scale

The Temporal Experience of Pleasure Scale (TEPS) developed by Gard et al. (2006), was used to assess participants' anticipatory and consummatory pleasure experiences. The scale consists of eighteen



Outcomes	Pre (n)	Post (n)	FU (n)
Door task	20	20	19^a
TEPS	20	20	20
2-back	20	20	19^b
3-back	20	20	19^b

Outcomes	Pre (n)	Post (n)	FU (n)
Door task	20	20	19^b
TEPS	20	20	18^b
2-back	20	19^c	20
3-back	20	20	20

Fig. 1. Participant flowchart. Note. TEPS = Temporal Experience of Pleasure Scale; Pre = pre-test; Post = post-test; FU = follow-up. Missing data: ^{a} participants completed the task but the valid trials were too low (< 10 for any condition) for the EEG data; ^{b} participants did not complete the tests; ^{c} participants finished the tests, but the data were not correctly stored due to a technical error.

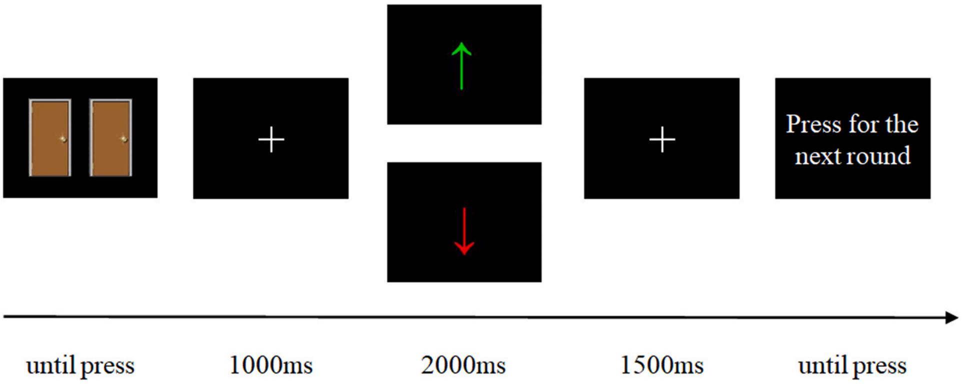


Fig. 2. Schematic representation of the doors task, which was completed by all participants at pre- and post-test and 3-month follow-up.

items on a 6-point Likert scale ranging from 1 (very false for me) to 6 (very true for me), with higher scores indicating better hedonic capability. After the revision of the Chinese version, it was further clarified that there are four dimensions in the Chinese cultural context: anticipatory contextual pleasure, anticipatory abstract pleasure, consummatory contextual pleasure, and consummatory abstract pleasure. Due to the low loadings of item 13, it was removed, and two new items were added, leaving 19 items in the final version. After the revision of the Chinese version, the scale has good reliability with an alpha coefficient of 0.83 (Chan et al., 2012).

2.2.4. WM capacity: N-back task

The 2-back and 3-back tasks were used to measure participants' working memory capacity. In the 2-back task, participants were asked to compare whether the current digit was the same as the second digit that had been presented previously. In the 3-back task, participants were asked to compare whether the current digit was the same as the third digit that had been presented previously. After excluding the results of the first two and three trials of 2-back and 3-back, respectively, the accuracy of the training and control groups in the pre- and post-test and 3-month follow-up were computed. Then, the reaction time of the training and control groups in the pre- and post-test and 3-month follow-up were computed after removing incorrect trials and trials with a reaction time exceeding 3 standard deviations from the mean.

2.3. Training task

The training task for the training group was an adaptive running working memory task, which was nested within a self-developed stand-alone application and trained on a ThinkPad laptop in the laboratory. The application has three main functional modules: a login, training, and report module, which implement the three core functions of randomly assigning groups, training, and generating daily training reports, respectively. The software was developed through requirement analysis, interactive interface design, code writing, application testing and iteration to achieve a balance between basic functions and page layout. The training task for the control group task was a simple memory task, which was developed using E-prime 2.0, and also ran on ThinkPad laptops in the laboratory. The following is a detailed description of the training tasks for the two groups.

2.3.1. Running working memory task

A modified version of the previously employed running working memory task was used (Xiu et al., 2016, 2018). In the present study, the first ten days of training were all unidimensional updating training, which includes three different versions: 'image', 'digit', and 'location [3]' (i.e., remembering the last 3 locations); while in the second ten days, the training was upgraded to a two-dimensional task, which also includes three different versions: 'image + image', 'letter + image', and 'location [4]' (i.e., remembering the last 4 locations), as shown in Fig. 3.

As an example, the procedure of the digit running working memory task was as follows: First, a 300-ms fixation appeared in the center of the screen, and then a series of digits were presented in sequence, with the number of digits varying randomly among 5, 7, 9, and 11. Participants were asked to remember the last three digits, in order. Finally, participants used the keyboard to enter the last three digits in sequences. After completing one trial, participants pressed the OK button to start the next trial. Participants were required to complete 30 trials that were separated into 6 blocks of 5 trials each. The presentation time of digits varied according to participants' performance on the task, starting with a presentation time of 1750 ms. The presentation time of digits in the next block would drop by 100 ms if participants correctly completed three or more trials in the present block. However, if participants correctly completed, in the present block, just two trials or just one trial or no trial, the presentation time of digits in the next block would increase by 100 ms. The presentation time of digits in the next day's training was set identical to the last block's presentation time on the previous day. The other versions were completely analogous to the digit running working memory task, except that the memory objects were replaced with images and spatial positions instead of digits. No strict time limit was set for training. Participants spent about 30 min a day completing the training at the beginning, and about 20 min on the last training day.

2.3.2. Simple memory task

In order to avoid the placebo effect, the control group was also assigned a simple memory task. Participants were asked to complete a 90-trial memory task every training day, five days a week (as shown in Fig. 4). Firstly, a 300-ms fixation appeared in the center of the screen. Next, an animal appeared in the center of the screen, which was displayed for 1750 ms. Then, nine different animals were presented as choice options, and participants were asked to recall which animal had been shown before. Because of the simplified nature of this memory task, participants were asked to complete it as quickly as possible. Participants spent about 10 min a day completing the training.

2.4. Procedure

Participants first completed the screening questionnaires online along with information on demographic variables (including sex, age, and profession, etc.), and then those who met the inclusion criteria came to the laboratory to complete the pre-test and were randomly assigned to the training or control group. Then, all participants came to the laboratory for the next four weeks to complete 20 corresponding training sessions according to their group. At the end of the training, participants came back to complete the post-test task and complete the follow-up task 3 months after the post-test. For each test, participants first completed the TEPS, then completed the EEG data collection, and finally completed the N-back task. Because there were differences in the time participants completed the training and slight differences in the time they took the 3-month follow-up test, independent samples *t*-tests were conducted for time interval 1 (i.e., the interval between pre- and post-tests, 34.97 ± 10.20 vs. 39.69 ± 11.59) and interval 2 (i.e., the interval between post-test and 3-month follow-up; 133.44 ± 35.40 vs. 130.20 ± 48.84) and found no significant differences between the two groups at either interval ($|t|s < 1.37, p > 0.18$).

