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SOUTĚŽNÍ TEXT

The effect of binaural beats on working memory capacity

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ABSTRAKT

Binaural beats sú definované ako auditívne percepcie, ktoré nastávajú vtedy, ak sú dva tóny jemne odlišnej frekvencie prezentované separátne do každého ucha. Pokiaľ rozdiel vo frekvenciách tónov, ktoré produkujú binaural beat, zodpovedá stavu mozgových vĺn v rozsahu alfa, tak by celková mozgová aktivita mala následne udržiavať tento stav. V práci je vyslovený predpoklad, že mozgová aktivita sa vplyvom určitého binaural beat zmení tak, že alfa vlnová aktivita bude posilnená, čo spôsobí krátkodobé zlepšenie kapacity pracovnej pamäte (WMC). Participanti boli rozdelení do 2 skupín- jedna skupina podstúpila binaural beat stimuláciu počas počúvania zvukov mora a druhá počúvala len zvuky mora bez binaural beat stimulácie. Obe skupiny podstúpili aj 2 testy pracovnej pamäte, merané Operation span task (OSPAN) metódou, pričom prvý absolvovali pred počúvaním a druhý po ňom. Participanti, ktorí podstúpili binaural beat stimuláciu, na rozdiel od kontrolnej skupiny, preukázali zlepšenie vo WMC.

Kľúčové slová: binaural beats, pracovná pamäť, kapacita pracovnej pamäte, Operation span task, alfa frekvencia, mozgová vlna

ABSTRACT

Binaural beats are defined as auditory perceptions, occuring when two tones of slightly different frequencies are presented separately to each ear. When the binaural beat beats with the frequency that corresponds to the state of alpha wave range, than it is believed that the overall brain activity changes accordingly. In this study it is assumed that binaural beat corresponding to alpha wave range will subsequently enhance working memory capacity (WMC). In the following study, participants were divided into two groups. One group underwent a binaural beat stimulation, while listening to the sound of sea. The other group was listening solely to the sound of sea without binaural beat stimulation. We measured baseline and post-stimulation working memory capacity using OSPAN method. As expected, only participants from the binaural beat group showed an improvement in WMC.

Keywords: binaural beats, working memory, working memory capacity, Operation span task, alpha frequency, brainwave

Introduction

It has been suggested that cognitive and executive functioning is accompanied by specific brain wave oscillations. Overall the brain activity within alpha rhythm (7.5-12.5 Hz in adults) has been associated with vigilance, inhibitory processes, attention, working memory, perceptual abilities and information processing speed (Braboszcz a Delorme, 2011; Clark et al., 2004; Freunberger et al., 2011; Lachat et al., 2012; Oprisan, 2004; Palva & Palva, 2007; VanRullen & Koch, 2003). For instance, an increase in the individual capacity of working memory (greater number of retained and recalled items) was accompanied by higher amplitude of alpha oscillations (Sauseng et al., 2009). Also, according to some authors, the oscillations in alpha rhythm indirectly enhance performance in working memory capacity in a way that they filter out irrelevant information and prevent disruption of the process in form of conflicting stimuli (Klimesch et al., 2007; Rihs et al., 2007; Tuladhar et al., 2007).

Other studies looked at to what extent can induction of specific brain waves alter subsequent cognition. One way of ensuring induction of electrical activity in the brain is through binaural beats (BB) (e.g. Kasprzak, C., 2011; Nozaradan et al., 2011; On et al., 2013). BB are defined as subjective auditory sensations that occur through a presentation of two tones corresponding to slightly different frequencies separately to each ear. As a result, a listener perceives a sound with amplitude that changes with a frequency equal to the difference of frequency of the presented tones (Kasprzak, 2011), and these two frequencies are integrated at the cortical level into above-mentioned binaural beat (Ozimek, 2002). Specifically, BB can alter the functioning of reticular formation, a neural network system in the brainstem responsible for regulation of vigilance, concentration and attention (Wahbeh, Calabrese & Zwickey, 2007). Based on the stimulation by binaural beats, reticular system changes the activity of brainwaves in a way that it could adapt the characteristics, quality, and functions of conscious state to the information, which it receives through the binaural beat (Wahbeh, Calabrese & Zwickey, 2007). Following this logic, if the difference of frequencies of two tones, which produces the resulting binaural beat corresponds to a certain brainwave state (e.g. . 130 Hz–110 Hz = 10 Hz = alpha range - 7,5-12,5 Hz) than the overall brain activity should subsequently maintain that state (Sornson, 1999). Some researchers call this process hemispheric synchronization and assume that by means of exposing an individual to binaural beat, the electrical activity of both hemispheres merges to one synchronized activity with overall frequency that represents the difference of the two originally presented tones (e.g. Foster, 1990; Kennerly, 1994).

