Cognitive and Emotional Benefits of Smartphone App-Based Dual n-Back Training (Postprint)

Authors: Pan Dongni, Wang Daotuan, Li Xuebing

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Abstract

The training benefits from working memory training can transfer to various fundamental cognitive activities related to working memory. Based on the close association between emotional cognitive control and working memory, this study designed a novel emotional dual n-back training paradigm and verified the applicability of implementing the training task via a smartphone app. The results demonstrated that short-term app-based dual n-back training could produce greater improvements relative to the control group in individuals' performance on visuospatial working memory tasks, running memory tasks, number switching tasks, and Stroop tasks, indicating that the training can enhance individuals' working memory capacity and central executive function. However, training based on different emotional materials (neutral, negative, positive) showed minimal differences across various transfer domains. Short-term training could not transfer to the emotional Stroop task, that is, it could not produce specific benefits in emotional control. The dual n-back task is single-modality and delivered via a smartphone app, conferring broad application prospects. However, the value and significance of simply integrating emotional materials into working memory tasks must be further investigated.

Full Text

Cognitive and Emotional Benefits of a Two-Dimensional n-Back Training Based on a Smartphone App

PAN Dong-ni[1][2], WANG Dao-tuan[3], LI Xue-bing[1][2]

[1]Key Laboratory of Mental Health, Institute of Psychology, Chinese Academy of Sciences, Beijing 100101, China
[2]University of Chinese Academy of Sciences, Beijing 100049, China
[3]School of Psychology, Beijing Normal University, Beijing 100875, China

Abstract

Working memory training can produce transfer effects to various basic cognitive activities related to working memory. Given the close association between emotional cognitive control and working memory, this study designed a novel emotional two-dimensional n-back training paradigm and examined the feasibility of delivering it via a smartphone app. Results showed that short-term app-based two-dimensional n-back training produced greater improvements compared to the control group on visuospatial working memory, running memory, numerical switching, and Stroop tasks, indicating that the training enhanced both working memory capacity and central executive functions. However, training based on different emotional materials (neutral, negative, positive) showed minimal differences in transfer effects. Short-term training did not transfer to the emotional Stroop task, failing to produce specific benefits for emotional control. The two-dimensional n-back task uses a single modality and is delivered via smartphone app, giving it broad application potential. However, the value and significance of simply incorporating emotional materials into working memory tasks requires further investigation.

Keywords: working memory training; dual n-back; transfer; emotional working memory; emotional working memory training; smartphone app
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Working memory is a capacity-limited system for temporarily storing and processing information that underlies many higher-order cognitive activities (Baddeley, 2003). Working memory is malleable, and training can improve performance on working memory tasks (Klingberg, Fernell, Olesen, Johnson, Gustafsson, & Dahlström, 2005) while influencing other cognitive functions associated with working memory, such as various executive functions and attentional control (Clark, Lawlor-Savage, & Goghari, 2017; Melby-Lervåg & Hulme, 2013; Melby-Lervåg, Redick, & Hulme, 2016; Weicker, Villringer, & Thone-Otto, 2016). Training effects may even transfer to reasoning ability and fluid intelligence (Jaeggi, Buschkuehl, Jonides, & Perrig, 2008; Jaeggi, Studer-Luethi, Buschkuehl, Su, Jonides, & Perrig, W. J., 2010). These functions overlap with or are similar to working memory components, and training benefits may arise from direct or broad strategy transfer at the behavioral level, as well as similar patterns of brain activation between training and test tasks (Clark et al., 2017; Salminen, Kuhn, Frensch, & Schubert, 2016).

As an intervention to enhance representational capacity, working memory training primarily involves repeated practice of one or more tasks with high working memory demands (von Bastian & Oberauer, 2014). Among these, the n-back task is the most widely used laboratory training paradigm (Soveri, Antfolk, Karlsson, Salo, & Laine, 2017; Soveri, Karlsson, Waris, Gronholm-Nyman, & Laine, 2017). It shows high correlations with other working memory tasks such as complex span, running memory, and sorting span tasks (Schmiedek, Lövdén, & Lindenberger, 2014) and demonstrates relatively broader training effects (Au, Sheehan, Tsai, Duncan, Buschkuehl, & Jaeggi,., 2015). In this task, trainees must determine whether the current trial' s stimulus matches the one from n trials back. Because memory materials are presented sequentially and continuously updated, trainees must constantly refresh their stored information. As the n-level increases, the amount of information to be retained grows, and memory difficulty gradually escalates.

The dual n-back task is a variant of the n-back task based on dual-task paradigms, requiring simultaneous performance of standard auditory and visual n-back tasks. Because dual n-back tasks involve integrating two concurrent tasks with independent channels that demand dual executive control, they discourage the development of task-specific strategies and automatic processing. Consequently, dual n-back is considered better for improving executive function, binding processes, and attentional control (Jaeggi et al., 2008; Jaeggi, Schmid, Buschkuehl, & Perrig, 2009; 宋宏珂, 2011). However, dual n-back tasks are not limited to dual sensory channels. Since a stimulus typically has multiple dimensions—such as shape, color, location, and meaning—these features are stored and processed relatively independently (Magnussen, Greenlee, & Thomas, 1996; 刘晓平, 王兆新, 陈湘川, 张达人, 2003) and can be represented as different subsystems of working memory. Therefore, using multiple dimensions of a single stimulus for n-back training also meets the requirements of independent attention, task integration, and prevention of strategy development. Moreover, it has greater ecological validity—real-world dual tasks often involve multiple binding operations on a stimulus rather than completely independent channels. Since single-modality training has lower environmental demands and is easier to promote, developing and examining the transfer effects of this single-channel, two-dimensional n-back training on basic cognitive abilities is valuable.

