Brain-train apps: Testing the efficacy of two applications for cognitive enhancement

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Abstract

With the ubiquitous trend of almost every individual in the world owning a smartphone, new trends have emerged within applied cognitive psychology regarding the use of applications for cognitive training purposes. Previous studies have found far-transfer benefits of training a single working memory component, such as gains in fluid abilities. We aimed to evaluate two smartphone applications - Dual n-back, Super Number Memory, *tapping the central executive and phonological loop, respectively. Young adults (*N=*176,* M_{age} *=21.5,* SD=*5.42; 87% female) were randomly assigned to either one of the three experimental groups (Dual n-back app, Super Number Memory app, combination of the two apps), or to a control group. A pre-post design with FU at three months was employed, with a 4-week training (5 sessions a week). A near transfer effect for updating ability in young adults was confirmed for the Dual n-back and combined group, while no other effects were found. The results are discussed in terms of the efficacy of mobile phone apps for cognitive functions improvement.*

Keywords: *working memory; brain-train apps; cognitive training; fluid abilities*

Introduction

There are around 6.3 billion smartphone users in the world who use more than 2.87 million applications (apps) from the Google Play Store, or 1.96 million apps from the Apple App Store (Buildfire, 2022). The most common users are people of younger age, and the most popular apps come from the games category. Although a large number of games are designed with the goal of entertaining users, some of them exhibit positive effects on cognitive functions (Jiwal et al., 2020). This gave developers the idea of using mobile apps as a cognition-enhancement tool, which has resulted in a large number of cognitive training apps (training apps). The emphasis in these apps is often placed on the working memory (WM) function, which is considered crucial for a wide range of cognitive processes. However, WM is not a unitary construct - it consists of several components with the differential effect on other cognitive functions (Baddeley et al., 2000). Furthermore, exercising more of these components could lead to a greater transfer of enhanced abilities to the untrained ones.

The impact of mobile devices on cognitive abilities has been widely explored. Studies show that specific types of smartphone use can have different effects on cognitive abilities. For example, frequent use of mobile devices while performing other tasks, i.e., media multitasking, generally shows negative effects on the attention control (Moisala et al., 2016), and is negatively associated with the selection of goal-directed information in WM and their recollection in long-term memory (Uncapher et al., 2015). However, the use of specific mobile apps can also have positive effects on cognitive functions. For example, a recent systematic review, focused on the usefulness of training apps, showed their positive effects on attention, memory, visuospatial functions, executive functions and problem solving (Vergani et al., 2019).

A large number of cognitive training studies are focused on strengthening WM. WM is a flexible, but limited mental workspace that retains, processes, manipulates and transforms information. It can explain about 50–70% of the variance of higher-level cognitive skills such as reading, mathematics, reasoning and fluid intelligence (e.g., Jarrold et al., 2008). However, different components of WM may contribute to different cognitive abilities. According to the multi-component model proposed by Baddeley et al. (2000), there are four main components of WM: central executive (CE), phonological loop (PL), visuospatial sketchpad and episodic buffer. In this study, we have focused on two frequently studied components - CE and PL.

CE is considered the central part of WM. It is a control system which manipulates the information within WM and controls other WM components. Updating – one important aspect of CE - represents the ability to constantly monitor the content of WM and encode new information that is relevant to the task. It is related to other abilities, such as inhibition, task-switching and fluid reasoning (Gajewski et al., 2018; Rac-Lubashevsky & Kessler, 2016). Meta-analysis of the efficiency of updating training shows that enhancing updating can lead to greater efficiency in other updating tasks, but the effects to WM, cognitive control, attention and fluid reasoning are small (Melby-Lervåg & Hulme, 2013; Soveri et al., 2017; Weicker et al., 2016).