Several studies looked at the possible effects of binaural beats within the alpha range on cognitive abilities. Significant improvement in cognitive processing measured by Stroop Effect exercise was found by BB stimulation of 10.2 Hz frequency (Cruceanu & Rotarescu, 2013). Carter and Russell (1993) exposed 8 to 12 year old boys with learning disabilities to 8-week long 10 and 18 Hz BB stimulation session. Their results illustrate improvement in Raven's progressive matrices and in subtest of auditory sequential memory (Carter & Russell, 1993). McMurray (2006) assessed the effect of 7 and 11 Hz binaural beat on the alpha brainwave activity, working memory, and attention in healthy elderly, who are known for their gradual decrease in physiological alpha activity. The 2 minutes exposure to BB resulted in altered electrical activity in the brain. Concretely speaking, the changes occurred within the alpha brainwave activity. Moreover there were improvements in Forward and Backward Digit Span Memory Tasks, and in a version of Continuous Performance Task. On the contrary to the previous results, Wahbeh et al. (2007) documented a significant deterioration in Rey Auditory Verbal Learning Test (RAVLT) as a consequence of stimulation by 7 Hz frequency binaural beat in duration of 30 minutes.

It thus appears that BB's possible positive effects on cognitive functions depend on many factors. These factors may be the specific frequency of BB; the targeted population- because it is known that the older people have different quality of brainwave activity than e.g. younglings (Bazanova & Aftanas, 2008; Clark et al., 2004), and the tests used to detect the possible changes in working memory capacity.

Based on the research showing the positive impact of alpha-range binaural beats on cognitive functioning, specifically attention, auditory sequential memory, working memory, working memory storage, reasoning ability, cognitive processing and hemispheric synchronization (Carter & Russell, 1993; Cruceanu & Rotarescu, 2013; Foster, 1990; Kennerly, 1994; McMurray, 2006) as well as on the wealth of research documenting the important role of alpha brain wave activity on vigilance, inhibitory processes, attention, filtering out irrelevant information working memory, visuo-spatial component of working memory, perceptual abilities and information processing speed (Braboszcz & Delorme, 2011; Clark et al., 2004; Engle et al., 1999a; Freunberger et al., 2011; Klimesch et al., 2007; Lachat et al., 2012; Oprisan, 2004; Palva a Palva, 2007; Rihs et al., 2007; Sauseng et al., 2009; Tuladhar et al., 2007; VanRullen a Koch, 2003), we believe that binaural beat of a frequency that corresponds to alpha range of brain activity has a temporary effect on the working memory capacity.

In our study, subjects were exposed to 9.55 Hz BB stimulation while we measured their working memory capacity through Automated Operation Span Task (AOSPAN). The goal was to explore the possible temporary improvement in working memory as a consequence of alpha-range BB stimulation.

Methods

Participants

In total, 50 university/college students participated in the study (M Age = 21.63 years; 29 (72,5%) women). Each participant was randomly assigned to either experimental or control group. 10 participants were rejected from further analysis due either to their inability to fulfill the 85% limit of correctly solved mathematical operations in Automated Operation Span Task (AOSPAN) or achieving 0 in the Ospan score. The rejection of these participants is fully in accordance with the instructions from authors of this method Unsworth, Heitz, Schrock & Engle (2005).