Emotion and cognition interact in complex ways, and cognitive control in emotional states is an important part of daily functioning. Given the fundamental role of working memory in human cognitive activity, whether emotional cognitive control can be enhanced through specific working memory training becomes an important question. Existing research shows extensive overlap between brain regions involved in emotion regulation and those involved in working memory (Schweizer, Grahn, Hampshire, Mobbs, & Dalgleish, 2013), and the theoretical structures share similarities: the core function of working memory is storing and processing information, involving not only temporary maintenance but also refreshing, inhibition, and shifting. Similarly, emotion regulation requires inhibiting maladaptive emotional information while continuously updating and transforming emotional value information. Thus, working memory processes can be seen as the cognitive foundation of emotion regulation (Etkin, Büchel, & Gross, 2015). Whether working memory training can transfer to emotional tasks has therefore attracted research attention, though findings remain controversial. Takeuchi, Taki, Rui, Hashizume, Sekiguchi, Kotozaki,⋯Kawashima.. (2013) found that comprehensive multi-task working memory training could reduce anger, fatigue, and depressive mood while enhancing brain efficiency in regulating negative emotions. Another study using running memory training found it could improve emotion regulation ability as indexed by high-frequency heart rate variability (Xiu, Zhou, & Jiang, 2016). However, in studies using active control groups, training effects on emotional states were difficult to observe at the behavioral level (Wanmaker, Geraerts, & Franken, 2015).

Meta-analyses indicate that working memory training benefits are largely task-specific, with limited far-transfer effects (Melby-Lervåg et al., 2016; Schwaighofer, Fischer, & Bühner, 2015; Soveri, Antfolk, et al., 2017; Weicker et al., 2016). Emotional benefits, as a form of far transfer from working memory training, are typically insensitive and unstable. However, as the link between emotional control and working memory becomes increasingly clear (Etkin et al., 2015), researchers have begun modifying training paradigms to specifically target emotional processes.

Emotional working memory training refers to working memory training where the context or materials are emotional, including induced emotional states and emotional pictures, words, or faces. The most direct evidence comes from Schweizer, Hampshire, and Dalgleish (2011), who used negative faces and words as training materials and found that negative training produced specific emotional benefits: negative working memory training could improve emotional control abilities, whereas neutral training could not. This emotional working memory training also altered prefrontal cortex activity patterns (Schweizer et al., 2013). However, the effects of negative working memory training are inconsistent in practice. When using more rigorous experimental designs, negative n-back training failed to effectively reduce rumination or alleviate depressive symptoms (Onraedt & Koster, 2014; de Voogd, Wiers, Zwitser, & Salemink, 2016).

Negative emotional n-back training raises several important issues: (1) Negative material working memory training has been found to have specific efficacy in improving emotional control in negative contexts, which is thought to result from trainees overcoming their natural cognitive bias toward negative materials and enhancing top-down cognitive control (Schweizer et al., 2013). However, as previously discussed, the frontoparietal network underlying working memory is also crucial for emotion regulation, and training without emotional valence can itself improve emotional control (Sari, Koster, Pourtois, & Derakshan, 2016; Takeuchi et al., 2013; Xiu et al., 2016). Emotional benefits may simply arise from consistency between training and test task materials—a confound not well clarified in existing research. (2) The proposed mechanism of negative n-back training is that trainees overcome negative attentional bias through training. However, although the training continuously refreshes materials, the negative materials themselves are task-relevant stimuli that must be attended to, requiring trainees to maintain attention to negative materials throughout. This differs substantially from attention bias modification training, which traditionally aims to improve negative attention. Most attention bias training manipulates the probability between negative/neutral materials and correct feedback to guide selective attention, reducing attention to negative stimuli through subliminal priming (MacLeod, Rutherford, Campbell, Ebsworthy, & Holker, 2002). In contrast, negative n-back directly requires processing negative stimuli, involving a process that ignores emotional valence information while focusing on task-relevant stimulus information—a form of supraliminal "exposure therapy" that corrects attentional bias.

However, this negative working memory intervention shows unstable effects, possibly due to insufficient training motivation resulting from fear of negative stimuli (Ansari, 2015). Directly correcting negative bias through negative n-back training may be painful for trainees, hindering further application of such emotional working memory training. These issues require clearer examination of whether and how emotional working memory training improves emotional attentional bias.

Currently, no studies have examined the transfer benefits of positive material working memory training. Research shows that positive emotions can broaden attentional scope in working memory (Bartolic, Basso, Schefft, Glauser, & Titanic-Schefft, 1999; Erk, Kleczar, & Walter, 2007; Esmaeili, Karimi, Tabatabaie, Moradi, & Farahini, 2011) or add motivational components to training. Moreover, different emotional valences have distinct effects on working memory: negative emotions focus attention on local details, while positive emotions bias toward global structure (Ostaszewski, Green, & Myerson, 1998). However, it remains unclear how organizing materials of different emotional valences into working memory training programs affects training outcomes.

In fact, comparing the training transfer of different types of emotional working memory training on cognitive and emotional control tasks can better verify the specificity and authenticity of potential emotional benefits. This study directly compares the transfer effects of positive, neutral, and negative working memory training across various tasks, including general executive control tasks and emotional attentional bias tasks, to conduct an exploratory investigation of positive and negative emotional working memory training transfer.

As mentioned, despite controversy regarding the far-transfer effects of dual n-back training, robust evidence shows it improves basic cognitive functions, including other working memory tasks (Au et al., 2015; Clark et al., 2017; Soveri, Karlsson, et al., 2017), updating tasks (Clark et al., 2017; Weicker et al., 2016), inhibition tasks (Melby-Lervåg & Hulme, 2013; Weicker et al., 2016), and attention switching tasks (Sari et al., 2016; Waddell & Mooney, 2017). Updating, inhibition, and shifting are considered important aspects of cognitive control and three components of working memory' s executive function (赵鑫, 周仁来, 2011). Examining a new working memory training' s applicability and general transfer requires investigating these aspects. Additionally, by comparing performance differences on emotional attentional bias tasks before and after training, we can clarify the effects and role of emotional components in working memory training. Overall, two scenarios may emerge for positive, negative, and neutral training across various tasks: (1) training material valence consistently affects transfer to both basic cognitive tasks and emotional attentional control tasks; or (2) the influence of training material valence is dissociated between basic cognitive tasks and emotional attentional control tasks, with positive or negative valence training specifically affecting emotional attentional bias. With no precedent for directly comparing positive and negative working memory training effects on emotional attentional bias, this study tests these competing hypotheses to evaluate the value of emotional materials in working memory training.