2.5. Data analysis

2.5.1. EEG data acquisition and primary outcome extraction

The EEG data were recorded using Curry8–40 scalp electrodes placed according to the International 10–20 system (passband: 0.01–100 Hz, sampling rate: 1000 Hz). Prior to recording, the impedances were below 10 kΩ. During recording, the ground lead and reference were both located at the midpoint of the FPz and Fz. The VEOG electrode was placed in the middle of the left orbital and infraorbital respectively, and the HEOG was placed in the left and right lateral canthus.

After collection, EEGLAB (Delorme & Makeig, 2004; https://sccn.ucsd.edu/eeglab/index.php) was used to pre-process the data. First, the data were re-referenced to the average mastoids. Second, 30 Hz low-pass filtering and 1 Hz high-pass filtering were performed on the data. Third, the EEG epochs were extracted using a window time from − 1000 to 2000 ms that was time-locked to the feedback onset. Fourth, the data of bad electrode sites was replaced with the arithmetic mean of adjacent electrode sites using the linear interpolation method, and epochs with large drift at any electrode were manually removed. Finally, trials contaminated by eye blinks and motion artifacts were corrected using an independent component analysis algorithm. The valid trials retained under each condition at each time point of each group are shown in Table 1.

Referring to previous studies (Bress et al., 2012, 2013), the EEG data used for event-related potentials (ERP) analysis were baseline corrected using the pre-stimulus interval (- 200–0 ms). Then, consistent with previous research and based on visual inspection of ERP waveforms and topographical maps, RewP amplitudes in the losses and gains conditions were quantified as the mean amplitude at FCz between 250 and 350 ms post-stimulus onset (Bress et al., 2012, 2013; Foti & Hajcak, 2009; Holroyd & Krigolson, 2007; Liu et al., 2014). Referring to Levinson et al. (2017), to assess the split-half reliability of the ERPs, we separately averaged the odd and even trials for the gain and loss feedback. The Spearman-Brown split-half reliability for gains was 0.91, 0.84, and 0.98 for pre-test, post-test, and 3-month follow-up, respectively. For the loss feedback, the Spearman-Brown split-half reliability was 0.96, 0.88, and 0.95 for pre-test, post-test, and 3-month follow-up, respectively. We

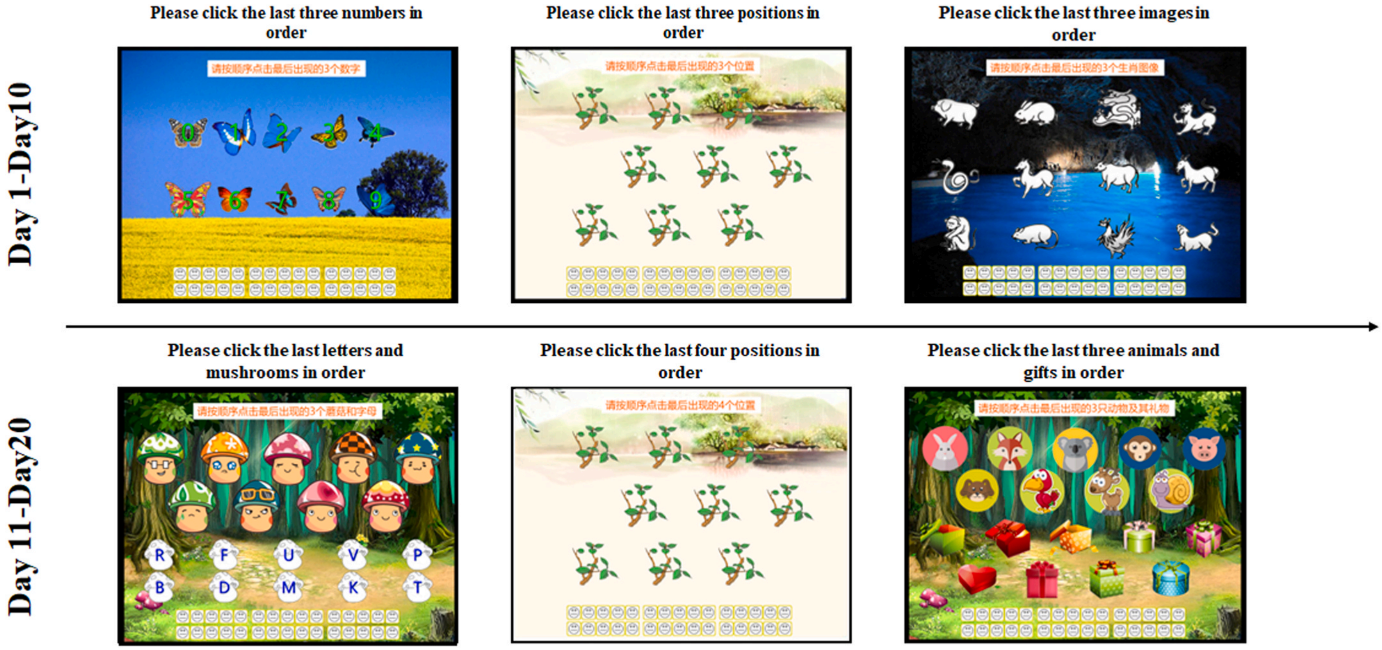


Fig. 3. Schematic representation of the running working memory task, which was completed by the training group every training day.

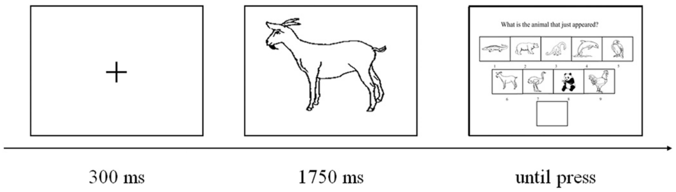


Fig. 4. Schematic representation of the easy memory task, which was completed by the control group every training day.

have also calculated Cronbach's alphas, which all demonstrated accepted reliability (> 0.70). Please refer to the Supplementary Materials for details. Referring to previous studies (Bress et al., 2013), we also computed ΔRewP, which was quantified as the difference between mean amplitude to monetary gains versus losses.

Time–frequency distributions of EEG trials were obtained using a windowed Fourier transform (WFT) with a fixed 200 ms Hanning window. This WFT yielded, for each EEG trial, a complex time–frequency estimate $F(t, f)$ at each time–frequency point (t, f), extending from − 2000–1000 ms in the time domain (in steps of 1 ms), and from 1 to 30 Hz (in steps of 1 Hz) in the frequency domain. The resulting spectrogram, $P(t, f) = ||F(t, f)||^2$, representing the signal power as a joint function of time and frequency at each time–frequency point, contained

Table 1
Summary statistics for data quality and outcomes by *Condition* and *Time* (*M* ± *SD*).

