Manipulating Episodic Memory Consolidation with Binaural Beats

Weiler, Joel

Citation

Weiler, J. (2021). *Manipulating Episodic Memory Consolidation with Binaural Beats*. Retrieved from http://hdl.handle.net/1887.1/item:3229851

Universiteit Leiden

Psychologie
Faculteit der Sociale Wetenschappen

Manipulating Episodic Memory Consolidation with Binaural Beats

Name: Joel Weiler
Student number: s2382954
Date: 11.06.2021
Supervisor: Samarth Varma
Second reader:
Word count: 10.754
Cognitive Psychology
Thesis Msci Applied Cognitive Psychology

Abstract

A recent study proclaimed that the optimal neurophysiological signature for memory consolidation during quiet rest is characterized by increased delta and decreased alpha rhythms, which constitutes an apparent contradiction with the existing literature regarding alpha oscillations. The present study aimed to artificially induce this signature through binaural beat stimulation and assess its effects on recognition, as well as examine factors that could potentially account for the observed interactions (e.g., autobiographical thought). It was expected that delta stimulation would facilitate, while alpha stimulation would interfere with memory consolidation, and that this effect was mediated by autobiographical thoughts during consolidation. The 8hz alpha, 0.5hz delta and control stimulations were administered for nine minutes post-encoding of several face stimuli, and a delayed recognition test, as well as experience-sampling questionnaires were employed. Delta stimulation yielded equal memory scores to control, while alpha stimulation decreased them. Vivid ABT negatively predicted memory scores under control stimulation. Further, ABT differentially affected memory scores under binaural beat and control stimulation but did not mediate the relationship between auditory stimulation and memory scores. None of the other factors were significant mediators of the observed differences in memory scores. These findings suggests that a binaural beat paradigm can modulate memory consolidation, while the underlying mechanism remains unknown. The implications entail a novel, modulatory paradigm and contributions to the literature assessing rhythmic oscillations, as well as the effects of autobiographical thought in relation to memory consolidation.

Keywords: binaural beats, episodic memory consolidation, retroactive facilitation, interference, autobiographical thinking, cognitive enhancement

Introduction

Memories of important past events and experiences, referred to as episodic memories, amount to a unique, as well as shared sense of personal history, allowing people to reflect on their lifetime achievements and interpersonal connections. Whilst the complex processes underlying episodic memory formation have been extensively studied in the past, many questions regarding at least one of its crucial components remain unanswered. This component, termed memory consolidation, guides the processing of experiences to form lasting memories. In the present paper, this component and its underlying mechanisms are elaborated and research paradigms pertaining to its modulation are reviewed. Thereafter, the neurophysiological changes that accompany memory consolidation are outlined, and finally, the present experiment is described and discussed.

Memory consolidation refers to a process of strengthening recently encoded experiences, as well as transforming them into long-term memory (LTM; Atkinson & Shiffrin, 1968). Following the encoding of the experience, it is coded in the hippocampus as a weak memory trace (Sekeres et al., 2018). The memory is then gradually stabilized through neural replay, in which the neuronal ensembles involved in the initial encoding of an item are spontaneously, iteratively reactivated (Giri et al., 2019). Neural replay also supports the information transfer from the hippocampus to the neocortex, where the encoded memories are integrated into the LTM (Mednick et al., 2013). It is further understood, that over weeks or years of neural replay, the hippocampus becomes progressively superfluous for the retrieval of these items (Almeida-Filho et al., 2018; Mednick et al., 2013; for alternative accounts see: Sekeres et al., 2018; Winocur et al., 2010).

Crucially, during the process of hippocampus-dependent memory consolidation, memories are weak and prone to disruption by other ongoing mental activity, such as novel tasks or encoding of other memories (Alves & Bueno, 2017; Mednick et al., 2013). This disruptive effect, called retroactive interference can severely affect the process of memory consolidation, e.g., by disrupting the spontaneous reactivation of the memory trace (Alves & Bueno, 2017; Mednick et al., 2013). It has been proposed that this occurs when processing related to the novel activity takes up limited hippocampal resources that were previously allocated to memory consolidation, thereby disrupting it (Mednick et al., 2013; Wixted & Cai, 2014). Inversely, offline states, which are characterized by reduced external focus, such as sleep or wakeful rest facilitate memory consolidation (Nere et al., 2013; Wamsley, 2019). It is understood that these states provide increased opportunity for spontaneous replay to occur, thereby facilitating ongoing memory consolidation (Diekelmann & Born, 2010; Wamsley, 2019).