In this study, all training was conducted through a self-developed app. As smartphone use has become an essential part of modern life, app-based training programs may further break spatiotemporal constraints, enhance training motivation, and have broad application prospects. Our primary goals were to examine the transfer effects of app-based, two-dimensional n-back working memory training combining negative, neutral, or positive materials on working memory capacity and the three components of the central executive system, and to explore the effects of emotional components in working memory training by examining differential transfer to emotional attentional bias.

2.1 Participants

Sixty-six healthy college students from Beijing (34 males, 32 females) participated in the experiment. They were randomly assigned via smartphone electronic lottery to a control group (n = 17, 9 males, 8 females), negative training group (n = 17, 10 males, 7 females), neutral training group (n = 16, 7 males, 9 females), or positive training group (n = 16, 8 males, 8 females). Ages ranged from 18 to 29 years (M = 20.57, SD = 2.13). Gender distribution did not differ significantly across groups, $^{2}(3) = 0.78$, $p = 0.855$, nor did age, $F(3, 62) = 1.50$, $p = 0.222$.

2.2 Training Tasks

All training tasks were embedded in a self-developed Android application. The app contained three main functional modules: participant login, training process, and training report. These modules implemented random group assignment, procedural training (with parallel versions of neutral, positive, and negative two-dimensional n-back tasks and control tasks based on different passwords, detailed in 2.3), and generation of daily training reports. The app was developed in Android Studio (SDK level 25) following requirements analysis, interface design, coding, testing, and iterative refinement to balance functionality and aesthetic layout. The app is compatible with mobile devices running Android 5.0 or higher, including smartphones and tablets.

2.2.1 Two-Dimensional n-Back Task The training task required participants to remember both the shape and location (3×3 grid, 9 positions) of Chinese characters and determine whether the current character’ s shape and position matched those from n trials back. If they matched, participants pressed corresponding screen buttons for character or position. Buttons followed Google Material Design guidelines, positioned at the bottom left and right of the screen with animated feedback. At level 1 (where level number equals n), participants compared the current character’ s shape and position with those from 1 trial back. At level 2, they compared with 2 trials back, and so on. Each block contained $20 + n$ trials. Characters were presented for 500 ms, followed by a 2500 ms blank screen. Target trials for both character and position ranged randomly from 4 to 6 to reduce guessing strategies. The interface provided real-time feedback on hits, false alarms, or misses to help participants quickly learn the rules and enhance motivation. After each block, a separate screen displayed hits, false alarms, misses, and total score. Total score was calculated as: (hits/targets) × (correct rejections/non-targets) × 100%, with a range of 0–100. As adaptive application is considered necessary for improving training levels and achieving far transfer (Pedullà et al., 2016), this training used an adaptive paradigm where task difficulty changed dynamically based on performance. If participants scored 90 for two consecutive blocks, they were prompted to advance to the next level; if they scored <10 for two consecutive blocks, they dropped one level. Participants completed 30 blocks daily (approximately 30 minutes). They could rest between blocks but were encouraged to train intensively. Daily training reports included completion status and highest level achieved. Historical scores were cleared daily, so participants always started from level 1.

The training had four versions based on the emotional valence of Chinese characters: negative (negative-valence characters), neutral (neutral-valence characters), and positive (positive-valence characters) versions, corresponding to the four training groups. Emotional characters were first selected from the Chinese Affective Word System (compiled by Luo Yuejia et al.). One hundred twenty high-familiarity adjectives (>4.5 on a 9-point scale) were chosen: 40 positive words (valence >6.5, arousal >5.0), 40 negative words (valence <3.5, arousal >4.8), and 40 neutral words (valence 4.6–5.6, arousal 3.1–5.2; both rated on 9-point scales). Core single characters were then extracted from two-character words (e.g., “贱” from “下贱”, “优” from “优秀”, “平” from “平凡”), with 30 selected per group. Selection criteria required single characters to convey the same valence as the original two-character word, with stroke counts between 6 and 20. Thirty-seven healthy college students then independently rated these single characters for familiarity, arousal, and valence. Based primarily on valence ratings, 20 single characters were finally selected as n-back stimuli per group. The three groups did not differ significantly in mean familiarity, $F(2, 57) = 0.34$, $p = 0.712$, but differed significantly in mean valence, $F(2, 57) = 4.50$, $p < 0.015$, with post-hoc tests showing positive words rated significantly higher than negative ($p < 0.001$) and neutral words ($p = 0.035$). Arousal also differed significantly across groups, $F(2, 57) = 20.89$, $p < 0.001$, with post-hoc tests showing both positive and negative words had significantly higher arousal than neutral words ($ps < 0.001$).

2.2.2 Control Group Task To prevent placebo effects, the control group completed an active training task: a number parity judgment task requiring judgments of whether randomly presented numbers in a 3×3 matrix were odd or even. This task used a similar interface to the training task but placed no working memory demands. The control group trained for 5 days, completing the same number of blocks daily as the training groups.

2.3 Pre- and Post-Test Tasks

All pre- and post-test tasks were programmed in E-prime 2.0 and administered on ThinkPad laptops in the laboratory.

2.3.1 Spatial Working Memory Span Task This task was adapted from Corsi' s Spatial Span Task, a classic measure of spatial working memory span (Smyth, & Scholey, 1994). In our version, a sequence of squares appeared randomly in a 5×5 matrix. After presentation, participants used a mouse to click the locations in the order they appeared. Correctly clicked squares turned green. Sequence length increased progressively from 3 to 9, with two trials per length. Testing terminated after two consecutive incorrect recalls, and the highest successful sequential recall number was recorded.

2.3.2 Running Memory Task The running memory paradigm is a classic task for assessing the updating component of working memory. It requires participants to listen to or view a series of items of unknown length and then recall the most recently presented items. In running memory tasks, participants maintain an active list of items in working memory. When the presented sequence exceeds the required response length, participants must remove the earliest item from memory and add each newly presented item to the end upon its presentation. Our running memory task was adapted from Morris and Jones (1990) using digits as updating materials. The task randomly presented 3–9 digits, each for 1000 ms with 800 ms inter-stimulus intervals. After the sequence ended, participants recalled the last 4 digits. Following practice, participants completed 27 test trials. Each perfectly recalled trial scored 1 point, and accuracy was recorded.