Outcomes	Training group ($n = 20$)[a]			Control group ($n = 20$)[a]		
	Pre-test	Post-test	3-month follow-up	Pre-test	Post-test	3-month follow-up
Data Quality						
Valid trials of the doors task_Gains	18.65 ± 1.79	18.90 ± 1.07	17.60 ± 3.47	18.45 ± 2.46	18.75 ± 2.02	19.00 ± 1.29
Valid trials of the doors task_Losses	18.70 ± 1.26	18.90 ± 1.33	17.15 ± 3.30	18.15 ± 2.68	18.35 ± 2.35	18.89 ± 1.29
Primary Outcomes						
Doors task_choice (f)	18.95 ± 6.35	20.50 ± 7.34	21.00 ± 3.89	20.40 ± 6.33	19.70 ± 6.04	21.40 ± 5.75
Doors task_RT (ms)	779.18 ± 416.98	570.85 ± 211.75	532.79 ± 140.86	1049.95 ± 1087.59	658.01 ± 451.03	852.52 ± 1161.20
RewP_Gains (μv)	2.98 ± 3.89	2.73 ± 3.89	3.80 ± 6.32	2.28 ± 3.24	2.16 ± 2.43	5.49 ± 7.62
RewP_Losses (μv)	1.85 ± 4.08	2.15 ± 3.27	2.96 ± 5.21	1.70 ± 2.86	1.81 ± 2.36	4.02 ± 6.33
Theta_Gains (μv^2)	0.10 ± 0.19	0.09 ± 0.15	0.04 ± 0.36	0.05 ± 0.08	0.01 ± 0.13	0.08 ± 0.38
Theta_Losses (μv^2)	0.18 ± 0.25	0.17 ± 0.21	0.18 ± 0.63	0.10 ± 0.14	0.11 ± 0.38	0.09 ± 0.28
Secondary Outcomes						
TEPS_AA	19.70 ± 3.05	19.80 ± 3.30	19.70 ± 3.13	20.25 ± 3.21	19.65 ± 3.94	19.89 ± 3.05
TEPS_AC	18.95 ± 4.37	19.35 ± 3.98	21.00 ± 3.77	18.60 ± 5.21	17.75 ± 3.74	19.89 ± 3.79
TEPS_CC	27.75 ± 6.03	28.90 ± 4.05	28.30 ± 3.79	28.60 ± 5.35	28.85 ± 3.42	30.06 ± 3.86
TEPS_CA	17.60 ± 3.44	16.75 ± 4.12	18.35 ± 2.94	15.85 ± 4.13	17.65 ± 4.12	17.28 ± 3.55
N-back task						
2-back_ACC	0.95 ± 0.05	0.97 ± 0.04	0.98 ± 0.03	0.93 ± 0.05	0.97 ± 0.04	0.97 ± 0.03
2-back_RT (ms)	552.41 ± 202.71	440.02 ± 215.20	399.50 ± 151.40	558.30 ± 198.40	492.81 ± 204.30	426.11 ± 175.44
3-back_ACC	0.89 ± 0.07	0.94 ± 0.06	0.95 ± 0.06	0.87 ± 0.09	0.96 ± 0.06	0.95 ± 0.04
3-back_RT (ms)	619.55 ± 226.53	453.25 ± 186.54	399.29 ± 187.43	636.69 ± 250.64	487.52 ± 217.23	469.56 ± 399.29

Note. RT = Reaction Time; TEPS_AA = Temporal Experience of Pleasure Scale—anticipatory abstract, TEPS_AC = Temporal Experience of Pleasure Scale—anticipatory contextual, TEPS_CA = Temporal Experience of Pleasure Scale—consummatory abstract, TEPS_CC = Temporal Experience of Pleasure Scale—consummatory contextual; ACC = Accuracy.

[a] The number of participants for the analysis of each variable is shown in Fig. 1.

brain responses both phase-locked (i.e., ERP) and non-phase-locked (event-related synchronization and desynchronization, ERS and ERD, respectively) to laser stimulation (Mouraux & Iannetti, 2008). Based on visual inspection of spectrograms and topographical maps and considering previous studies that have shown feedback theta peaks at frontal midline sites (see Glazer et al., 2018), consistent with previous research, we extracted power values of theta (4–8 Hz, 200–400 ms) at the FCz electrode (Ethridge et al., 2020; Tsypes et al., 2021). Furthermore, the EEG data used for time–frequency analysis were baseline corrected using the pre-stimulus interval (-500 to -200 ms) by subtracting the mean values of the baseline (Cona et al., 2020). Referring to previous studies (Tsypes et al., 2021), we also computed Δtheta power, which was quantified as the difference between mean power to monetary losses versus gains.

2.5.2. *Statistical analysis*

Given the exploratory nature of this study, training effects at both post-test and 3-month follow-up were primarily tested by using a complete case analysis method. Specifically, training effects at post-test were evaluated based on participants who completed outcomes at both pre-test and post-test, and training effects at 3-month follow-up were evaluated based on participants who completed outcomes at both pre-test and 3-month follow-up (see Fig. 1 for participant flowchart).

First, a series of independent samples *t*-tests and ANOVAs were used to test for between-group differences in the pre-test. Specifically, 2 (*Group*: training group vs. control group) × 2 (*Condition*: losses vs. gains) repeated measures ANOVAs were used to examine the effects of *Group* and *Condition* on RewP amplitude and theta power, respectively, and independent samples *t*-tests were used to test for between-group differences in pre-test ΔRewP, Δtheta, TEPS questionnaire scores, and N-back task data. Second, a series of paired samples *t*-tests were used to examine the change in performance on the running working memory task. Third, a series of ANOVAs were used to examine the training effects of post-test and 3-month follow-up. Specifically, for the EEG data, mixed ANOVAs of 2 (*Group*: training group vs. control group) × 2 (*Condition*: losses vs. gains) × 2 (*Time*: pre-test vs. post-test/3-month follow-up) were used to examine the effects of *Group*, *Condition* and *Time* on RewP amplitude and theta power, respectively. Furthermore, mixed ANOVAs of 2 (*Group*: training group vs. control group) × 2 (*Time*: pre-test vs. post-test/3-month follow-up) were used to examine the effects of *Group* and *Time* on ΔRewP and Δtheta, respectively. For the TEPS scale scores, 2 (*Group*: training group vs. control group) × 2 (*Time*: pre-test vs. post-test/3-month follow-up) mixed ANOVAs were used to examine the effects of *Group* and *Time* on TEPS scores, respectively. For the N-back task data, 2 (*Group*: training group vs. control group) × 2 (*Time*: pre-test vs. post-test/3-month follow-up) mixed ANOVAs were used to examine the effects of *Group* and *Time* on the reaction time and accuracy of 2-back and 3-back tasks. For all of the ANOVAs, *Group* was a between-group variable, while *Time* and *Condition* were within-group variables. Finally, a series of linear-regressions analyses with *Group*, *severity of depression*, and their interaction term as independent variables and the change values (*post-test – pre-test* and *follow-up – pre-test*, respectively) of the primary and secondary outcomes as dependent variables were used to examine whether the training effects were influenced by baseline *severity of depression*. In this case, *Group* was treated as a dummy variable, while *severity of depression* and the dependent variables were analyzed using Z-standardized scores. Where necessary, Greenhouse–Geisser correction was used. Significant findings underwent follow-up assessment with the Bonferroni post hoc test. Effect sizes are reported as η_p^2 and *Cohen's d* values. The above data analyses were performed using the SPSS 22.0 software package.