Modulating Memory Consolidation

A growing body of literature suggests that memory consolidation is amenable by interacting with the underlying components. Various experimental paradigms aimed at externally inducing retroactive interference or facilitating memory consolidation have been explored within the field of cognitive enhancement (Farah et al., 2014; Hills & Hertwig, 2011; Metzinger & Hildt, 2011). The following section outlines the current state of the field regarding paradigms of manipulating memory consolidation during wake. Thereafter, the rationale for the present study is construed, which aimed to target both retroactive interference and facilitation with a novel paradigm. Finally, the present findings are discussed.

Retroactive Interference

Wakeful rest, discussed as promoting consolidation (Wamsley, 2019) may itself provide fertile soil for retroactive inhibition, as a period of wakeful rest is not void of thought, and mindwandering can ensue (Gruberger et al., 2011). If such mindwandering entails rich autobiographical thought (ABT; thinking about one's past or future), it has been shown to impair memory consolidation. This has been reported by a study conducted by Craig et al., (2014), who compared the effects of a 9-minute post-encoding period of quiet rest with cued retrieval or future imagination (ABT) through familiar sound cues. The participants showed decreased consolidation following cued ABT (if it was rich) compared to a period of wakeful rest. Thus, it has become evident that rich ABT during a period of wakeful rest is capable of disrupting memory consolidation.

Beyond interference caused by internal thought, a case can be made for retroactive inhibition caused by cognitive engagement, that disrupts ongoing consolidation processes. Initially, Müller & Pilzecker (1900) investigated whether different forms of cognitive engagement during a post-encoding period differentially affected memory consolidation of nonsense syllable pair lists. Within such cognitive engagement, a distinction between content that is similar (specific) or dissimilar (non-specific) to the encoded material can be made. The similar tasks comprised studying a second syllable list, and the dissimilar tasks were the study and description of a landscape painting. Müller & Pilzecker (1900) proclaimed, that according to the results of their experiment, either form of mental effort caused retroactive interference.

A study corroborating the findings for specific interference comes from Tabrizi & Jansson (2016), who let participants encode intrusive mental imagery (e.g., violence) through exposure to a soundtrack depicting traumatic scenes. Immediately after encoding, participants underwent a 10-min retroactive interference task or rest period. The retroactive interference tasks comprised two phonetic tasks (counting down loudly or repeatedly counting to ten), and a non-phonetic task (shaping clay). The tasks that resembled the encoded material by means of their phonetic nature (both counting tasks) resulted in reduced involuntary memory (spontaneous recall) of the intrusive mental images (as measured by a 7-day diary, where participants noted every time that they recalled the intrusive mental images). Thus, the similarity of the post-encoding task to the memory in terms of their phonetic nature was likely able to induce retroactive interference.

The findings by Müller & Pilzecker (1900) regarding retroactive interference through post-encoding engagement with non-specific material, as well as undergoing dissimilar tasks have been successfully replicated by (Dewar et al., 2007). Further reports exist that engaging in a short, post-encoding spot-the-difference-puzzle task diminished early memory consolidation for a learned wordlist when compared to a post-encoding period of wakeful rest (Dewar et al., 2012; 2014). However, recent studies showed that this phenomenon occurred in children but not adults and that longer encoding and consolidation periods diminished this effect (Fatania & Mercer, 2017). It appears, that the impact of non-specific retroactive interference decreases with age (Darby & Sloutsky, 2015). In sum, these studies largely support Müller & Pilzecker's (1900) proposition, that specific and non-specific tasks, and beyond that, the richness of ABT (Craig et al., 2014) can interfere with components underlying memory consolidation.

Retroactive Facilitation

In contrast to retroactive interference, retroactive facilitation is defined here as post-encoding instantiation or facilitation of components that aid or underly memory consolidation. To date, several studies examined the capacities of various paradigms to induce retroactive facilitation. As previously elaborated, offline states provide fertile soil for memory consolidation. It is evident, that a post-encoding period of wakeful rest can promote memory consolidation (Wamsley & Summer, 2020), even in the complete absence of rehearsal (Himmer et al., 2019). In one study, sleep, wakeful rest, and engaged rest (watching an educational movie) were compared; both sleep and wakeful rest showed increased memory consolidation effects on an auditory sequence learning task (Gottselig et al., 2004). Further, a 15-30 minute period of wakeful rest following encoding improved consolidation when tested immediately post-consolidating, and the effect persisted after one week (Dewar et al., 2012). Thus, wakeful rest is understood to have similar capacities of retrograde facilitation as sleep itself.