2.3.3 Number Switching Task Shifting is another important component of working memory' s central executive function. Task-switching paradigms are important measures of this ability, requiring participants to switch between two or more simple cognitive tasks and comparing performance differences between repeat and switch trials. The difference in reaction time (or error rate) between repeat and switch trials is called "switch cost," a key indicator of shifting ability (Koch, 2005). Task-switching research can involve switching between single dimensions of different materials (e.g., between letter consonant/vowel judgments and number parity judgments) or between dual dimensions of the same material (e.g., between number parity and magnitude judgments). Our number switching task was adapted from Qi, Bai, and Shen (2007), with color cues indicating switching. The task randomly presented Arabic digits 1–9 (excluding 5). Participants completed three phases: Phase 1 required magnitude judgments (press ‘f’ for numbers >5, ‘j’ for numbers <5); Phase 2 required parity judgments (press ‘f’ for odd, ‘j’ for even); Phase 3 required switching based on color (yellow = magnitude judgment, blue = parity judgment). Participants practiced extensively before formal testing. Mean reaction times for all three phases were recorded, and switch cost was calculated as the difference between Phase 3 mean RT and the average of Phases 1 and 2. Smaller switch cost indicated better performance.

2.3.4 Stroop Task Inhibition is an important function of working memory’ s central executive system. We used the classic Stroop task (Stroop, 1992) to measure inhibition. Participants reported the ink color (red, green, yellow, blue) of color words rather than the word meaning. The four color words and colors were randomly paired, with all trials being incongruent (no word meaning matched its ink color). Colors corresponded to ‘D’ , ‘F’ , ‘J’ , and ‘K’ keys. Participants familiarized themselves with color-key mappings before formal testing. During formal trials, the color word disappeared upon response, followed by a 2000 ms blank screen before the next trial. Words disappeared automatically after 2000 ms without response. Response times were recorded, and mean correct RT was calculated.

2.3.5 Emotional Stroop Task The emotional Stroop effect refers to longer color-naming times for “emotional words” compared to “neutral words” when naming the colors of different ink colors, considered an important indicator of individual emotional attentional bias (Williams, Mathews & Macleod, 1996). Our emotional Stroop task was adapted from Zhong, Sun, and Zhang (2007). Participants repeated emotional adjectives while judging their colors (red, green, yellow, blue corresponding to ‘D’ , ‘F’ , ‘J’ , ‘K’ keys), with RT recorded. Words were selected from the Chinese Affective Word System (Wang, Zhou, & Luo, 2008), including 120 high-familiarity adjectives (>4.5): 40 positive (valence >6.0, arousal >5.0), 40 negative (valence <4, arousal >4.8), and 40 neutral (valence 4.5–5.5, arousal 3–5.2). Mean standardized valence was 6.92 ± 0.21 for positive, 2.99 ± 0.18 for negative, and 5.13 ± 0.34 for neutral words. Valence differed significantly across types, $F(2, 117) = 2531.42$, $p < 0.001$, with all pairwise differences significant ($ps < 0.001$). Arousal also differed significantly, $F(2,117) = 65.13$, $p < 0.001$, with neutral words differing significantly from both positive and negative words ($ps < 0.001$), while positive and negative words did not differ significantly. The 40 words were randomly assigned to pre-test and post-test sets, with 20 different valence adjectives in each.

2.3.6 Mood Measurement The Chinese version of the Profile of Mood States (POMS) (Zhu, 1995) was used to assess participants’ basic mood states before and after training. The 40-item scale required participants to evaluate their mood state over the recent period (the past 5 days in this study). The scale includes six subscales: tension, anger, fatigue, confusion, depression, vigor, and self-esteem. Mean scores were calculated for each subscale.

2.4 Experimental Procedure

Participants first completed personal information forms and the POMS, followed by pre-test tasks in order: spatial working memory span, running memory, number switching, Stroop, and emotional Stroop tasks to assess baseline levels of visuospatial working memory span, updating, shifting, inhibition, and emotional attentional bias. Participants could rest briefly between tasks to adjust their state. All participants then installed the self-developed training app, entered their participant number and a six-digit password, and accessed the training interface. The control, negative, neutral, and positive training groups had different passwords randomly assigned across the four groups. To familiarize participants with training rules, experimenters demonstrated the app after installation and emailed a task manual outlining autonomous training 注意事项, such as requiring personal training and recommending intensive training, to ensure all participants understood the rules and requirements. Participants completed 5 days of autonomous training, sending daily generated reports to experimenters to receive compensation. After the training period, participants returned to the same laboratory to complete post-test tasks in the same order: spatial working memory span, running memory, number switching, Stroop, and emotional Stroop tasks (using different emotional adjectives from pre-test to prevent practice effects). To control for potential task order effects, pre-test and post-test task sequences were identical. Finally, participants completed the POMS again, evaluating their general mood during the 5-day training period. Figure 1 [Figure 1: see original paper] illustrates the experimental procedure.

3.1 Training Task

Short-term two-dimensional n-back training significantly improved training performance itself. Figure 2 [Figure 2: see original paper] shows the improvement across 5 days for the four training groups. After 5 days, all groups showed performance gains over time, reaching maximum levels (n values) ranging from 2 to 6. The negative training group reached an average maximum level of n = 3.53 (SD = 0.80), the neutral group n = 3.38 (SD = 0.50), and the positive group n = 3.63 (SD = 0.50). Group differences in maximum training level were not significant, F(2, 48) = 0.66, p = 0.521. For the control group' s number parity task, all participants maintained daily accuracy above 90%.

3.2 Spatial Working Memory Span Task

Pre- and post-training spatial working memory span performance and training effects are shown in Table 1 . Training effect size was calculated as post-training span score minus pre-training span score.

