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DOES AUDIBILITY MEDIATE THE EFFECTS OF BINAURAL BEATS ON WORKING MEMORY AND MENTAL WORKLOAD?

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ABSTRACT

Studies on the cognitive and psychological benefits of binaural beats (BB) often yield divergent or inconclusive results. While some studies suggest that BB are beneficial for e.g. relaxation, creativity and concentration, others fail to replicate these findings. Recent reviews on the subject reveal this may be explained by dissimilarities in methodologies and incomplete reporting thereof. Some important variables for binaural beat research are not always sufficiently reported, such as carrier frequencies, masking types, or stimulus levels. Information on the volume of the BB versus potential background audio is especially lacking in many instances. To create a better understanding of the possible benefits of listening to BB on cognitive functioning, we propose a study in which we assess different signal-to-noise ratios of BB in noise. Specifically, we aim to measure the effects of listening to 40 Hz BB in noise on working memory performance, operationalized through an N-back task. This way, we can assess to what extent BB need to be audible to reach potential beneficial psychological effects.

Keywords: *binaural beats, 40Hz, signal-to-noise ratio, working memory, N-back task.*

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1. INTRODUCTION

When two pure tones of slightly different frequencies (e.g., 200Hz and 210Hz) are present simultaneously, an interference pattern is created in the signal, equal in frequency to the difference between the two tones. This so-called beating pattern manifests physically as a modulation in the amplitude of the signal. Perceptually, this results in a periodic variation in loudness, at the rate of this beating frequency. Curiously, a similar percept arises when the two tones do not physically coexist, but are presented separately to each ear, via headphones. This illusory phenomenon, known as Binaural Beats (BB), has in recent years captured public attention as a means to reduce anxiety and stress [1], improve cognitive performance [2] and creativity [3], enhance sleep quality [4], promote mindfulness, or achieve altered states of consciousness [5]. Scientific interest in the effects of BB on cognitive, affective, and brain function has also grown, partly in response to public popularity. Recent systematic reviews and meta-analyses [6-7] have indicated that there is moderate evidence for a potential benefit associated with BB stimulation, but that the scientific literature suffers from methodological and theoretical fragmentation. In other words, there is little understanding of the putative mechanisms for effects of BB and little consistency in the methodologies that are used to assess them.

One of the key, but not yet well understood, parameters of BB is their audibility and the mediating role thereof on psychological outcomes. The audibility of BB can be influenced by many factors, such as individual differences like age, assigned sex [8-9] and extraversion [10], but also by masking with noise or music, or choice of carrier frequencies. Some findings suggest that BB do not need to be within the frequency range of human perception to induce changes in brainwave activity and outcomes such as memory performance [11-12], suggesting frequency-based audibility is not a prerequisite for BB benefits. There is little known on loudness-based audibility, because while many studies report masking BB with different types of noise or music [6-7], they rarely specify the volume of the BB versus the background audio (signal-to-noise ratio - SNR), e.g. to which extent the BB were clearly audible or not. To address this, we will perform controlled lab experiments, manipulating SNRs of the stimuli (BB in noise) to assess to what extent BB within the human hearing range need to be audible (e.g. loud enough) to influence cognitive performance.

2. METHODOLOGY

2.1 Participants

We aim to include 20 participants per condition in this study. Participants will be undergraduate students in the psychology program of the University of Groningen. We strive for an equal number of male and female (sex assigned at birth) participants per condition. Participants will sign up voluntarily and be compensated with SONA credits, which they need to fulfill their study program. Participants are eligible for the study if they have no history of chronic hearing problems and are proficient in English. All participants need to actively consent to participate, in accordance with the guidelines of and as approved by the Ethics Committee of the University of Groningen, and receive a debriefing post-study.

2.2 Design

This study employs a double blind between-subjects design to investigate the effects of BB on working memory and perceived workload.

- Independent variable (IV) = presence of BB (embedded in continuous brown noise). Two levels (present/absent, as a start; depending on the outcome, this may include variation in the SNR)
- Dependent variables (DV) = working memory performance, and experienced workload.

Participants are randomly assigned to the conditions.

2.3 Materials

Based on previous findings and a pilot study we ran [13], we decided to use 40 Hz BB [7] and set the carrier frequencies at 390 Hz (left ear) and 430 Hz (right ear) for the experimental condition. Both the noise and BB are created using Logic Pro software and the “Test Oscillator” plugin. To ensure consistent auditory stimulation, the volume of the noise will be fixed across all participants at a comfortable level. The SNR of the BB in noise will be 10dB (within the critical band) in the first experimental condition. Participants are instructed not to adjust the volume to maintain uniform sound exposure.

To assess the effects of the stimuli on working memory, we use a 3-Back Task [14]. In this task, participants view a sequence of letters and decide whether the current letter matches the one shown three positions earlier. The task includes eight possible letters (“A” to “H”), presented in a pseudo-randomized order, with 25% of trials containing a match. Each letter appears on the screen for 750 milliseconds, followed by a 1000-millisecond inter-stimulus interval. Participants respond by pressing the spacebar whenever they detect a match. Immediate feedback is provided on response accuracy. The primary outcome measure for this task is accuracy (i.e., correct identifications of matches and correct rejections of non-matches) and reaction time on correct responses. We decided on a 3-Back Task because a pilot study employing the 2-Back Task [13] revealed ceiling effects, leading to reduced discriminative power.