Recent studies have also yielded results that contrast the findings of task engagement being detrimental for memory consolidation (Gottselig et al. 2004; Müller & Pilzecker, 1900). Varma et al., (2017) demonstrated that engaging in a post-encoding distractor task (2-back task; Kirchner, 1958), which has minimal semantic involvement and is void of hippocampal memory processing requirements, entails the same facilitative capacities as quiet rest in young adults. Revisiting this paradigm a year later, Varma et al. (2018) compared a post-encoding 2-back task to using familiar sound cues during quiet rest that triggered ABT (as previously employed by Craig et al., 2014). They successfully replicated the interference effect caused by cued ABT, as well as the non-interference effect of the 2-back task from their previous experiment (Varma et al., 2017). Finally, the same team compared a post-encoding 2-back task with a quiet rest condition and documented the general mindwandering propensity of their participants. They established that participants with higher mindwandering tendencies yielded greater consolidation facilitation in a rest condition, whereas participants with less mindwandering tendency benefitted from engaging in a 2-back distractor task (Varma et al., 2019). This line of research establishes that post-encoding task engagement is not necessarily inhibitory.

While these studies contradict the findings of interference caused by post-encoding task engagement (Gottselig et al. 2004; Müller & Pilzecker, 1900), further research suggests facilitative effects of task engagement on memory consolidation. Liu et al. (2015) reported that short post-encoding engagement with a video game facilitated the consolidation of visual material, as measured after a one-week interval. Further, Tibi et al., (2013) reported that solving a math problem post-encoding enhanced motor memory consolidation as tested after one day. Finally, children and adolescents of age 9-15 years with ADHD exhibited increased wordlist retention following the exploration of an unknown compared to a familiar VR environment post-encoding, suggesting a facilitative effect of novelty (Baumann et al., 2020).

Overall, these findings extend the proposition from Varma et al. (2017, 2018, 2019), by suggesting that post-encoding (online) task engagement might facilitate memory consolidation. In sum, several paradigms exist that have successfully been used to modulate memory consolidation in a facilitative or inhibitory manner. In the following, evidence regarding the neurophysiological signatures that accompany memory consolidation during wake is presented, and the relation to the hitherto presented states and components underlying memory consolidation is reviewed.

Endogenous Oscillations and Memory Consolidation

Different signatures of rhythmic oscillations accompany consolidation-related activity in the hippocampal and neocortical sites (Wixted & Cai, 2013). These endogenous rhythms possess an amplitude (power) level, that can be quantified with an Electro-encephalograph (EEG; Jackson & Bolger, 2014). Evidence of an EEG analysis of consolidation-related brain activity exists, where participants underwent 15-minutes of either a quiet rest condition or a distractor task (playing a puzzling game on a computer), post-encoding of a short story which was followed by a delayed recall test (Brokaw et al., 2016). Undergoing the quiet rest period led to improved recall of the short story, compared to the distractor task. During the quiet rest period, increased power in the delta (<1hz) bands and decreased power in the alpha (8-12hz) bands predicted increased memory performance. Additionally, decreased focus on the environment and increased ABT (measured by a post-consolidation questionnaire) during both conditions were also predictive of memory improvements.

Based on these findings, it is plausible that modulating endogenous oscillations would influence memory consolidation processes. This study is the only one to date that measured the changes in endogenous signatures accompanying memory consolidation directly. However, a large body of work presents indirect evidence linking alpha and delta oscillations with components underlying memory consolidation. In the following, this link will be presented separately for delta and alpha rhythms.

Occurrence of Delta Rhythms Along Components Underlying Memory Consolidation

Research has shown that non-rapid eye movement (N-REM) sleep, which is rich in (<1hz) delta oscillations (Brodbeck et al., 2012, Lokhandwala & Spencer, 2021), plays a crucial role in memory consolidation. This relationship is thought to stem from the hippocampal-neocortical transmission by means of neural replay, which occurs alongside the synchronous interplay between endogenous slow (delta) oscillations and sleep spindles during N-REM sleep (Diekelmann & Born, 2010; Mikutta et al., 2019). The importance of delta oscillations for this process is supported by an overnight EEG analysis of amnestic mild cognitive impairment patients, whose decreased delta power during N-REM sleep predicted inhibited memory consolidation (Westerberg et al., 2012). Additionally, the interruption of slow-wave sleep stages can disrupt memory consolidation (Casey et al., 2016). Thus, the occurrence of delta oscillations in offline states appears critically involved with memory consolidation and their interruption (e.g., of N-REM sleep) can induce retroactive interference.