Furthermore, Bayes Factor (BF) results were also calculated using the default settings of JASP (https://jasp-stats.org/). We reported BF_{10} and BF_{01} for significant and nonsignificant *p*-values in *t*-tests to indicate the evidence of support for H1 and H0 models, respectively. For ANOVAs, we reported BF inclusion / BF exclusion values (i.e., BF_{incl} and BF_{excl}) from the tables of *Analysis of Effects* across matched models for significant and nonsignificant *p*-values, respectively as suggested by Sebastiaan Mathôt (see van den Bergh et al., 2020)[1] and widely used in the previous studies (e.g., Fratescu et al., 2019; Shen et al., 2020; Wardhani et al., 2020). For linear regression models, we reported BF_{incl} and BF_{excl} from the tables of *Posterior Summaries of Coefficients* across matched models for significant and nonsignificant *p*-values,[2] respectively (see van den Bergh et al., 2021). For BF values, 1–3 is considered to be anecdotal evidence supporting the corresponding hypothesis (e.g., BF_{10} or $BF_{\text{incl}} = 1.20$ means anecdotal evidence supporting the hypothesis H1, while BF_{01} or $BF_{\text{excl}} = 1.20$ means anecdotal evidence supporting the hypothesis H0); 3–10 is considered to be moderate evidence supporting the corresponding hypothesis; 10–30 is considered to be strong evidence supporting the corresponding hypothesis; 30–100 is considered to be very strong evidence supporting the corresponding hypothesis; > 100 is considered to be extremely strong evidence supporting the corresponding hypothesis (Litton, 1961).

3. Results

Means and standard deviations for all of the outcomes for the training group and the control group at the pre-test, post-test, and 3-month follow-up are presented in Table 1.

3.1. *Baseline differences between the training and control groups*

The results of the ANOVA showed that for RewP amplitude, the main effect of *Condition* was significant ($F\,[1,38] = 9.74$, $p = 0.003$, $\eta_p^2 = 0.20$, $BF_{\text{incl}} = 10.34$), with higher amplitude in the gains than in the losses; while the main effect of *Group* and the *Group* × *Condition* interaction effect were not significant (*F*s $[1,38] < 1.00$, *p*s > 0.32, $BF_{\text{excl}} = 1.75$ and 2.12 for the main effect of *Group* and the *Group* × *Condition* interaction effect, respectively). For theta power, the main effect of *Condition* was significant ($F\,[1,38] = 8.60$, $p = 0.01$, $\eta_p^2 = 0.19$, $BF_{\text{incl}} = 7.14$), with the power in the losses significantly higher than the gains; while neither the main effect of *Group* nor the *Group* × *Condition* interaction effect were significant (*F*s $[1,38] < 1.33$, *p*s > 0.26, $BF_{\text{excl}} = 1.54$ and 2.63 for the main effect of *Group* and the *Group* × *Condition* interaction effect, respectively). Independent samples *t*-tests showed that the two groups did not differ significantly on the ΔRewP, Δtheta, N-back tasks, TEPS scale scores, and behavioral indicators of the doors task ($|t|$s < 1.46, *p*s > 0.15, $1.41 < BF_{01} < 3.23$). Therefore, there were no significant baseline differences between the two groups.

3.2. *Training gains*

As shown in Fig. 5, the performance of the training group continually improved with training. The improvement in working memory capacity was demonstrated by the fact that at each stage, the stimulus presentation time on the last day was significantly smaller than the stimulus presentation time on the first day. Specifically, during the first ten days of training the times were, for the 'digit' version: 1437.50 ± 161.78 vs. 201.20 ± 30.32, $t\,(19) = 34.46$, $p < 0.001$, $Cohen's\ d = 10.62$, $BF_{10} = 2.38 * 10^{15}$; for the 'location [3]' version: 1539.35 ± 159.77 vs. 219.65 ± 55.02, $t\,(19) = 35.04$, $p < 0.001$, $Cohen's\ d = 11.04$, $BF_{10} = 3.20 * 10^{15}$; for the 'image' version: 1431.75 ± 207.97 vs. 494.85 ± 102.84, $t\,(19) = 17.86$, $p < 0.001$, $Cohen's\ d = 5.71$, $BF_{10} = 2.58 * 10^{10}$.

During the latter 10 days of training, for the 'letter + image' version:

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[1] See also https://www.cogsci.nl/blog/interpreting-bayesian-repeated-measures-in-jasp

[2] Although the relationships between BF_{10} and BF_{01} and BF_{incl} and BF_{excl} are obvious, it is more plausible and better interpreted to report different indicators when their *p*-values are significant and non-significant, respectively.

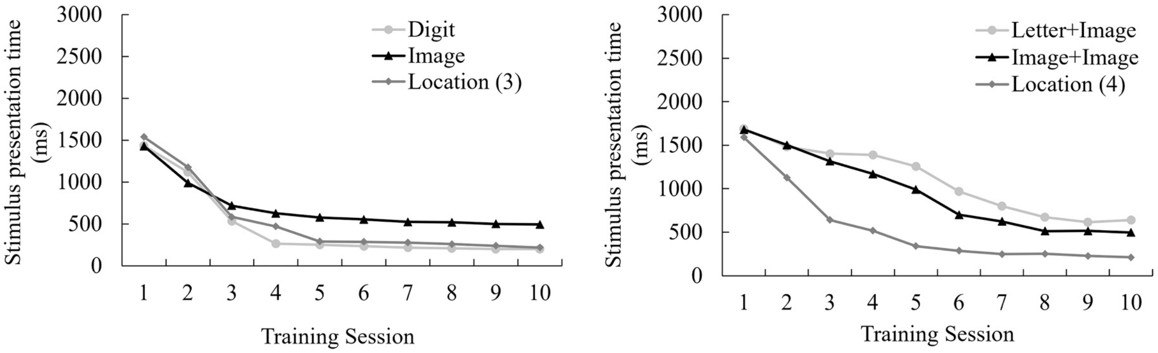

Fig. 5. Item presentation time of the three working memory training tasks throughout the (left) first 10 training days (for digit, image, and location [3] running working memory tasks, respectively); and (b) last 10 training days (for letter + image, image + image, and location [4] and running working memory tasks, respectively).