The final sample of participants included 40 students with the effect size d=1.06 and statistical power of 0.95.

The experiment was approved by an Institutional Review Board (IRB) at Farmingdale State College, NY, USA.

Methods

Automated Operation Span Task

Operation Span Task measures working memory capacity in a way as it was defined by Engle et al. (1999a). Unsworth, Heitz, Schrock & Engle (2005) developed computer-administered Automated Operation span task, which works automatically. The test consists of a training period and the actual test. The training allows elimination of testing effect.

During the task, a person is asked to retain randomly presented 3 to 7 sets of defined letters (F, H, J, K, N, P, Q, R, S, T and Y). The letters are presented one at a time for 800 milliseconds. After presentation of each letter, a simple mathematical equation appears on the screen. An example of such operation may be like this:

(2*3) + 7 = ?

The participant has to assess whether the proposed solution is correct. The mathematical operation is presented to each participant for a specific amount of seconds calculated from his/hers individual tempo measured during his/her individual rehearsal task +- 2SDs. Afterwards, a letter comes up for 800ms. This process is presented anywhere between 3 and 7 times. Afterwards, a set of letters (a table of all possible letters) is presented to the participant. Participant has to choose the letters that were presented in that trial.

The whole task consists of 3 series of each set size. The set sizes range from 3 to 7 letters along with the mathematical operations. In total, 75 letters and 75 mathematical operations are administered to the participant.

Furthermore, the results are obtained only from those participants, who meet the 85% accuracy criterion in solving the mathematical operations. This criterion serves for the purpose of dealing with the possible problem of participants concentrating only on remembering the letters while ignoring the mathematical operations.