PL is responsible for the storage and maintenance of the verbal and auditory information in WM. It serves in language comprehension and vocabulary acquisition (Baddeley et al., 1998; Gathercole, 2006). Also, PL is considered important in tasks which are apparently not dependent on verbal control - switching between tasks (Baddeley et al., 2001), or action control in long-term task conflict (Saeki et al., 2013). Some studies show that PL could also contribute to fluid reasoning (e.g., Chuderski & Necka, 2012), but the results in this area are mixed, often showing non-significant results (e.g., Engle et al., 1999). Although PL is one of the most frequently researched components of WM, surprisingly little studies have been undertaken on its enhancement. Existing studies show that the training designed to strengthen PL has positive effects on the trained ability, but their transfer to other measures is limited (Li et al., 2022).

Given that both types of training confirm near transfer (i.e., to trained abilities), not the lack of far transfer (non-trained abilities), combining both types of training can lead to greater transfer to untrained tasks that have similar underlying mechanisms as the trained ones. Although smartphone users very often employ a large number of mobile apps, there is still a small number of studies that have investigated the efficacy of a single training and/or their combined use on cognitive functioning. In addition, existing studies on training apps have focused on specific populations (e.g., the elderly, people with dementia; Hill et al., 2018; Zmily et al., 2014), while studies with young participants, who have greater benefit from using training apps, are lacking (Bonnechere et al., 2020). Therefore, the aim of this study was twofold: 1) we wanted to investigate the efficacy of a single updating and PL training apps on cognitive function in younger adults, and 2) to investigate whether combining training apps to enhance different components of WM could lead to greater transfer to other non-trained abilities.

Method

Participants

Undergraduate psychology students (N=176, M_{age} =21.5, SD=5.42; 87% female) were randomly assigned to either one of the three experimental groups (Dual *n*-back group (DNB), N=44; Super Number Memory group (SNM), N=51; combined DNB & SNM, N=36) or to the control group (Mandala, N=45).

All participants have signed an informed consent and received course credit for participation in the study. The study was approved by the Ethics Committee of the Faculty of Media and Communication, Singidunum University.

Material

Several cognitive tasks were included in the battery to assess pre-post-FU (follow-up) differences in the training outcomes. All tasks were administered through the Inquisit software.

Digit and letter memory span task (Lumiley & Calhoon, 1934) assesses the short-term memory capacity, i.e., PL. The task is to memorize a visually presented sequence of either digits or letters in the presented order. In both tasks the score range is 0-16. The longest digit/number sequence recalled correctly is the dependent variable in both tasks.

Dual n**-back task** (DNB; Jaeggi et al., 2010) is used to test the updating ability. Participants' monitors simultaneously presented sequences of letters on screen and phonemes via speakers. Each time that the currently presented stimuli (in either of the sequences) matched the stimuli presented *n*-positions earlier in the sequence, participants responded by clicking on the right square (same letters) or the left square (same phonemes) on the screen. In the task started at level n=2 participants responded if the currently presented stimuli were the same as the one seen/heard two stimuli earlier, and continued on to level n=3, and after that to level n=4. Each sequence contains 20 + n stimuli, and each level is performed twice. The dependent variable is the proportion of correct answers across all test blocks.

Automated operation span tasks (AOSPAN; Turner & Engle, 1989) is a measure of WM. Participants decide on the correctness of simple arithmetic equations, while simultaneously memorizing a list of visually presented letters (range from 3 to 7). The dependent variable is the sum of all correctly recalled sets of letters (absolute OSPAN).

Baddeley grammatical reasoning task (BGRT; Baddeley, 1968) measures fluid reasoning. In this task, the letters (for instance, AB or BA) precede the statements related to the relation between the presented letters (A precedes B; B follows A). Participants have to verify whether the statement is true or false. The score range is 0-64. The dependent variable is the total number of correct test responses in 3 min.

Training apps

Dual n-back app (DNB; Tyskeranta, 2019) was used to train the updating function of the central executive. The dual n-back task requires the monitoring of a sequence of auditorily presented letters and visually presented squares. Participants' response is required when presented stimuli are equal to the either visual or auditory stimuli presented n-stimuli earlier. DNB starts at n=2, and 21 stimuli are presented at each n-level. DNB is adaptive; with less than three or over five mismatches at one level, n is increased or decreased by one, respectively.