Table 1 Mean differences in spatial working memory span task performance (items) across groups

Group	Pre-test	Post-test	Effect Size
Control (N = 17)	5.41 (0.99)	5.71 (1.21)	0.29 (1.13)
Negative (N = 17)	5.65 (0.98)	6.44 (1.03)	0.79 (1.28)
Neutral (N = 16)	5.19 (0.87)	6.53 (0.90)	1.34 (0.83)
Positive (N = 16)	5.29 (1.47)	6.06 (1.29)	0.78 (0.75)

A one-way ANOVA on pre-training spatial working memory span scores revealed no significant differences among the four groups, F(3, 62) = 0.55, p = 0.653. A 4 (Group: control/negative/neutral/positive) × 2 (Time: pre/post) repeated-measures ANOVA showed no significant main effect of Group, F < 1, but a significant main effect of Time, F(1, 62) = 40.03, p < 0.001, ^{2} = 0.39, and a significant Group × Time interaction, F(3, 62) = 2.85, p = 0.045, ^{2} = 0.12. To further compare training effects across groups, paired-samples t-tests examined pre- versus post-training performance within each group. Results showed no significant difference for the control group, t(16) = -1.07, p = 0.3. The negative training group showed significantly higher post-training performance, t(16) = -2.54, p = 0.022. The neutral training group also showed higher post-training performance, t(15) = -6.47, p < 0.001, as did the positive training group, t(15) = -4.16, p = 0.001.

3.3 Running Memory Task (Updating)

Pre- and post-training running memory task performance (accuracy) and training effects are shown in Table 2 . Training effect size was calculated as post-training accuracy minus pre-training accuracy.

Table 2 Differences in running memory task accuracy (%) across groups

Group	Pre-test	Post-test	Effect Size
Control (N = 17)	0.96 (0.09)	0.96 (0.06)	0 (0.12)
Negative (N = 17)	0.94 (0.06)	0.96 (0.04)	0.02 (0.05)
Neutral (N = 16)	0.96 (0.06)	0.98 (0.03)	0.02 (0.04)
Positive (N = 16)	0.95 (0.06)	0.99 (0.02)	0.04 (0.05)

A one-way ANOVA on pre-training running memory scores revealed no significant differences among groups, F(3, 62) = 0.38, p = 0.766. A 4 (Group) × 2 (Time) repeated-measures ANOVA showed no significant main effect of Group, F < 1, but a significant main effect of Time, F(1, 62) = 5.22, p = 0.026, ^{2} = 0.078, and a non-significant Group × Time interaction, F(3, 62) = 0.81, p = 0.493. Due to substantial ceiling effects, paired-samples t-tests examined pre- versus post-training performance within each group. The control group showed no significant difference, t(16) = 0.00, p > 0.1. The negative training group showed higher post-training performance, t(16) = -1.57, p = 0.136, but not significantly. The neutral training group showed marginally higher post-training performance, t(15) = -2.08, p = 0.055. The positive training group showed significantly higher post-training performance, t(15) = -3.09, p = 0.007.

3.4 Number Switching Task (Shifting)

Pre- and post-training switch costs (difference between switch and non-switch trial RTs) and training effects are shown in Table 3 . Training effect size was calculated as pre-training switch cost minus post-training switch cost.

Table 3 Differences in number switching costs (ms) across groups

Group	Pre-test	Post-test	Effect Size
Control (N = 17)	517 (118)	501 (167)	15 (171)
Negative (N = 17)	494 (144)	427 (174)	67 (84)
Neutral (N = 16)	422 (154)	386 (135)	46 (121)
Positive (N = 16)	521 (116)	419 (83)	102 (132)

A one-way ANOVA on pre-training switch costs revealed no significant differences among groups, F(3, 62) = 1.51, p = 0.233. A 4 (Group) × 2 (Time) repeated-measures ANOVA showed no significant main effect of Group, F < 1, but a significant main effect of Time, F(1, 62) = 12.77, p = 0.01, ^{2} = 1.71, and a marginally significant Group × Time interaction, F(3, 62) = 1.28, p = 0.288, ^{2} = 0.058. Paired-samples t-tests examined pre- versus post-training switch costs within each group. The control group showed no significant difference, t(16) = 0.36, p = 0.721. The negative training group showed reduced switch cost post-training, t(16) = 3.29, p = 0.005. The neutral training group showed marginally reduced switch cost, t(15) = 1.53, p = 0.14. The positive training group showed significantly reduced switch cost, t(15) = 3.09, p = 0.007.

3.5 Stroop Task (Inhibition)

Pre- and post-training Stroop task RTs and training effects are shown in Table 4 . Training effect size was calculated as pre-training RT minus post-training RT.

Table 4 Differences in Stroop task performance (ms) across groups

Group	Pre-test	Post-test	Effect Size
Control (N = 17)	818 (81)	773 (64)	45 (47)
Negative (N = 17)	858 (122)	745 (88)	113 (92)
Neutral (N = 16)	788 (162)	685 (143)	103 (115)
Positive (N = 16)	853 (104)	729 (84)	123 (117)

A one-way ANOVA on pre-training spatial working memory span scores revealed no significant differences among groups, F(3, 62) = 1.18, p = 0.325. A 4 (Group)

× 2 (Time) repeated-measures ANOVA showed no significant main effect of Group, $F < 1$, but a significant main effect of Time, $F(1, 62) = 65.77$, $p < 0.001$, $^2 = 0.52$, and a marginally significant Group × Time interaction, $F(3, 62) = 2.23$, $p = 0.093$, $^2 = 0.098$. Simple effects analysis showed significant pre-post improvements for negative ($p < 0.001$), neutral ($p < 0.001$), and positive training groups ($p < 0.001$), but not for the control group ($p = 0.059$). A one-way ANOVA on Stroop training effect sizes showed a marginally significant main effect of Group, $F(3,62) = 2.23$, $p = 0.093$, $^2 = 0.098$. Pairwise comparisons revealed significant differences between the control group and negative training group ($p = 0.043$) and between control and positive training group ($p = 0.023$), with a marginally significant difference between control and neutral training group ($p = 0.086$). Training groups showed better inhibition benefits than the control group, with emotional material training (positive or negative) showing better effects than neutral material.