Figure 1

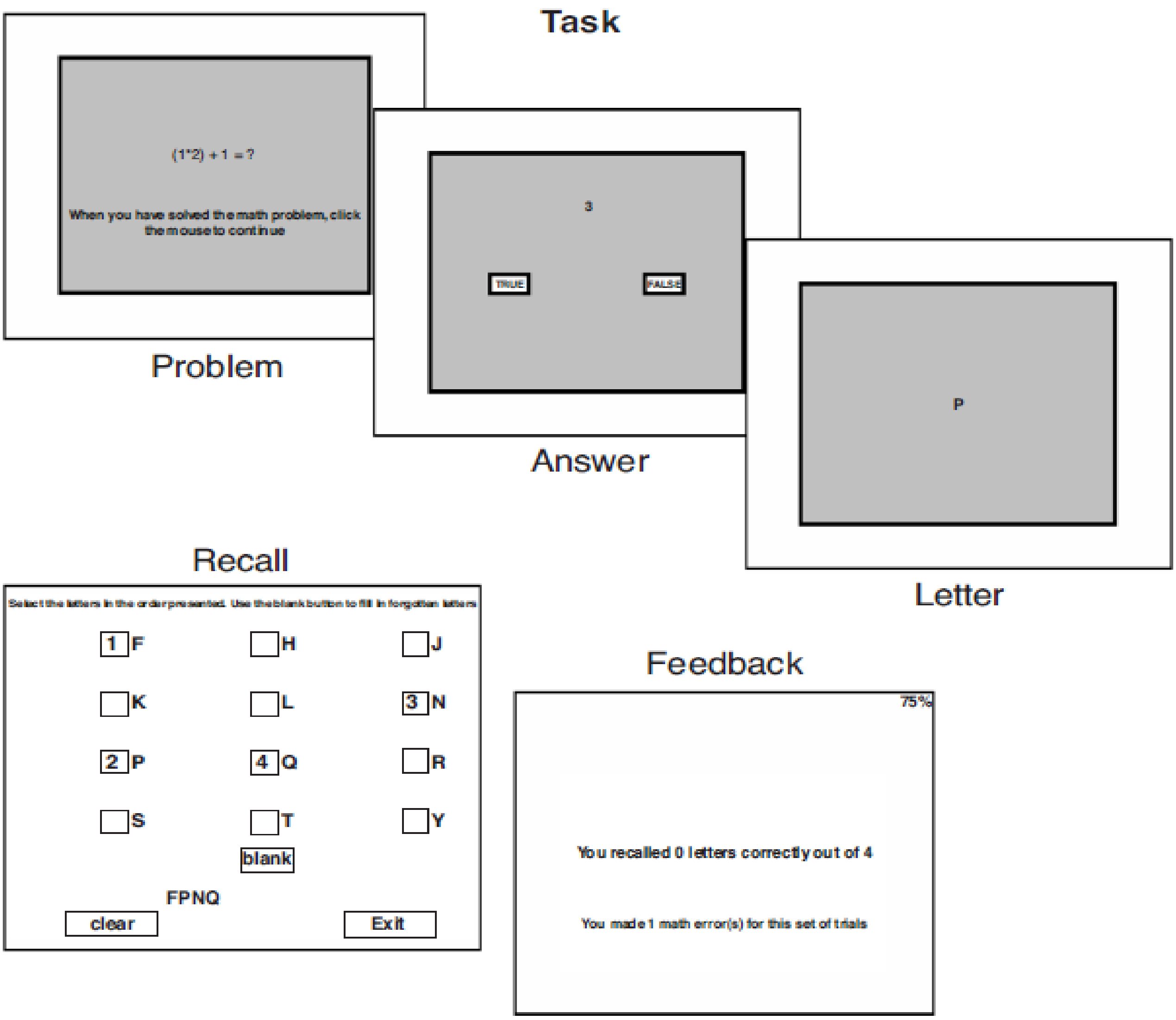


Illustration of AOSPAN task. At first, participant is presented with a mathematical operation. After solving of the operation, participant clicks with a mouse button and an offered answer displays on screen. If one thinks that the offered answer is right, than he/she selects "true", if not than he/she selects "false". Subsequently, in the middle of the screen appears a letter which remains there just for 800 miliseconds. Then the program offers a matrix of letters, where the participant has to select letters, which he or she had to remember in the correct order. At last, participant is presented with a feedback, where he or she finds out about his/hers success in the concrete sequence (remembered letters and correctly answerd mathematical operations). The illustration of the AOSPAN task presented here is adapted from Unsworth et al. (2005).

After completing the task, 5 scores pertaining to measure of working memory capacity are produced.

The first is *Ospan score*, an absolute scoring method, which represents the sum of all correctly recalled sets of letters in the correct order. So, for instance, if a participant correctly recalls 3

letters in a set size of 3, 4 letters in a set size of 4, and 3 letters in a set size of 5, his/her Ospan score would be 7 (3 + 4 + 0) (Unsworth et al., 2005).
The second score is a *value*, which reflects the number of letters recalled in a correct order.
The third additional score reflects the total number of errors made during solving the mathematical operation. This score is further divided into "speed errors" and "accuracy errors". Speed errors are all of the errors that are made due to the fact that the participant wasn't able to catch up with the time that was given to him or her for solving the problem. The accuracy errors score reflects all of the incorrectly solved operations.
For the purposes of this work, the score which was further analyzed was the first Ospan score. It is a score which is stable in terms of test-retest reliability when repeating the test after few minutes ($r = 0.77 – 0.79$; Turley-Ames & Whitfield, 2002), weeks (0.82; Klein & Fiss, 1999), or months (0.76; Klein & Fiss, 1999). Other sources in relation to this score present even higher test-retest reliability ($r = 0.83$; Unsworth et al., 2005).
Further, when two versions of OSPAN task different in difficulty of the mathematic operations were compared, relatively high correlations ranging from 0.7 to 0.8 were observed (Conway & Engle, 1996; Lehto, 1996). This information is important because in our study participants had to solve 2 AOSPAN tasks during a short period of time.

In this study, the AOSPAN task used was identical to that, which was created and described byUnsworth et al., (2005) and was scripted in MATLAB program (version 8.1).

