THE EFFECT OF BINAURAL BEATS ON WORKING MEMORY CAPACITY

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Abstract: The research explored the effect of binaural beats on working memory capacity (WMC). When the binaural beat beats with the frequency that corresponds to the state of alpha wave range, then it is believed that the overall brain activity changes accordingly. Brainwave activity within the alpha range has been generally correlated with many cognitive functions along with working memory improvement. Therefore, in this study it is assumed that binaural beat corresponding to alpha wave range will enhance subsequently WMC. In the following study, participants were divided into two groups. One group underwent a binaural beat stimulation while listening to the sound of the sea. The other group was listening solely to the sound of the sea without binaural beat stimulation. We measured baseline and post-stimulation working memory capacity using the OSPAN method. As expected, only participants from the binaural beat group showed an improvement in WMC.

Key words: binaural beats, 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 & 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 capacity of working memory (a greater number of retained and recalled items) was accompanied by a 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 such a way that they filter out irrelevant information and prevent disruptions caused by conflicting stimuli (Klimesch et al., 2007; Rihs et al., 2007; Tuladhar et al., 2007).

Other studies looked at the extent to which the induction of specific brain waves can alter subsequent cognition. One way of ensuring induction of electrical activity in the brain is through binaural beats (BB) (e.g., Kasprzak, 2011; Nozaradan et al., 2011; On et al., 2013). BB are defined as subjective audi-

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tory sensations caused by presenting tones of slightly different frequencies separately to each ear. As a result, a listener perceives a sound with an amplitude that changes with a frequency equal to the difference of frequency in the presented tones (Kasprzak, 2011), and these two frequencies are integrated at the cortical level into the abovementioned binaural beat (Ozimek, 2002). Specifically, BB can alter the functioning of the reticular formation, a neural network system in the brainstem responsible for regulation of vigilance, concentration and attention (Wahbeh, Calabrese, & Zwickey, 2007). Binaural beats stimulation can, through changes in the reticular formation, enhance the processing of presented information (Wahbeh, Calabrese, & Zwickey, 2007). Following this logic, if the difference in the frequencies of the two tones, which produce 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), then 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 an overall frequency that represents the difference of the two originally presented tones (e.g., Foster, 1990; Kennerly, 1994).

Several studies have looked at the possible effects of binaural beats within the alpha range on cognitive abilities. A significant improvement in cognitive processing, as measured by the Stroop Effect exercise, was found by a 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 sessions, and they found an improvement in Raven's progressive matrices and in a subtest of auditory sequential memory (Carter & Russell, 1993). McMurray (2006) assessed the effect of 7 and 11 Hz BB on alpha brainwave activity, working memory, and attention in healthy elderly people, who are known for experiencing gradual decrease in physiological alpha activity. The 2 minutes exposure to BB resulted in an 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 the Continuous Performance Task. Contrary to the previous results, Wahbeh et al. (2007) documented a significant deterioration in the Rey Auditory Verbal Learning Test (RAVLT), as a consequence of stimulation by a 7 Hz frequency BB in durations 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 older people have different quality of brainwave activity than, e.g., youngsters (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 a positive impact of alpha-range BB 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, the 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 & Palva, 2007; Rihs et al., 2007; Sauseng et al., 2009; Tuladhar et al., 2007; VanRullen & Koch, 2003), we believe that BB of a frequency that corresponds to the alpha range of brain activity has a temporary effect on working memory capacity.

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

Method

Participants

In total, 50 university/college students participated in the study. Each participant was randomly assigned to either an experimental or control group. Ten participants were rejected from further analysis for either failing to reach an 85% limit of correctly solved mathematical operations in AOSPAN or achieving 0 in the Ospan score. The rejection of these participants is fully in accordance with the instructions from the authors of this method Unsworth, Heitz, Schrock & Engle (2005).

The final sample of participants included 40 students (M Age = 21.63 years; 29 (72.5%) were women) with an effect size of 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.

Instruments

Automated Operation Span Task

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

During the task, a person is asked to retain randomly presented series of 3 to 7 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 the presentation of each letter, a simple mathematical equation appears on the screen. Here is an example equation: (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/her individual tempo as measured during his/her individual rehearsal task $\pm$ 2 SDs. Afterwards, a letter comes up for 800 ms. 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. The 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 plus 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.