3.6 Effects of Emotional Working Memory Training on Emotional Bias

The emotional Stroop task required participants to name and judge the colors of words with different valences. Typically, naming emotional words produces longer RTs. Pre-test Stroop effects were first examined, showing no significant difference between neutral and positive word RTs, $t(65) = 0.28$, $p = 0.783$, but a marginally significant difference between negative and neutral words, with negative words showing longer RTs, $t(65) = 1.88$, $p = 0.06$. This indicates an emotional Stroop effect present only for negative words. In the post-test, the emotional Stroop effect remained: no significant difference between neutral and positive word RTs, $t(65) = 0.71$, $p = 0.483$, but a significant difference between negative and neutral words, $t(65) = 2.06$, $p = 0.044$.

To examine whether negative bias improved after training, paired-samples t-tests compared pre- and post-training negative Stroop effects (negative Stroop effect = RT for negative words minus RT for neutral words) within each group. Results showed no significant differences for the control group, $t(16) = -0.51$, $p = 0.619$, nor for the negative training group, $t(16) = -0.04$, $p = 0.973$, neutral training group, $t(15) = 1.09$, $p = 0.294$, or positive training group, $t(15) = -1.33$, $p = 0.205$. This indicates that negative Stroop effects were not reduced by practice or working memory training.

Additionally, separate 2 (Time: pre/post) × 4 (Group) repeated-measures ANOVAs were conducted for neutral, negative, and positive words. All showed significant main effects of Time: neutral words $F(1,62) = 15.84$, $p < 0.001$; negative words $F(1,62) = 8.275$, $p = 0.006$; positive words $F(1,62) = 12.584$, $p = 0.001$. However, Group × Time interactions were not significant ($ps < 0.01$). This suggests that emotional word RTs in the emotional Stroop task were not sensitive to training group, with overall RT improvements likely due to practice effects. Table 5 shows RTs for different word valences across groups and time points.

Table 5 Emotional Stroop task RTs (ms) across groups and time points

Group	Negative Words	Neutral Words	Positive Words
Control	736 (53)	708 (56)	730 (78)
Negative Training	690 (80)	693 (79)	672 (77)
Neutral Training	744 (67)	724 (62)	744 (69)
Positive Training	741 (53)	727 (74)	678 (56)
Control	692 (68)	685 (82)	731 (47)
Negative Training	694 (65)	747 (61)	729 (77)
Neutral Training	753 (76)	704 (82)	724 (82)
Positive Training	696 (92)	729 (64)	710 (76)

3.7 General Emotional Effects of Emotional Working Memory Training

Pre-training mood levels were first examined using MANOVA to assess group differences on POMS subscale scores. Results showed no group differences on tension, anger, fatigue, depression, vigor, confusion, or self-esteem subscales (Fs < 2, ps > 0.5). MANOVA examined general emotional benefits (post-test subscale score minus pre-test subscale score) across groups. The tension subscale showed marginally significant change, F(3,62) = 2.188, p = 0.098, ^{2} = 0.096, and the confusion subscale showed a trend toward difference, F(3,62) = 1.695, p = 0.185, ^{2} = 0.074, though neither reached significance. Other subscales showed no significant changes. Multiple comparisons indicated that tension reduction was significantly greater in the positive training group than the control group (p = 0.029), while confusion increase was significantly greater in the negative training group than the neutral training group (p = 0.04). Table 6 shows training-related changes in POMS subscale scores across groups.

Table 6 Changes in POMS subscale scores (post-test minus pre-test means)

Subscale	Control	Negative Training	Neutral Training	Positive Training
Increased Tension	0.59 (1.97)	0.47 (5.65)	-1.00 (3.72)	-2.50 (3.65)
Increased Anger	0.76 (3.91)	-1.13 (2.53)	-1.13 (3.91)	-0.06 (5.66)
Increased Fatigue	1.76 (7.28)	0.41 (3.30)	-0.18 (1.85)	-0.06 (4.04)
Increased Depression	1.13 (6.56)	-0.06 (5.66)	0.35 (3.86)	-0.13 (3.91)
Increased Vigor	-1.50 (2.50)	-0.56 (3.12)	-1.81 (2.54)	-0.94 (3.23)

Subscale	Control	Negative Training	Neutral Training	Positive Training
Increased Confusion	-0.06 (4.37)	-2.00 (2.45)	0.12 (1.32)	0.18 (1.24)
Increased Self-Esteem	-0.81 (3.33)	0.94 (3.89)	0.88 (2.60)	–

4.1 Applicability of the Spatial-Verbal Two-Dimensional n-Back Task as Working Memory Training

Dual n-back tasks have attracted widespread attention due to their potential to improve fluid intelligence (Jaeggi et al., 2008). Although far-transfer effects remain controversial (Melby-Lervåg et al., 2016; Redick, Shipstead, Harrison, Hicks, Fried, Hambrick, & Engle, 2013; Shipstead, Redick, & Engle, 2010, 2012), dual n-back is considered more effective than single-task paradigms. Higher task complexity promotes broad utilization of cognitive resources (Salminen et al., 2016), and training effects successfully transfer to executive function and attention tasks (Lilienthal, Tamez, Shelton, Myerson, & Hale, 2013; Shipstead et al., 2012). A primary goal of this study was to examine the applicability of a new two-dimensional n-back training task using Chinese characters'orthographic form and spatial location as independent target attributes. Results showed that even with compressed training duration (5 days), this training produced broad transfer effects based on core working memory components.

The visuospatial working memory task examined changes in spatial working memory span. Similar to previous n-back training studies (Cortese, Ferrin, Brandeis, Buitelaar, Daley, Dittmann,···& Stringaris, 2015; Melby-Lervåg & Hulme, 2013; Schwaighofer et al., 2015), our study showed that both emotional and neutral training groups improved more than the control group on memory span. Although n-back tasks are considered better for training executive components, the adaptive n-level in our study meant that as level increased, the number of items to be maintained also increased. Notably, working memory capacity and processing efficiency are two sides of the same coin (von Bastian & Oberauer, 2014). Updating training can free up working memory capacity by improving processing efficiency (刘春雷, 周仁来, 2012; 史战, 2016), and our two-dimensional n-back updating training achieved this goal.