Binaural Beats Stimulation
As stated above, binaural beat is defined as a subjective auditory sensation, which occurs when two tones of slightly different frequencies are presented separately to each ear. A listener then receives a resultant sound with amplitude which changes with a frequency equal to the difference of frequency of presented tones (Kasprzak, 2011). Two tones of the frequencies of 230 and 220.45 Hz were generated through Audacity Program in a way, that each of them was present in one headphone only by using stereo listening. The frequency of the following binaural beat equals to the difference between used frequencies (9.55 Hz- alpha range).
2 different recordings were created. The first contained the binaural beat of the frequency of 9.55 Hz, plus an overlapping sound, which represented the sound of sea. This overlapping sound is important for the participants not to fully perceive the binaural beat. Similar overlapping sounds are common in binaural beat literature (e.g., Wahbeh et al., 2007). Further, the use of neutral overlapping sounds (sounds of rain, wind, water) seem to be as more appropriate than any meditation, relaxing or other similar recordings, which may themselves been causing the changes in cognition (e.g. Hodges, 2010; Pelletier, 2004; Rickard, Wong, & Velik, 2012).
The second recording included only the above-mentioned sound of sea without the binaural beat component. Both recordings lasted 12 minutes and were to the exception of the presence/absence of binaural beat identical. In McMurray's (2006) experiment, participants couldn't distinguish between two such recordings.

DESIGN AND PROCEDURE

Procedure

All participants signed Informed Consent and indicated no history of seizures and epilepsy. Participants were told to be involved in a memory study while being exposed to a break in which they would listen to music.
The baseline measure of AOSPAN was received at the beginning of the experiment. After the first round of AOSPAN, participants were randomly assigned to either binaural beats or music piece condition. Afterwards, they were asked to retake the AOSPAN.

Both experimental and control group were exposed to the same procedure with the exception of the content of the music piece during the 12 minute break between individual AOSPANs. The completion of the experiment lasted approximately 50 minutes.

RESULTS

We were interested in the effect of BB stimulation on Ospan score. The baseline Ospan score was substracted from post-BB/music exposure Ospan score. The resulting score provides information about the change in Ospan score as a result of exposure to the music/BB. For clarity, this score will be referred to as SOS (Substracted Ospan Score).

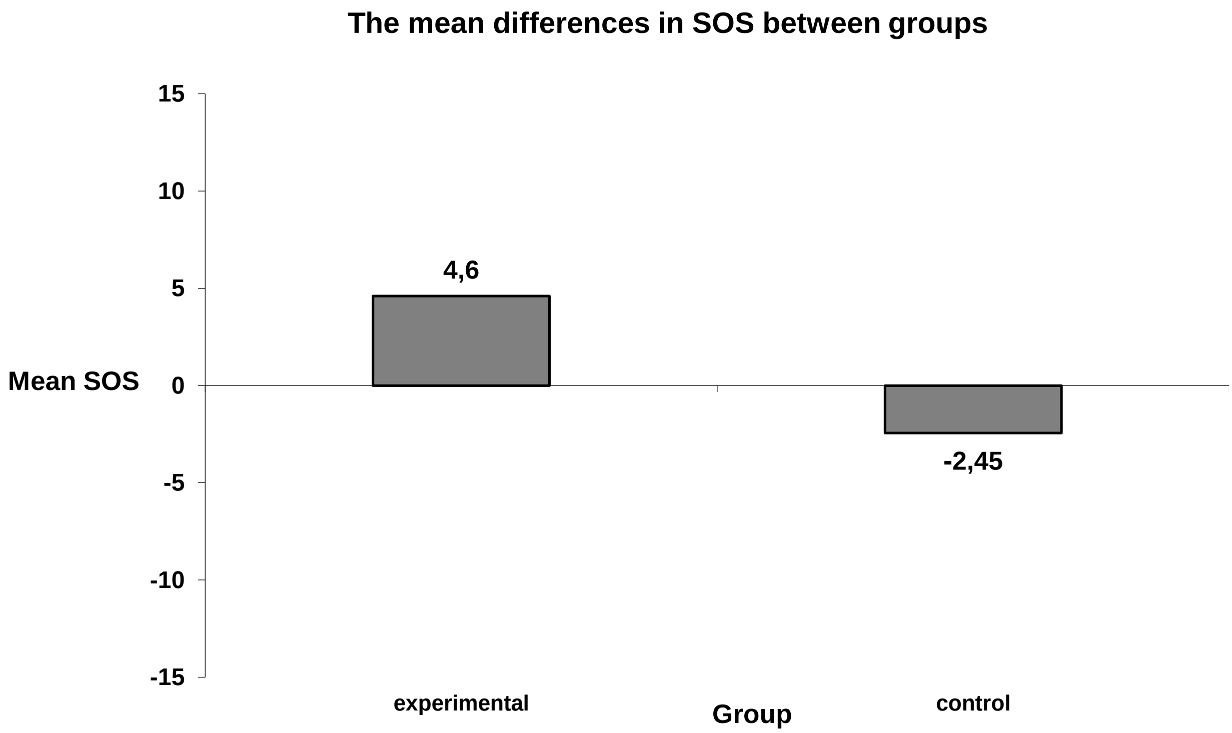
Additionally, the total number of mathematical errors in the AOSPAN was used in the analysis. This score was obtained by subtracting the total number of mathematical errors obtained in the first AOSPAN task from the total number of mathematical errors obtained in the second AOSPAN task. The score informed about the improvement/deterioration in making of arithmetic errors after participants completed the second AOSPAN task. This score will be further labeled as SNME (Substracted Number of Mathematical Errors).