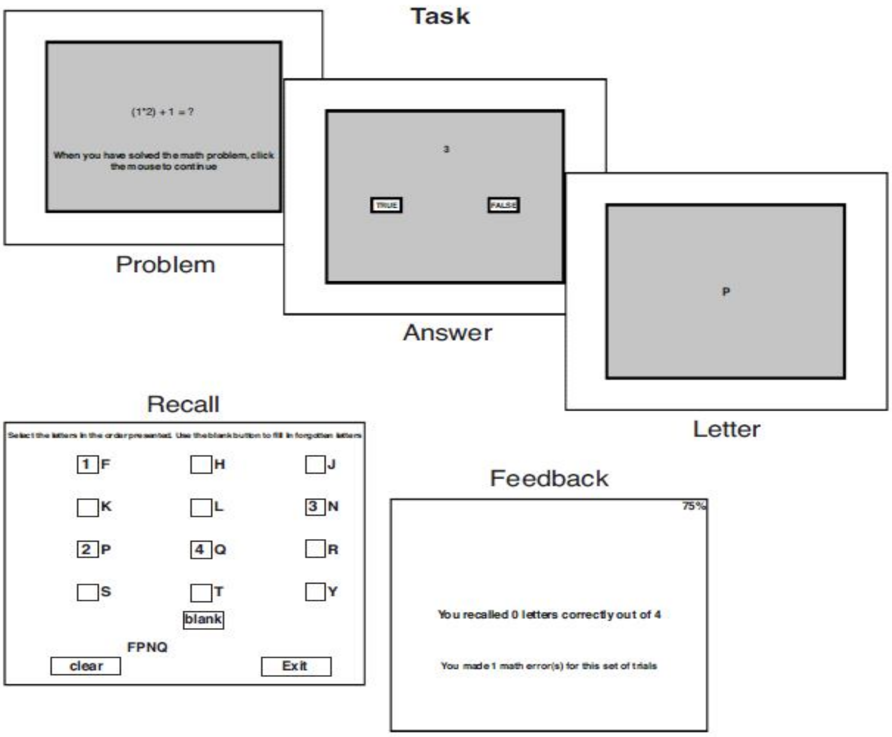

Figure 1. Illustration of AOSPAN task. At first, participant is presented with a mathematical operation. After solving of the operation, participant clicks with a mouse button and an offered answer displays on screen. If one thinks that the offered answer is right, than he/she selects “true”, if not than he/she selects “false”. Subsequently, in the middle of the screen appears a letter which remains there just for 800 milliseconds. 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 answered mathematical operations). The illustration of the AOSPAN task presented here is adapted from Unsworth et al. (2005).

After completing the AOSPAN task, two scores related to the assessment of working memory capacity were computed.

The first score, the Ospan score, has an absolute scoring method, and it 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 additional score reflects the total number of errors made solving the mathematical operations. This score consists of "speed errors" and "accuracy errors". Speed errors are errors made due to the participant not solving the task within the time limit. The accuracy errors score reflects incorrectly solved operations.

For the purposes of this study, the score used most in the analysis 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 comparing two versions of the OSPAN task, which differ in the difficulty of the mathematic operations, 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 two AOSPAN tasks during a short period of time.

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

Binaural Beats Stimulation

As stated above, BB is defined as a subjective auditory sensation, which occurs when two tones of slightly different frequency are presented separately to each ear. A listener then experiences a resultant sound with an amplitude which changes with a frequency equal to the difference in the frequencies of presented tones (Kasprzak, 2011). Two tones of the frequencies of 230 and 220.45 Hz were generated through the Audacity Program via stereo headphones presenting a different tone to each ear. The frequency of the BB is equal to the difference between the used frequencies (9.55 Hz - alpha range).