1690.15 ± 66.77 vs. 638.55 ± 120.32, $t\ (19) = 34.71$, $p < 0.001$, *Cohen's d* $= 10.81$, $BF_{10} = 2.72 * 10^{15}$; for the 'location [4]' version: 1591.40 ± 162.74 vs. 212.25 ± 31.96, $t\ (19) = 36.21$, $p < 0.001$, *Cohen's d* $= 11.76$, $BF_{10} = 5.76 * 10^{15}$; for the 'image + image' version: 1680.00 ± 97.87 vs. 498.35 ± 98.81, $t\,(19) = 37.96$, $p < 0.001$, *Cohen's d* $= 12.01$, $BF_{10} = 1.33 * 10^{16}$.

3.3. *Training effects at post-test*

3.3.1. *Primary outcomes: behavioral and EEG results for doors task*

For the choice of doors task (pressing 'f' or 'j'), the main effect of *Time*, the main effect of *Group*, and the *Group* × *Time* interaction effect were not significant (*Fs* $[1,38] < 1.50$, *ps* > 0.23, $1.81 < BF_{\text{excl}} < 3.79$). For the reaction time of the doors task, the main effect of *Time* was significant ($F\ [1,38] = 9.09$, $p = 0.005$, $\eta_p^2 = 0.19$, $BF_{\text{incl}} = 8.95$), with a shorter reaction time post-test than the pre-test; while the main effect of *Group* and the *Group* × *Time* interaction effect were not significant (*Fs* $[1,38] < 1.06$, *ps* > 0.31, $BF_{\text{excl}} = 1.95$ and 2.24 for the main effect of *Group* and the *Group* × *Condition* interaction effect, respectively).

For RewP amplitude, the main effect of the *Condition* was significant ($F\ [1,38] = 14.70$, $p < 0.001$, $\eta_p^2 = 0.28$, $BF_{\text{incl}} = 0.62$, see Fig. 6), with higher amplitude in the gains than that in the losses; while other main and interaction effects were not significant (*Fs* $[1,38] < 1.36$, *ps* > 0.25, $2.91 < BF_{\text{excl}} < 5.76$). For ΔRewP, no significant effect was found (*Fs* $[1,38] < 1.36$, *ps* > 0.25, $2.18 < BF_{\text{excl}} < 3.03$).

For theta power, the main effect of the *Condition* was significant ($F\ [1,38] = 9.18$, $p = 0.004$, $\eta_p^2 = 0.20$, $BF_{\text{incl}} = 3.26$, see Fig. 7), with the power in the losses significantly higher than the gains; while other main and interaction effects were not significant (*Fs* $[1,38] < 2.62$, *ps* > 0.11, $1.64 < BF_{\text{excl}} < 5.53$). For Δtheta power, no significant effect was found (*Fs* $[1,38] < 1.19$, *ps* > 0.67, $2.80 < BF_{\text{excl}} < 3.95$).

Regression analyses revealed that for changes (*post-test – pre-test*) in RewP amplitude, ΔRewP, and theta power, none of the predictive effects of the *severity of depression* × *Group* interaction term were significant (*ps* > 0.09, $0.60 < BF_{\text{excl}} < 3.86$). However, for the changes in Δtheta, the predictive effects of the *severity of depression* ($\beta = 0.40$, $t = 2.93$, $p = 0.01$, $BF_{\text{incl}} = 12.35$) and *severity of depression* × *Group* interaction term ($\beta = -0.35$, $t = -2.52$, $p = 0.02$, $BF_{\text{incl}} = 5.72$, see Fig. 8) were significant. Specifically, for the control group, the changes in Δtheta increased with increasing *severity of depression* ($\beta = 0.76$, $t = 4.22$, $p = 0.001$), but for the training group, the change in Δtheta did not increase with increasing *severity of depression* ($\beta = 0.05$, $t = 0.24$, $p = 0.81$). Furthermore, no significant differences were found in the change in Δtheta between the training and control groups for individuals with either low or high severity of depression (*ps* > 0.08).

3.3.2. *Secondary Outcomes: self-reported pleasure experience*

The ANOVA results showed that for the anticipatory abstract pleasure of the TEPS questionnaire, the main effects of *Time* and *Group*, and the *Group* × *Time* were not significant (*Fs* $[1,38] < 0.18$, *ps* > 0.68, $3.47 < BF_{\text{excl}} < 3.83$); for the anticipatory contextual pleasure of the TEPS questionnaire, the main effects of *Time* and *Group*, and the *Group* × *Time* were not significant (*Fs* $[1,38] < 1.01$, *ps* > 0.32, $2.57 < BF_{\text{excl}} < 4.26$); for the consummatory abstract pleasure of the TEPS questionnaire, the main effects of *Time* and *Group*, and the *Group* × *Time* were not significant (*Fs* $[1,38] < 0.34$, *ps* > 0.57, $3.11 < BF_{\text{excl}} < 3.63$); for the consummatory contextual pleasure of the TEPS questionnaire, the main effects of *Time* and *Group*, and the *Group* × *Time* were not significant (*Fs* $[1,38] < 2.82$, *ps* > 0.10, $1.02 < BF_{\text{excl}} < 3.43$). In addition, the *severity of depression* × *Group* interaction term was not significant in predicting the change in TEPS scores for each dimension (*ps* > 0.25, $2.46 < BF_{\text{excl}} < 3.26$).

3.3.3. *WM capacity*

For the accuracy of 2-back task, the main effect of *Time* was significant ($F\ [1,37] = 15.30$, $p < 0.001$, $\eta_p^2 = 0.29$, $BF_{\text{incl}} = 148.23$), with increased accuracy from pre-test to post-test; while the main effect of *Group* and the *Group* × *Condition* interaction effect were not significant (*Fs* $[1,37] < 1.84$, *ps* > 0.18, $BF_{\text{excl}} = 3.06$ and 1.42 for the main effect of *Group* and the *Group* × *Condition* interaction effect, respectively). For the reaction time of 2-back task, the main effect of *Time* was significant ($F\ [1,37] = 4.74$, $p = 0.04$, $\eta_p^2 = 0.11$, $BF_{\text{incl}} = 2.25$), with decreased reaction time from pre-test to post-test; while the main effect of *Group* and the *Group* × *Condition* interaction effect were not significant (*Fs* $[1,37] < 0.39$, *ps* > 0.54, $BF_{\text{excl}} = 2.94$ and 2.90 for the main effect of *Group* and the *Group* × *Condition* interaction effect, respectively).