Super number memory app (SNM, Schatten, 2015) provides conditions to train PL. At the beginning, participants are presented with a three-digit sequence, and the task is to repeat that sequence. Correct repetition leads to the increase of +1 in the sequence length. There is no maximum length, and participants' task is to repeat the longest length they can during a 20-minute session.

Colorfly: Art Coloring Game (Fun Games For Free, 2022). This app was used for control conditions. It offers various mandala shapes. Participants choose a shape and color it by touching its parts.

Procedure

The study employed a pre-post design with a FU at three months (Figure 1). Participants underwent a 4-week training period, at the rate of five 20’-session/week. The combined group (DNB&SNM) trained with each app for 10 minutes, always in the same order (first DNB, then SNM). All apps could be downloaded for free.

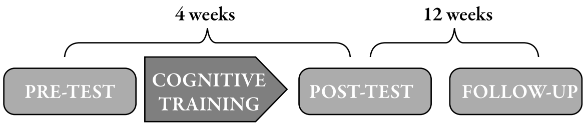

Figure 1. Scheme of study design

Participants were self-tested using the above described task over the Inquisite platform, which was downloaded to their computer. Adherence was assured via screenshots of the final screen after each training session, and mailed to the experimenter.

Results

Data analysis was conducted using the R software (2020) and the lme4 package (Bates et al., 2015). Linear mixed-effects models were used to test the differences in the dependent variables within and between groups. Group (DNB, SNM, DNB&SNM and Mandala group), session (pretest, posttest, follow-up), and group by session interaction were included as fixed effects, and subjects as a random effect in the model. All parameters were estimated using the restricted maximum likelihood (REML) technique. Tukey HSD post-hoc contrasts were performed for significant effects in the main analysis. Cohen’s *d* (Cohen,1988) was used to compute effect sizes comparing pretest with posttest, and follow-up change scores.

Preliminary analysis showed that 17% of the values were missing, with 80% of them referring to the results at the follow-up. Participants who dropped out did not differ significantly in the initial abilities compared to participants who remained in the study. Two outlier values were found in the data and were excluded from further analysis. No deviations from normal distributions were observed.

Descriptive data are shown in Table 1. The analysis of the efficacy of proposed trainings on cognitive outcomes is shown in Table 2.

The results showed a significant interaction only for the DNB task. Participants in the DNB and DNB&SNM group did not differ in the task performance, and they were significantly better at the posttest and follow-up compared to the pretest. Both groups outperformed participants in the SNM and Mandala group at the posttest and follow-up (effect

Table 1. Descriptive data for four groups (DNB, SNM, DNB&SNM, Mandala) and three measurement points (pretest, post-test and follow-up)

	Pretest				Post-test				Follow-up			
	DNB	SNM	DNB& SNM	Mandala	DNB	SNM	DNB& SNM	Mandala	DNB	SNM	DNB& SNM	Mandala
Letter span	*n*=43	*n*=51	*n*=34	*n*=44	*n*=38	*n*=49	*n*=28	*n*=44	*n*=19	*n*=29	*n*=24	*n*=31
	7.67 (1.886)	8.65 (2.904)	7.35 (1.668)	8.82 (2.739)	8.97 (2.804)	8.61 (3.239)	8.36 (2.407)	9.14 (2.483)	8.79 (2.551)	8.72 (2.506)	7.58 (1.248)	8.68 (3.310)
Digit span	*n*=43	n=51	*n*=36	*n*=45	*n*=38	n=49	*n*=29	*n*=45	n=20	*n*=30	*n*=24	*n*=31
	8.09 (2.021)	8.18 (2.463)	7.44 (1.482)	8.18 (2.026)	9.24 (2.399)	9.08 (2.326)	8.28 (1.750)	8.58 (2.210)	9.00 (2.471)	8.60 (2.415)	7.83 (1.239)	8.74 (2.221)
DNB	*n*=44	*n*=50	*n*=35	*n*=45	*n*=38	*n*=49	*n*=28	*n*=45	*n*=20	*n*=29	*n*=24	*n*=29
	0.54 (0.081)	0.50 (0.064)	0.52 (0.060)	0.50 (0.066)	0.68 (0.133)	0.49 (0.092)	0.65 (0.094)	0.54 (0.100)	0.67 (0.110)	0.47 (0.108)	0.62 (0.106)	0.50 (0.098)
AOSPAN	*n*=42	*n*=51	*n*=36	*n*=43	*n*=38	*n*=49	*n*=28	*n*=44	*n*=20	*n*=29	*n*=24	*n*=30
	27.07 (21.822)	36.02 (23.934)	27.14 (18.216)	36.95 (26.403)	35.66 (22.109)	45.92 (20.760)	40.57 (18.614)	41.25 (24.943)	31.25 (25.957)	37.97 (26.000)	31.79 (22.502)	36.13 (25.551)
BGRT	*n*=43	*n*=51	*n*=36	*n*=45	*n*=38	*n*=50	*n*=30	*n*=45	*n*=20	*n*=30	*n*=24	*n*=29
	25.47 (8.453)	23.90 (7.716)	22.69 (7.942)	24.13 (8.698)	30.92 (9.222)	28.32 (8.272)	27.63 (8.950)	26.62 (9.311)	34.35 (7.869)	30.30 (7.804)	29.58 (8.005)	27.90 (10.024)