Two different recordings were created. The first contained a BB at the frequency of 9.55 Hz, plus an overlapping sound (the sound of the sea). This overlapping sound is important so that the participants do not fully perceive the BB. Similar overlapping sounds are common in BB literature (e.g., Wahbeh et al., 2007). Further, the use of neutral overlapping sounds (sounds of rain, wind, water) seem more appropriate than any recording meant for meditation, relaxation or other aims, which may themselves cause changes in cognition (e.g., Hodges, 2010; Pelletier, 2004; Rickard, Wong, & Velik, 2012).

The second recording included only the above-mentioned sound of the sea without the BB component. Both recordings lasted 12 minutes and were, with the exception of the presence/absence of the BB, identical. In McMurray's (2006) experiment, participants could not distinguish between two such recordings, though in her and other BB studies, the authors do not explicitly describe the exact volume of the BBs in terms of their total inaudibility. None of the participants in this experiment reported an awareness of such sounds when asked after the experiment took place.

Procedure

All participants signed an Informed Consent form and indicated no history of seizures and epilepsy. Participants were told they would be involved in a memory study while being exposed to a break in which they would listen to music, and they were not aware of the purpose of the study.

The baseline measure of the AOSPAN was obtained at the beginning of the experiment. After the first completion of the AOSPAN, participants were randomly assigned to either music with a BB or music without a BB. All participants then listened to a 12 minute-long recording of one of the recordings. After those 12 minutes they were asked to retake the AOSPAN.

Both the experimental and control group were exposed to the same procedure with the exception of the inclusion of BB in the music in the experimental condition. Completing the experiment took approximately 50 minutes.

Results

We were interested in understanding the effect of BB stimulation on the Ospan score. The baseline Ospan score was subtracted from the 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

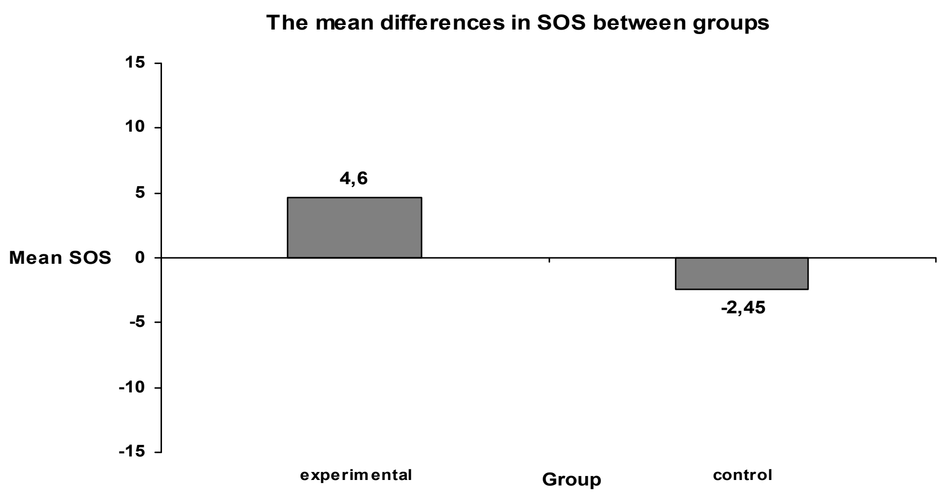

Diagram 1. The diagram shows mean differences in SOS between groups

obtained in the second AOSPAN task. The score informs about the improvement/deterioration in making 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 the experimental and control condition, an independent t-test was used.

The variances of the SOS score in the experimental and control groups were equal, $F(1, 38) = 2.16, p > 0.05$. On average, participants from the experimental group received a 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., $t(38)= -0.05, p > 0.05$.

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 a 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 working memory capacity in our sample of healthy, adult university students.

Lim, Quevenco, and Kwok (2013) state that in tasks testing higher cognitive functions, such as working memory, 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 were given a break in comparison to those participants who were not. DeLuca (2005a) defines fatigue as a result of intense and lasting exertion caused by cognitive effort. The break prevented the effects of fatigue and allowed participants to relax. Several studies showed a connection between alpha brainwave activity and relaxed states (e.g., Lagopoulos et al., 2009; Newberg et al., 2001; Stinson & Arthur, 2013). Lim et al. (2013) observed improved performance in an auditory oddball task (sustained attention and its capacity) in 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 with increase in alpha activity during the break (Lim et al., 2013).