Updating is considered the core of executive function and the main process in n-back training (Szmalec, Verbruggen, Vandierendonck, & Kemps, 2011), involving loading task-relevant information and filtering irrelevant information (Kim, Wittenberg, & Nam, 2017). Audiovisual dual-channel n-back training can improve running memory performance, whereas single n-back training cannot (Salminen et al., 2016). In our study, two-dimensional n-back training improved running memory performance overall compared to the control group, showing advantages over single n-back tasks. Inhibition function, as measured by the Stroop task, was also enhanced by two-dimensional n-back training. Some studies suggest that pure working memory updating training cannot transfer to inhibition tasks (Dahlin, Neely, Larsson, Backman, & Nyberg, 2008). However, our two-dimensional n-back updating task effectively improved Stroop performance, similar to dual-channel n-back training transfer effects (Melby-Lervåg & Hulme, 2013). This is because the two-dimensional n-back task is not pure updating—it also involves inhibiting currently irrelevant stimuli. When n 2, stimuli to be recalled are not identical to those maintained in memory; they are inhibited in the memory system awaiting retrieval in subsequent trials. In dual tasks, interference from the other task line must also be inhibited, making inhibition demands more salient. Importantly, dual-attribute tasks differ from completely independent dual-channel n-back tasks: although attributes are independent, they are presented as integrated objects, necessarily involving feature integration and binding processes. Inhibiting a stimulus attribute within this integrated context may impose higher inhibition demands. Research shows that inhibition and updating tasks share highly correlated neural activation patterns (Kim, Wittenberg, & Nam, 2017), which may explain why our two-dimensional n-back training produced consistent transfer to both updating and inhibition tasks.

The number switching task essentially depends on attentional shifting and cognitive flexibility (Anderson, 2002). Shifting ability is measured by switch cost —our study defined this as increased correct RT after task rule changes. No previous literature has directly verified n-back training transfer to this task, though positive transfer has been demonstrated in other tasks requiring cognitive switching and attentional control (Clark et al., 2017; Melby-Lervåg & Hulme, 2013; Weicker et al., 2016). Our results showed that emotional training significantly improved numerical rule-switching ability, with neutral training also producing good effects, indicating that two-dimensional n-back training generally improved task-switching ability. The number switching task shares operational similarities with dual n-back tasks, both involving attentional switching based on dual attributes of a stimulus, allowing attention allocation strategies during training to transfer relatively completely to the test task. Additionally, Senn, Espy, and Kaufmann (2004) propose that inhibition and working memory are prerequisites for successful task switching (as participants must inhibit previously familiar task rules while maintaining new rules in working memory). Two-dimensional n-back training may thus produce coordinated improvements in working memory, inhibition, and shifting.

The dual-task component in working memory training is considered crucial for achieving near and far transfer (Klingberg, 2009). Dual-task switching execution requires high cognitive flexibility, strengthening modality networks rather than task-specific strategies. Our study found that two-dimensional n-back training based on different attributes of the same stimulus produced transfer similar to dual-channel n-back tasks. Short-term training produced greater improvements than the control group on visuospatial working memory, running memory, number switching, and classic Stroop tasks. These behavioral tasks respectively represent spatial working memory capacity, updating, shifting, and inhibition functions, comprehensively characterizing working memory. Because this training uses a single modality, it has broad application potential and can become a further developed training paradigm.

4.2 Emotional Transfer of Different Emotional Material Working Memory Training

This study introduced positive material training to clarify general issues in emotional working memory training. We found that neither positive nor negative emotional training produced valuable main effects or interactions with valence, suggesting that different emotional valence working memory training is insensitive on the emotional word Stroop task. Compared to control and neutral groups, the negative training group did not affect color-naming RTs for negative emotional words post-training, nor did it improve negative bias. The positive training group also did not produce specific changes in color-naming RTs for positive emotional words or affect positive bias. This study observed general negative bias pre- and post-training (longer RTs for negative than neutral words), consistent with previous research (钟毅平 et al., 2007). However, this negative bias was not improved by any emotional or non-emotional working memory training. Post-test color-naming times improved generally compared to pre-test, but this appeared due to task familiarization, with neither emotional variables nor working memory training producing specific RT changes. Results suggest that specific processing of emotional materials is stable and cannot be changed through short-term working memory training or training that simply incorporates emotional materials.

As previously discussed, we found similar transfer effects of emotional and non-emotional training on basic cognitive abilities, with no differences on emotional tasks. Even compared to the control group, no benefit evidence emerged. This may be because the emotional Stroop task differs from the classic Stroop based on selective attention mechanisms—it is thought to reflect general delay in response units caused by emotional activation after Chinese character orthographic-phonological-semantic processing (钟毅平 et al., 2007). Correcting this emotional delay requires controlling individual emotional activation, making prior emotional control processes necessary. For working memory training, such emotional inhibition represents a far transfer. Short training duration in this study may have prevented significant emotional benefits. Evidence suggests that longer training duration is necessary for far transfer (von Bastian & Oberauer, 2014). During short-term training, participants' performance was still improving and had not reached a plateau or maximum extension. Compressed training duration was used to validate the new task' s effectiveness but may have sacrificed potential far transfer. Notably, however, different emotional material training had simple consistent transfer effects on participants' general mood:

the negative training group showed slight increases in confusion post-training, though not reaching significance. This suggests that future applications of negative emotional working memory training for emotional disorder populations should be more cautious to avoid worsening mood due to negative training.