Note. DNB – Dual n-back, SNM – Super Number Memory, AOSPAN - Automated Operation Span Task; BGRT - Baddeley Grammatical Reasoning Test sizes are shown in Figure 2). As for the remaining tasks, all groups performed better at the posttest compared to the pretest ($d_{letter\text{-}span}$=0.23, $d_{digit\text{-}span}$=0.39, d_{AOSPAN}=0.40, d_{BGRT}=0.49). Furthermore, participants were better in the AOSPAN task at the posttest compared to the follow-up (*d*=0.28), and better in the BGRT at the follow-up compared to the pretest (*d*=0.72).

Table 2. Results of linear mixed-effects model analyses

		F	*df*	*p*
Letter span	Group	1.18	3/173.12	.320
	Session	5.68	2/265.52	.004
	G x S	1.88	6/265.10	.084
Digit span	Group	1.89	3/169.95	.133
	Session	11.56	2/267.67	<.001
	G x S	0.52	6/266.94	.791
DNB	Group	29.763	3/179.38	<.001
	Session	52.34	2/273.13	<.001
	G x S	14.41	6/272.62	<.001
AOSPAN	Group	1.48	3/174.37	.220
	Session	13.41	2/265.92	<.001
	G x S	1.05	6/265.40	.393
BGRT	Group	1.89	3/175.70	.133
	Session	38.42	2/273.58	<.001
	G x S	0.59	6/272.94	.738

Note. DNB – Dual *n*-back task; AOSPAN - Automated Operation Span Task; BGRT - Baddeley Grammatical Reasoning Test

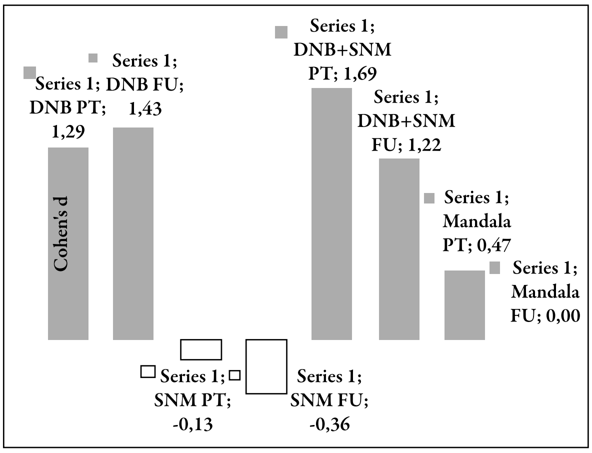

Figure 2. Standardized effect sizes (Cohen's d) comparing each group at posttest (PT) and follow-up (FU) versus pretest in DNB task

Note. DNB – Dual n-back, SNM – Super Number Memory, PT – posttest; FU – follow up

Discussion

In this study, we tried to answer two questions. First, we investigated whether smartphone apps designed to strengthen a single WM component have an effect on young adults' cognitive functioning, in terms of near and far transfer to different cognitive processes. Secondly, we explored whether combining two training apps within the same training protocol, with each app training one WM component, might exhibit different transfer effects.