For the accuracy of 3-back task, the main effect of *Time* was significant ($F\ [1,38] = 31.71$, $p < 0.001$, $\eta_p^2 = 0.46$, $BF_{\text{incl}} = 21204.20$), with increased accuracy from pre-test to post-test; while the main effect of *Group* and the *Group* × *Condition* interaction effect were not significant (*Fs* $[1,38] < 1.57$, *ps* > 0.22, $BF_{\text{excl}} = 3.21$ and 1.61 for the main effect of *Group* and the *Group* × *Condition* interaction effect, respectively). For the reaction time of 2-back task, the main effect of *Time* was significant ($F\ [1,38] = 13.97$, $p = 0.001$, $\eta_p^2 = 0.27$, $BF_{\text{incl}} = 91.75$), with decreased reaction time from pre-test to post-test; while the main effect of *Group* and the *Group* × *Condition* interaction effect were not significant (*Fs* $[1,38] < 0.21$, *ps* > 0.65, $BF_{\text{excl}} = 3.01$ and 2.82 for the main effect of *Group* and the *Group* × *Condition* interaction effect, respectively).

3.4. *Training effects at 3-month follow-up*

The results demonstrated no group-related effects in the primary and secondary outcomes, nor in the N-back task. Additionally, regression analyses showed no significant interaction effects of *Group* and *severity of depression* on all outcomes at the 3-month follow-up (See Supplementary materials for details).

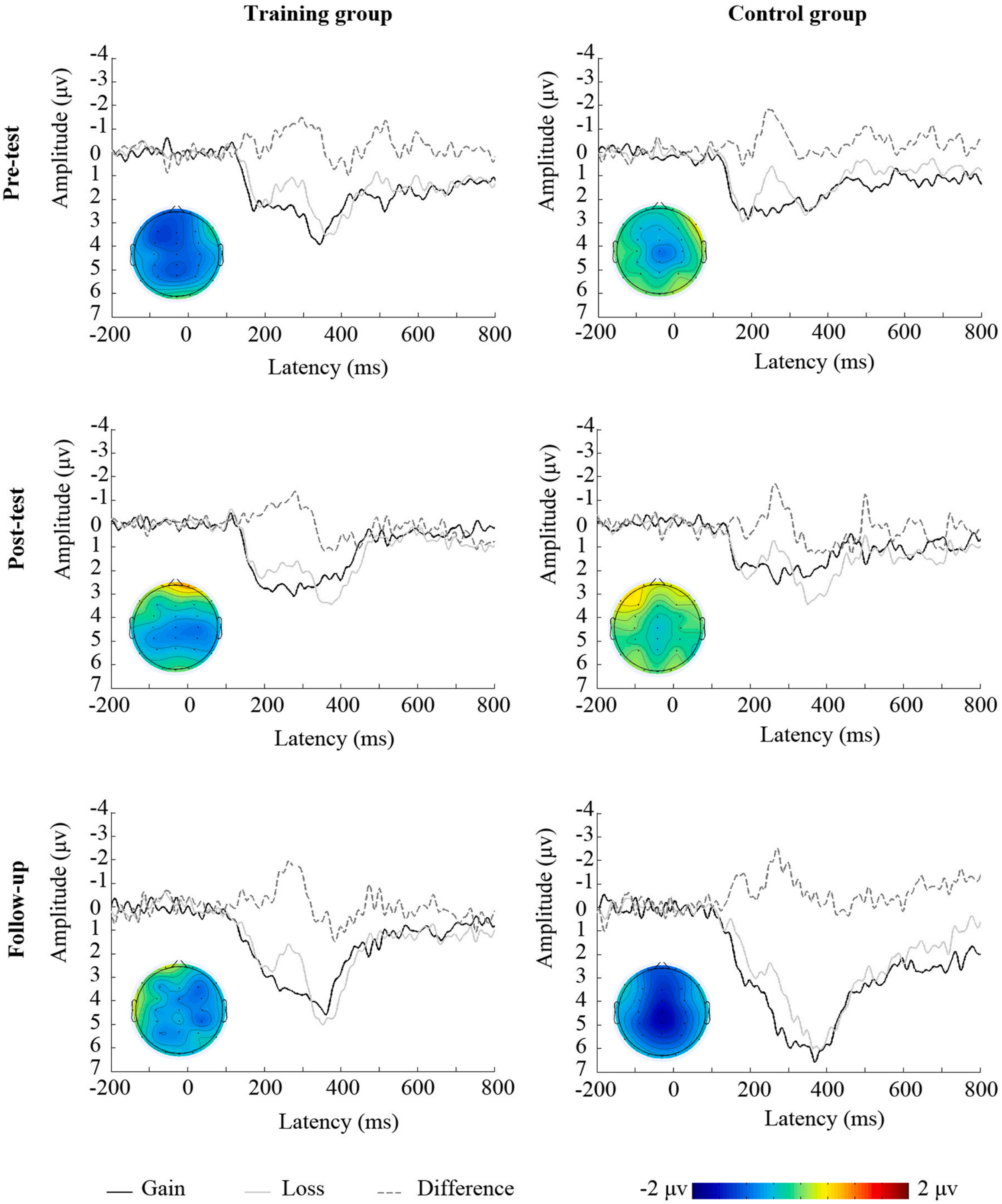

Fig. 6. The ERP waveforms for all gains (shown in black solid line), losses (shown in light gray solid line), and their differences (*losses – gains* for better visualization; shown in dark gray dashed line) at electrode site FCz and the topographies for their differences between 250 ms and 350 ms.

4. Discussion

The present study addressed the shortcomings of previous studies examining the effects of WMT on reward processing by examining the short- and long-term effects of WMT on neuroelectrophysiological activity upon receipt of reward feedback (primary outcomes), self-reported pleasant experiences (secondary outcome), and working memory capacity in a university student with subsyndromal depression, using an active control group. The results, contrary to the hypothesis, did not reveal an improvement in the primary and secondary outcomes for either the training task after the running memory task or the simple memory task. Although performance on the training task itself improved, WMT did not lead to greater improvement in the N-back task compared to the control group, and both groups showed a decrease in reaction time and an increase in accuracy in the N-back task. Furthermore, our results showed that the changes at post-test in Δtheta power were influenced by baseline severity of depression, however, this was primarily driven by a significant increase of change values in Δtheta power as the severity of depression increased in the control group.

First, for the primary and secondary outcomes, the present study did not find elevations in neurophysiological indicators of reward processing and self-reported pleasurable experiences by WMT, which differed from the results of previous studies (Li, Li, et al., 2016; Li, Xiao, et al., 2016; Zhang et al., 2019). This may be due to the differences in the