In order to compare differences in AOSPAN scores between experimental and control condition independent t-test was used.

The variances of SOS score in experimental and control group were equal, $F(1, 38) = 2.16$, $p > 0.05$. On average, participants from the experimental group received higher SOS (M = 4.60; SE = 1.95) than the participants from the control group (M = -2.45; SE = 2.55). This difference was statistically significant $t(38) = 2.20$, $p = 0.017$ (*one-tailed*); representing a medium-sized effect r = 0.34.

Participants in the experimental condition did not differ from those in the control condition in terms of SNME; M = - 0.20; SE= 0.72 versus M= - 0.15, SE= 0.65., $t(38)$= -0.05, p > 0.05.

Diagram 1



The diagram shows mean differences in SOS between groups.

DISCUSSION

The goal of the study was to observe the effect of exposure to BB on working memory capacity. As suggested by many studies, BBs corresponding to alpha brain waves can positively influence cognitive processing, namely attention, auditory sequential memory, working memory, working memory storage, and reasoning ability (Carter & Russell, 1993; Cruceanu & Rotarescu, 2013; Foster, 1990; Kennerly, 1994; McMurray, 2006).
The results show that the BB of the frequency of 9.55 Hz – which is a representation of the alpha frequency range of the brain activity, had a temporary positive effect on the working memory capacity in the sample of healthy adult university students.

Lim, Quevenco, and Kwok (2013) state that in tasks testing higher cognitive functions, such as working memory, an increased alpha activity is positively associated with quality performance (Doppelmayr et al., as cited in Lim, Quevenco & Kwok, 2013). In the research of Lim et al. (2013) lower delta and theta activities which are associated with fatigue, were recorded in participants who underwent the break in comparison those participants who did not. DeLuca (2005a) defines fatigue as a result of intense and lasting exertion caused by a cognitive effort. The break prevented the effects of fatigue and allowed participants to relax. Lim et al. (2013) observed improved performance in auditory oddball task (sustained attention and its capacity) in the participants who underwent the break, while the performance of the control group deteriorated. These individual differences were correlated on one hand with the decreasing delta and theta activity, and on the other hand also with increase in alpha activity during the break (Lim et al., 2013).
In our research, participants were similarly provided with a break from a cognitively demanding task, i.e., working memory capacity task. The break was represented by 12-minutes listening to the sea waves sounds during which the participants were supposed to relax. In our case, the break influenced each participant differently; in those exposed to BB we assume it supported alpha synchronization and thus improved participants' performance in the second AOSPAN test, while performance of the control group deteriorated.
The results of our research support the findings of McMurray (2006) and Carter and Russell (1993). McMurray (2006) had older adults listen a 2-minute track including alternately binaural beat of 7 and 11 Hz and found a significant improvement in their attention and working memory. Carter and Russel (1993) explored the effects of binaural beats on various cognitive processes in boys with the learning deficits. During several 25-minute sessions, the participants were alternately stimulated by audiovisual, as well as solely by BB of frequencies 10 and 18 Hz. Boys exposed to BB stimulation showed an increased performance in Raven's progressive matrices and in subtest of auditory sequential memory. Huang and Charyton (2008) investigated and evaluated the data from all of the available research studies, which were dealing with the brain stimulation in any kind of form (not just BB). They came to the conclusion that just one session of such stimulation may be beneficial for immediate states of memory, attention, stress, pain, and migraine (Huang & Charyton, 2008). Our work is consistent with this finding.