In our research, participants were similarly provided a break from a cognitively demanding task, i.e., working memory capacity task. The break was represented by the 12-minutes of listening to the sounds of the sea, 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 the alpha synchronization. Therefore, based on the previous research (Klimesch et al., 2007; Lagopoulos et al., 2009; Newberg et al., 2001; Rihs et al., 2007; Stinson & Arthur, 2013; Tuladhar et al., 2007), we assume that the alpha synchronization might have induced a state of relaxation, which might have helped to filter out irrelevant information and improved participants' performance in working memory tasks 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 to a 2-minute track including alternately BBs of 7 and 11 Hz and found a significant improvement in their attention and working memory. Carter and Russel (1993) explored the effects of BBs on various cognitive processes in boys with learning deficits. During several 25-minute sessions, the participants were alternately stimulated by audiovisual, as well as solely by BBs with frequencies of 10 and 18 Hz. Boys exposed to BB stimulation showed an increased performance in Raven's progressive matrices and in a subtest of auditory sequential memory. Huang and Charyton (2008) investigated and evaluated the data from all of the available research studies which dealt with brain stimulation of any 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 the above-mentioned findings. To the best of our knowledge, this was the first time a BB of the frequency of 9.55 Hz was experimentally studied in the context of working memory employing the Operation Span Task (AOSPAN). Unsworth et al. (2005) compared the score of 78 participants who solved the AOSPAN task two times over several days. Within the Ospan score, he observed an increase of about 1 point. On the other hand, the results from the control group in our study suggest just the opposite trend. The participants' scores deteriorated as a result of exposure to only music. 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 average 4.6 points improvement after the second AOSPAN task as a result of BB stimulation. If we think again of the scoring method used, we will find that individuals 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 represent approximately 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 at 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 unchanged, by means of measured performance, 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, 4 correctly recalled letters.

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

Our results illustrate that although the participants from the experimental group improved in their capacity of working memory, their performance in solving mathematical operations was unaffected by the exposure to the BB. However, one should not expect a significant improvement in the mathematical task performance since it serves as a distractor or filler in the controlled attention. Although overall capacity of working memory may be improved by BB stimulation, the processing of distracting stimuli such as solving of the mathematical operations probably remains unchanged, as this is not the indicator of working memory capacity in its own right but it is just a method to challenge/measure it (Engle et al., 1999a).

The results of our research indicate that the BB may positively affect retention, attentional control, the storage and the activation of information, which contribute to memorization of that information.

It would be interesting to see what results would be achieved by individuals with memory or other cognitive deficits, older individuals or people without university/college experiences. From the point of 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 to some extent, so that the potential effect of fatigue or an immediate training effect would be minimized.

Conclusion

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

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VPLYV BINAURAL BEATS NA KAPACITU PRACOVNEJ PAMÄTE

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Súhrn: Výskum sa zaoberal vplyvom binaural beats na kapacitu pracovnej pamäte (WMC). Pokiaľ aplikovaný binaural beat zodpovedá frekvenčnému stavu, ktorý je charakteristický pre alfa frekvenčný rozsah mozgových vĺn, tak sa predpokladá, že by aj celková mozgová aktivita mala následne v určitej miere udržiavať tento stav. Mozgová aktivita v rámci alfa rozsahu je vo všeobecnosti korelovaná s viacerými kognitívnymi funkciami, medzi inými aj s pracovnou pamäťou. V nasledujúcej práci je preto vyslovený predpoklad, že binaural beat o alfa frekvencii by následne mohol posilniť WMC. V tejto štúdii boli participanti rozdelení do dvoch skupín. Prvá skupina podstúpila binaural beat stimuláciu počas počúvania zvukov mora. Druhá počúvala len zvuky mora bez binaural beat stimulácie. Pomocou testovej metódy Operation span task (OSPAN) sme merali východiskovú a post-stimulačnú kapacitu pracovnej pamäte. V súlade s očakávaniami, len participanti, ktorí podstúpili binaural beat stimuláciu, preukázali zlepšenie v rámci WMC.