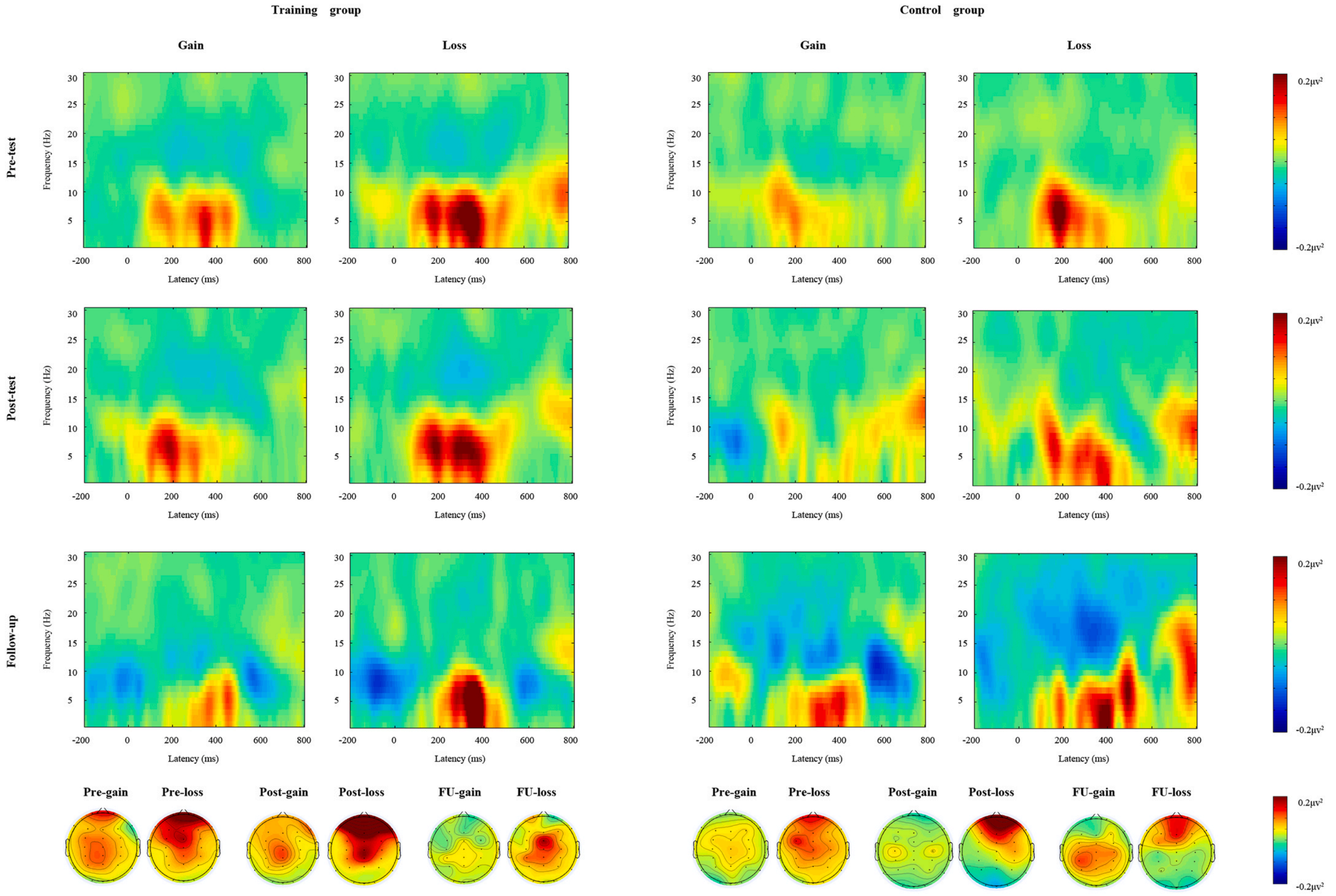

Fig. 7. The spectrograms of the mean power at electrode FCz and the topographies of theta power between 200 ms and 400 ms. Pre = pre-test; Post = post-test; FU = follow-up.

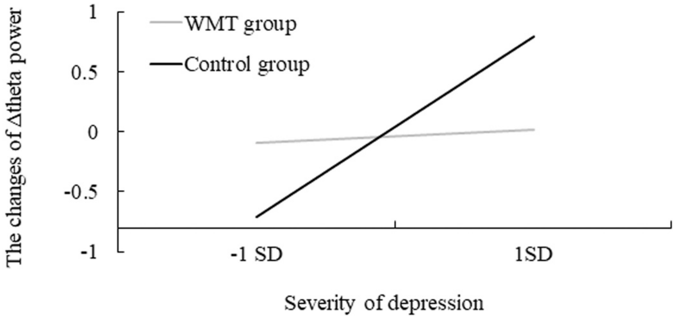

Fig. 8. The interaction between *Group* and *severity of depression* (−1 SD vs. + 1 SD) in predicting Δtheta power changes at post-test.

measurement tasks. Reward processing is a multifaceted structure that can be simply divided into different temporal components—including anticipatory ("want") and consummatory ("like") reward processing—of which the former is a motivational component that helps to motivate the pursuit of rewarding stimuli, and the latter is an emotional component that refers to the pleasurable experience that results from receiving a rewarding stimulus (Robinson & Berridge, 1993). In addition, as proposed by Berridge and Robinson (1998) in the incentive salience hypothesis, there is generally a strong positive correlation between reward anticipation and reward outcome. However, it is also possible for these two factors to become dissociated. That is to say, people may no longer like something we really want after getting it. Previous studies have primarily found effects of WMT on reward anticipation. For example, Li, Xiao, et al. (2016), found a significant decrease in reaction time following the appearance of a reward cue in an affective incentive delay (AID) task for individuals with high social anhedonia who received the WMT; meanwhile no significant *Time* × *Group* interaction effects on anticipatory and consummatory ratings and TEPS scores were found. In other words, WMT enhanced motivation rather than the subjective evaluation of the reward stimulus (i.e., "wanting it more" rather than "liking it more"). Zhang et al. (2019) administered WMT to participants in both the depressive and non-depressive groups and found that the depressive group showed a significantly reduced reaction time in all conditions, while the non-depressive group only showed reduced reaction time in the negative condition in the AID task, and that TEPS scores increased after training in both groups. Li, Li, et al. (2016) found no changes in TEPS scores after WMT; for the reward processing, they observed increased brain activation in the right anterior cingulate cortex, left dorsal striatum, and left precuneus in anticipation of emotional rewards and in the bilateral superior frontal gyrus and right supramarginal gyrus in anticipation of monetary rewards. However, when receiving both affective and monetary rewards, they observed decreased brain activation in various frontal and parietal regions, as well as some subcortical regions (e.g., the cingulate cortex, insula, caudate, and bilateral parahippocampus). The above study revealed that the effect of WMT on TEPS had inconsistent results, while the effect of WMT on the reward processing was mainly reflected in the anticipation phase. That is, working memory is primarily involved in the anticipation of future rewards rather than the subjective experience of rewards. Li, Li, et al. (2016), proposed that the training effect observed in the AID and the MID tasks could be interpreted as the optimization of brain functions for information processing within WM. The doors task used in the present study mainly examined the reward outcome and therefore did not yield a corresponding effect, and our results further suggest that the insignificant effect of the reward outcome was not due to a temporary masking of the effect, as it was not highlighted even at the 3-month follow-up.