The results of our work expand on above-mentioned findings. The BB of the frequency of 9.55 Hz was, to our knowledge, first time experimentally studied in the context of working memory employing Operation Span Task (AOSPAN).

Unsworth et al. (2005) compared the score of 78 participants, who were solving AOSPAN task two times in a several days period. Within Ospan score, he observed an increase of about 1 point. On the other hand, the results from the control group in this very paper suggest just the opposite trend. The participants' scores as a result of exposure to music deteriorated. A possible explanation could be the above mentioned effect of fatigue. Increasing fatigue subsequently affects the degradation of performance in cognitive tasks (Kato et al., 2009; Lorist, 2008).

Participants spent approximately 40 minutes from the total duration of the experiment solving the AOSPAN tasks. However, participants exposed to BB just for 12 minutes, showed an improvement in their working memory capacity on average by 4.6 points in their Ospan score.

As mentioned above, our participants showed an improvement after the second AOSPAN task of on average 4.6 points as a result of BB stimulation. If we think again of the scoring method used, we will find out that the people from the experimental group improved by about one set from the total of 15 sets. Since in the test sets of 3 to 7 letters (= 3 to 7 points) were used and the points were gained only when participant answered the whole set correctly, we can assume that the above mentioned 4.6 points represents just one set. This represents an improvement of almost 7% which is a relatively decent growth since the participants were young and healthy university students whose cognitive functioning is presumably in its apex. One could surmise that patients with memory deficits could show even greater improvement. In terms of the control group, we may assume that this group either remained, by means of measured performance, unchanged or deteriorated by the maximum of one set on average (deterioration of 2.45 points). Thus the ultimate difference between the experimental and control group represents the difference of 1-2 correctly recalled sets, roughly a range of 7 – 13 %. While the experimental group improved by an average of slightly more than one remembered letter, the control group deteriorated by almost 3 letters in total. The overall mean difference between the two groups was thus on average of correctly recalled 4 letters.

For the assessment of working memory capacity it seems crucial to be able to recall the whole set. For a participant to be successful in this task, he should be able to actively navigate his attention, and to store and activate the presented information (letters) while solving each set (Engle, Tuholski, & Kane, 1999a).

The results of our research indicate that the BB may positively effect retention, attentional control, the storage and the activation of information, which serve for memorizing of that information.

It would be interesting to see what results would achieve individuals with memory or other cognitive deficits, older individuals or people without university/college experiences. From the point of the external validity it is important that any other future research in this area should be realized in as heterogeneous population as possible. Also, it would be appropriate to extend the time period between the solving of the two AOSPAN tasks in a way, so the potential effect of fatigue or immediate training effect would be minimized.

CONCLUSION

The results of our study illustrate that binaural beat frequency corresponding to alpha range of brain activity, had a temporary positive effect on the capacity of working memory. Participants undergoing 12-minute binaural beat stimulation of 9.55 Hz frequency, achieved significant increase in the capacity of working memory in comparison to the control group which wasn't exposed to the binaural beat stimulation.

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NOTE

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