Concerning the efficacy of the training via apps, we found that updating training (DNB) resulted in significant near-transfer effects, which were thus maintained at the follow-up at least three months after the training. The combined training of CE and PL (DNB&SNM) has yielded positive effects only for the executive aspects of WM, i.e., near-transfer effects were found on updating. Effect sizes (Figure 2) show comparable size effects found in the combined training group at the posttest and the follow-up, as well as in the DNB training group. This suggests that a shorter DNB training might reap similar levels of efficacy as a longer DNB training. It would be interesting to investigate whether a 10-minute DNB training (as in the combined group) and a 20-minute DNB training itself have comparable effects, or if the similar efficacy of combined training and DNB training was catalyzed by the addition of SNM training to the 10-minute DNB training in the mixed group. Effect was found neither in the case of the PL training (SNM) nor on any of the far-transfer measures.

Our results are in accordance with findings which show that updating training will have the most effect on the updating ability itself, with a small or neutral effect in terms of far transfer to abilities, such as fluid reasoning (Melby-Lervåg & Hulme, 2013; Soveri et al., 2017; Weicker et al., 2016). Studies which find far transfer of updating training to fluid abilities have used nonverbal reasoning tests (Jaeggi et al., 2008, 2010; Stephenson & Halpern, 2013). Since DNB aimed at visuospatial processes, testing for far transfer on nonverbal measures of reasoning might have been a more successful avenue.

Although some studies have shown that the PL training could enhance the PL, i.e., STM abilities (e.g., Li et al., 2022; Norris et al., 2019), we did not confirm these findings. These previous training sessions were more intense (e.g., a 40-minute session; up to three trainings in one day; Norris et al., 2014), which could be a key factor in enhancing PL. In addition, STM trainings, especially those relying on the verbal component, seem less challenging compared to updating trainings, and therefore show smaller transfer effects (Stephenson & Halpern, 2013). It is possible that participants would have a greater effect on the tasks if they were trained to use a specific mnemonics, freeing thereby their limited PL capacity (e.g., Borella et al., 2017).

However, the lack of near- and far-transfer effects could result from the methodological flaws of the study. For instance, we conducted an online/out-of-lab study. Participants have trained at home, with no supervision during the testing and training sessions. Further research should take into consideration the methodological issues we have faced, especially concerning the selected (updating) task. For instance, our participants trained the updating function with the same task as in the pre- and post-test. By using an additional near-transfer measure (Waris et al., 2015), i.e., a cognitive task that overlaps to a lesser extent with the training task, we could be more certain regarding the effects of a specific training on the updating WM function.

Within the brain-training industry there are numerous possibilities for psychological research to advance the field. Due to their wide use among various population segments, apps offer a practical platform to investigate, for example, the role of various predictors of one's cognitive success, such as sociodemographic characteristics, personality, motivation, beliefs of the malleability of intelligence (the so-called growth mindset). For example, Double and Birney (2016) found that some personality traits, as well as the growth mindset, influence task performance, training adherence and/or its discontinuation. Findings of this nature would further advance the approach and enable the personalization of training protocols.

In conclusion, our study confirmed the efficacy of smartphone apps in enhancing the updating WM function. Since both training groups have used the DNB app, we can conclude that training with this task is beneficial for updating WM function in young adults, but not for other cognitive functions, such as verbal fluid reasoning. Since numerous brain-training applications are on the market, and their popularity among the general population grows daily, it is becoming essential to conduct validation studies in the field. Based on our research, we cannot state that brain-training apps provide no benefits. However, the criteria for advertising those apps should be tightened by giving straightforward guidelines: for which population the app is intended, how long training should last and which cognitive function it enhances.

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