In addition, a growing number of researchers view the reward process as a more complex psychological structure that includes, but is not limited to, (1) option generation: the generation of potentially rewarding behavioral options; (2) decision making, in which options are evaluated for cost-benefit, balancing the utility of potential rewards against the associated costs (e.g., the potential effort to obtain those rewards) to select one of the options; (3) reward anticipation, in which anticipation or preparation phase associated with physiological arousal prior to obtaining a reward; (4) action and effort, engaging in an action to obtain a reward; (5) consummation, the hedonic experience resulting from interactions with reward goals; and (6) reinforcement learning, learning how to use update signals to modify behavior in future interactions with similar stimuli (Husain & Roiser, 2018). Previous research has found that working memory capacity is significantly associated with delayed discounting of the decision making component (Heerey et al., 2007, 2011; Shamosh et al., 2008), with the overlap between the two on the brain located in the left lateral prefrontal lobe (Wesley & Bickel, 2014). And, working memory capacity is also strongly associated with a willingness to exert cognitive (rather than physical) effort to obtain rewards (Lopez-Gamundi & Wardle, 2018). Furthermore, individuals with greater working memory capacity are better able to use value-assessment information to guide behavior (Heerey & Gold, 2007) and weigh the best potential outcomes to make more optimal decisions (Heerey et al., 2008). Taken together, working memory is primarily associated with maintaining, updating, and integrating information about values from different information sources over short periods of time to guide target behavior. The simple gambling task used in the present study examined the immediate neurophysiological response to receive rewarding feedback and was less related to information maintenance, updating, and integration, and thus failed to yield significant results, and whether these abilities were enhanced after WMT should be examined in the future.

Second, for the results of the N-back task, WMT did not lead to greater improvement in the N-back performance compared to the control group, and both groups showed decreased reaction time and increased accuracy. This may be due to the fact that the ability to improve on both the running working memory task and the simple memory task were related to the N-back task. Previous research has shown that although the N-back task has high face validity in measuring working memory capacity, it is weakly correlated with the working memory span task (Kane et al., 2007), and a composite of 2- through 5-back performance correlates more strongly with simple short-term memory span than it does with complex WM span (Roberts & Gibson, 2002). Therefore, both working memory capacity enhanced by WMT, and short-term memory capacity enhanced by the simple memory task are reflected in the pre- and post-test differences on the N-back task, similar to studies done by other groups (Leone de Voogd et al., 2016; Rass et al., 2015; Sweeney et al., 2018). Of course, the effect of the practice cannot be ruled out.

Finally, the results of the regression analysis showed that the pre- and post-test changes in Δtheta power were influenced by baseline severity of depression in the control group, whereas the change values did not vary with the severity of depression in the WMT group. It has been shown that oscillatory activity in the theta band increases more when punishment feedback is received than when reward feedback is received (Cohen et al., 2007) and that oscillatory activity in the theta band is localized to the anterior cingulate cortex (Foti et al., 2015) and is associated with cognitive control (Botvinick et al., 2001; Cavanagh & Frank, 2014; Cavanagh & Shackman, 2015). Further analysis found that the effect of Δtheta power mainly comes from theta power to losses rather than gains, as indicated by non-significant predicting effect of interaction term of *Group* and *severity of depression* on theta power to gains and significant trend of predicting effect of interaction term on theta power to losses. Webb et al. (2017) found increased loss-related theta activity in depressed youth. The results of the present study further revealed that individual-level BDI scores were associated with alterations in theta band activity, particularly for losses. Therefore, the results of the present study can be interpreted as for participants in the WMT group, their cognitive control ability was enhanced together due to the WMT, so their changes in cognitive control processes did not vary significantly with the severity of depression increased. However, for participants in the control group, they did not receive an effective intervention for cognitive control, so there was a high degree of heterogeneity in the changes in their responses after receiving punishment feedback, which is detrimental to individuals with higher depression severity although the differences in the change in theta power to losses between the training and control groups for individuals with either low or high severity of depression were not significant.

The present study has some limitations: First, the training task used in the present study (running working memory task) was different from previous studies (dual N-back; Zhang et al., 2019), so it is not possible to fully determine whether the differences in the results obtained from previous studies are due to different training or control group tasks, or to other factors. The same training task or control group task should be used in subsequent studies to exclude these possibilities. Second, the small sample size in this study resulted in no significant group-related effects being obtained, although it was seen that the spectrograms of the training group were closer to the normal group in previous studies (Hou et al., 2020) after training, while the spectrograms of the control group were somewhat disorganized, and therefore, a further examination should be conducted in subsequent studies by increasing the sample size. Thirdly, doors task only briefly examined the participants' levels of liking for rewards, without reflecting working memory manipulation of reward information or their response to rewards under high working memory load. Future research should further examine the intervention effects of working memory training on reward processes using other tasks. For example, Fribourg reward task (Gaillard et al., 2019) could be used to examine whether working memory training could alleviate the weakening effect of high working memory load on reward response. Fourthly, most research examines delta to gain trials and theta to loss trials (e.g., Ethridge et al., 2020; Tsypes et al., 2021), but our data did not display obvious delta activity to gains (see Supplementary materials for spectrograms), this may be due to the fact that our groups were all university students with subsyndromal depression. Tsypes et al. (2021) found that individuals with suicide attempters (SA) exhibited larger delta responses to losses than gains, whereas the no-SA group exhibited larger delta responses to gains than losses. Similarly, for the subthreshold depressed group, delta activity may not be gains over losses for them. Future research should include individuals without depressive symptoms in studies to better examine the effects of working memory training on delta band activity. Fifthly, although the COVID-19 outbreak in China was less severe during the sampling period of this study, the uncertainty brought about by the pandemic and the impact of changes in lifestyle, etc., on different individuals (especially in terms of emotions) varied due to the long period of time between pre-testing and follow-up (Besser et al., 2020; Osimo et al., 2021). Our failure to control for and examine these factors in the study may have some influence on the interpretation of the results, so the effect of WMT intervention on the reward outcome should be examined again in the future once the COVID-19 pandemic is over. Finally, in this study, we provided results from both Null hypothesis significance test (NHST) and Bayesian factor to provide richer information. It is worth noting that although in most cases, the two statistical methods point to the same conclusion, there is obvious inconsistency in some ANOVAs (e.g., the p-value of the main effect of the *Condition* for the training effects at post-test for RewP amplitude was significant but the BF_{incl} value was only equal to 0.62), which may be due to the unstable effects of the current research (see Wang et al., 2023). Although this has been common in previous studies (e.g., Wei & Zhou, 2020), sufficient attention and caution should be given when drawing conclusions.

Ethical standards

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

Role of the funding source

The funders had no role in the study design; in the collection, analysis and interpretation of data; in the writing of the report; and in the decision to submit the article for publication.

CRediT authorship contribution statement

Hou Lulu: Conceptualization, Methodology, Formal analysis, Funding acquisition, Visualization, Writing – original draft. **Long Fangfang**: Investigation. **Zhou Weiyi**: Investigation. **Zhou Renlai**: Conceptualization, Supervision, Funding acquisition, Writing – review & editing.

Declaration of Competing Interest

None.

Data Availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.biopsycho.2023.108710.

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