After the 3-Back Task, we measure experienced workload through the NASA Task Load Index [15]. The NASA-TLX is a widely used and reliable multidimensional scale measuring perceived task demands. It evaluates six factors: mental demand, physical demand, temporal demand, effort, performance, and frustration. Each of these subscales is rated on a Likert-type scale ranging from very low to very high. This measure allows for a structured evaluation of the cognitive and physical effort required during the task.

2.4 Analysis

To examine the effects of BB on working memory performance, reaction time and accuracy on the 3-back task will be analyzed as dependent variables. We will use a between-subjects independent samples t-test to compare reaction times and accuracy scores between the BB group and the control group. Similarly, the effects on workload (outcomes of the NASA-TLX test) will be tested using an independent samples t-test. To account for potential confounds, an ANCOVA will be conducted using personality traits, sound sensitivity, and recent alcohol, caffeine, medication use, and exercise.

2.5 Procedure

The whole procedure consists of four phases: Preparation, Induction, Measurements, Debriefing (see Fig. 1). In the first phase (Preparation), participants receive information on the study and provide informed consent. We collect information on demographics (age, assigned sex), and the following possible confounders: medication use, exercise in the past day, alcohol consumption of the past 24 hours, and caffeine intake of the current day. The response options for these single item questions are “No”, “Yes”, and “Prefer not to say”. Furthermore, participants complete the Sound Sensitivity Symptoms Questionnaire [16] which assesses individual sound sensitivity over the preceding two weeks on a five-point scale. As studies have shown that personality traits influence noise sensitivity and auditory perception [17], we assessed participants´ personalities using the Ten-Item Personality Inventory (TIPI). The TIPI consists of 10 items, with each of the five personality traits (Extraversion, Agreeableness, Conscientiousness, Emotional Stability, and Openness to Experience) assessed using two adjective-pair statements rated on a 7-point Likert scale where 1 = disagree strongly, and 7 = agree strongly [18]. To conclude the first phase, the 3-Back Task will be introduced to the participants who will complete four minutes of practice trials.

After the practice trials, participants start the second phase (Induction) during which participants are instructed solely to sit and relax and listen to the stimuli for 10 minutes (in accordance with the Garcia-Argibay protocol [19]). For the experimental condition, 40 Hz BB are embedded within brown noise with a critical band SNR of 10dB, whereas the control condition consists of noise without BB.

Subsequently, the third phase (Measurements) follows in which participants complete six minutes (3 blocks of 2 minutes each) of 3-Back Task. In between the task blocks, there is a short break of 5 seconds. The auditory stimulus is played continuously without breaks during the experiment starting at the onset of the induction phase and ending after the 3-Back Task is completed. After this, participants are prompted to complete the NASA-TLX.

To conclude, the last phase (Debriefing) consists of a post experimental enquiry to explore participants´ subjective experiences on three key aspects: the induction period phase, the BB experience and their audibility, and their prior knowledge and usage of BB in everyday life. We conduct 5-minute semi-structured interviews following a predefined script and record responses in written form for later analysis.

3. RESULTS

As data is expected to be collected in the course of 2025, we aim to present the first preliminary results at Forum Acusticum Euronoise 2025.

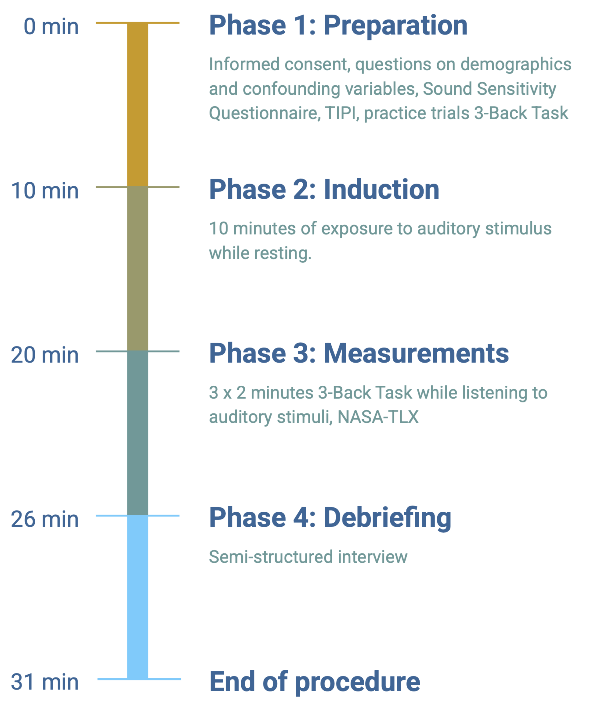

Figure 1. Overview of experimental procedure.

4. DISCUSSION

While research has indicated that BB with carrier frequencies outside the human hearing range can influence brainwave activity [11], little is known about the mediating role of BB audibility based on the loudness of BB compared to masking sounds (SNR). When we better understand the influence of audibility of BB based on carrier frequencies and loudness, we can further the research by investing for example the influence of audibility based on fluctuations in female hormone levels. To further the field of BB research, we advocate to make the assessment of audibility of BB by participants a standard part of procedures and methodologies.

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