4.3 Role of Emotional Components in Working Memory Training

Emotional control is an important aspect of daily functioning and a key mechanism in the maintenance and development of emotional disorders. Since emotional control depends on working memory-based cognitive control, emotional working memory training has attracted research attention. However, controversy exists regarding how to train emotional working memory. Some researchers found that incorporating negative emotional materials into dual n-back tasks produces specific emotional benefits (Schweizer et al., 2011). However, this study behaviorally examined emotional (positive and negative) versus neutral dual n-back training and found no specific differences in transfer effects to various basic cognitive abilities, nor expected 定向 effects on emotional attentional bias tasks. Previous research showed that using positive, negative, and neutral faces and scenes as n-back materials did not affect task performance (Román et al., 2015). Our study found that using positive, neutral, and negative valence words as emotional working memory training materials also produced no significant differences in training gains or various transfer effects. Therefore, training models that simply incorporate emotional materials into working memory tasks must be examined more cautiously.

Because emotional components in working memory occupy substantial attentional resources (Lavric, Rippon, & Gray, 2003; Shackman, Sarinopoulos, Maxwell, Pizzagalli, Lavric, & Davidson, 2006), emotional working memory training essentially requires attention allocation operations during tasks, minimizing processing of emotional valence information to better complete the primary two-dimensional n-back task. However, this process is an automatic strategy selection—once familiar with the rules, participants easily ignore analysis and evaluation of material emotional properties. In high-load working memory tasks, insufficient processing of emotional information prevents effective emotional state induction during training (高鑫, 周仁来, 董云英, 2013), making claims that training can affect top-down emotional control logically invalid, as emotion itself is not generated and thus cannot be controlled. Moreover, because emotional materials in n-back tasks appear randomly and repeatedly, participants become highly familiar with them after multiple days of training, while the n-back recurrence pattern remains unpredictable. If training continued temporally, the distinction between emotional and non-emotional n-back training would essentially disappear—one reason this study used compressed training duration. Results showed that participation of emotional materials did not substantially differ in various basic transfers. Simply involving fixed emotional materials in n-back tasks may fail to achieve emotional training goals. In fact, valuable emotional working memory training may require more individual emotional and motivational involvement. For example, researchers developed a Back-span task combining n-back with operation span tasks, using threatening descriptions during span trials to directly elicit anxiety and irrelevant thoughts. This task was found to improve working memory updating function and emotional control in test-anxious individuals under irrelevant thought conditions, accompanied by increased frontal midline theta activity during tasks (史战, 2016). Future research could integrate direct emotional components such as reward and punishment into working memory tasks to enhance ecological validity of emotional working memory training.

4.4 Applicability of Smartphone App-Based Working Memory Training

With mobile phone proliferation, recent research has begun integrating various intervention programs into apps and examining their applicability. However, most apps target comprehensive interventions for specific clinical patients: for example, mindfulness apps to reduce anger and aggression in psychiatric patients (Mistler, Ben-Zeev, Carpenter-Song, Brunette, & Friedman, 2017); mobile virtual reality apps to reduce social anxiety and increase confidence (Kim, Hong, Kim, Jung, Kyeong, & Kim, 2017); comprehensive apps combining psychoeducation, social engagement, and relaxation units to reduce PTSD symptoms (Roy et al., 2017); and apps integrating knowledge content and cognitive behavioral therapy to improve motivational behavior and life satisfaction in schizophrenia (Schlosser et al., 2016). These studies demonstrate that mobile interventions are feasible. Moreover, compared to health tip (content push) apps, cognition-related apps better improve depressive patients' emotional states (Arean et al., 2016), suggesting cognitive training apps may have better development prospects, especially for clinical intervention. In our study, broad positive effects of training groups versus control group indicate application potential for this mobile training. For working memory training specifically, research on mobile device-based training is very limited. To increase training flexibility, previous non-laboratory training often used home computers via web pages, but training effectiveness showed great inconsistency (Oh, Park, & Seo, 2017), largely due to inability to guarantee prescribed training volume. This problem may be mitigated with mobile devices, as mobile training offers greater freedom, convenience, and interest. These advantages can compensate for limitations of non-laboratory training in meeting training requirements. In fact, smartphone training can maximally break spatiotemporal constraints, enabling participants to train in optimal readiness states (including motivation and attention levels), which is necessary for obtaining training progress and transfer benefits (von Bastian & Eschen, 2016; von Bastian & Oberauer, 2014). With China' s large mobile internet user base and growing mobile app users, such training apps may have good prospects. Of course, this study targeted experimental validation and did not 完善 functions beyond training units. Future app development should pay more attention to user experience and optimize product design based on thorough market research.

5 Limitations and Future Directions

This study has several limitations. First, the digit running memory task was used as an updating ability measure. Pre-test performance was already high, and ceiling effects may have hindered further demonstration of training benefits. Additionally, using a single task may not fully represent independent working memory components, making it difficult to systematically examine associations between training gains. Future research should use additional tasks to validate training effects on working memory and examine systematic relationships between transfer effects. Second, in examining cognitive and emotional benefits of working memory training, an implicit assumption is that training effects on emotional states and cognitive functions are independent. However, because emotions and cognitive tasks interact, training gains may have interactive effects on emotional and cognitive function improvement. Future studies should use more refined designs to track emotional changes and cognitive performance levels during training, thereby comprehensively examining the combined effects of working memory training on emotional and cognitive functions. Third, our sample consisted of healthy college students, limiting generalizability. Individual differences substantially affect training transfer (Jaeggi, Buschkuehl, Shah, & Jonides, 2014). Healthy populations have limited room for cognitive improvement, making working memory training gains harder to achieve and maintain (潘东旎, 李雪冰, 2017). In individuals with emotional cognitive deficits, training may show compensatory effects, making benefits more pronounced (von Bastian & Oberauer, 2014). Therefore, populations with emotional working memory deficits, such as depressed patients (Joormann, Levens, & Gotlib, 2011), may be the true beneficiaries of emotional working memory training. Future research should extend training to various emotional disorder populations to examine the value of emotional working memory training for clinical individuals.

Conclusion

The character-space two-dimensional n-back training can improve individual working memory capacity and central executive functions. However, differences in character valence during training did not produce specific effects on emotional cognitive control. In terms of training format, delivering working memory training via smartphone app is feasible. In terms of training content, the two-dimensional n-back task is an effective working memory training task, but the value and significance of emotional materials in working memory training require further investigation.

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Note: Figure translations are in progress. See original paper for figures.