Another line of research suggests that delta rhythms can be manipulated through external stimulation, which in turn affects the underlying (sleep-dependent) mechanisms of memory consolidation, such as neural replay (Bartsch et al., 2019; Himmer et al., 2019; Staley et al., 2011). Marshall et al. (2004) applied 0.75hz transcranial direct current stimulation (tDCS) during N-REM sleep in healthy adults, which increased endogenous slow oscillations and in turn enhanced declarative memory consolidation. This finding was extended to verbal memory in older adults by Westerberg et al., (2015), and to visual declarative memory consolidation by Ladenbauer et al. (2016), who reported increased fast spindle activity in addition to the slow oscillatory activities. Finally, the same team extended the paradigm to adults with mild cognitive impairments (Ladenbauer et al., 2017), where the tDCS stimulation was only administered in up-phases of cortical slow-oscillations, and in turn enhanced the synchronicity between slow oscillations and spindles. These studies not only support a critical involvement of endogenous delta oscillations in the hippocampal-neocortical information transfer underlying memory consolidation but also suggest that they are malleable by external (tDCS) delta stimulation.

Occurrence of Alpha Rhythms Along Components Underlying Memory Consolidation

Increases of endogenous alpha oscillations have been reported in states of wakeful rest (Sharma & Singh, 2016). As previously discussed, such offline states possess the capacity to facilitate memory consolidation through reduced interference (Wamsley & Summer, 2020). In line with this, increased alpha power is understood to correlate with decreased external attention and increased focus on internal thoughts (Foulkes & Fleisher, 1975). Among internal thoughts, increased alpha oscillations have been observed alongside mindwandering (Compton et al., 2019), and specifically ABT (Knyazev et al., 2012). This is further corroborated by the findings of Sharma & Singh (2016), who showed that alpha power decreased when switching between a state of wakeful rest to on-task attention, and the findings of decreased (8-12hz) alpha, and decreased (0.3-1hz) delta power in the EEG signatures of task-focused (online) states (Wamsley & Summer, 2020). Thus, alpha increases appear to accompany the switch into states that are understood to facilitate memory consolidation.

Similar functions are attributed to the default mode network (DMN; Andrews-Hanna, 2012). The DMN is a large-scale brain system that becomes active when entering offline states with internally focused thoughts (e.g. daydreaming; Andrews-Hanna, 2012). It comprises a dorsal medial subsystem, which has been related to social thought (e.g., inferences about others), a medial temporal subsystem (including the hippocampus), which has been linked to episodic memories and self-referential thoughts (e.g., ABT), and several functional hubs that are linked to the evaluation and decisions about personally-relevant information (Andrews-Hanna et al., 2014). This suggests that constituent DMN-regions are related to processes underlying memory consolidation. Additionally, the DMN needs to be suppressed to enter online states of task-engagement and task-related processing (McCormick & Telzer, 2018), comparable with the alpha activity transition when entering this state (Wamsley & Stickgold, 2019). Further, just like alpha activity (Compton et al., 2019), DMN activity in offline states has been linked to mindwandering (Christoff et al., 2009). Beyond this, DMN-activity has been linked to memory replay (K. Wang et al., 2009). Thus, a link between increases in alpha oscillations and DMN activity accompanying consolidation-related processes is conceivable.

In support of this notion, past work combining EEG and fMRI during wakeful rest showed correlations between increased alpha power and DMN activity (Mo et al., 2013). In this study, participants underwent a seven-minute wakeful rest period and were instructed not to think any systematic (coherent) thoughts. The observed EEG and fMRI patterns suggest, that during eyes-open wakeful rest, increased alpha power accompanied state changes in the DMN that reflected entering offline states. Inversely, decreased alpha accompanied state changes in the DMN that reflect external attention. These findings suggest an involvement of the interplay between alpha oscillations and DMN activity with components underlying memory consolidation. Specifically, it is conceivable that changes in endogenous alpha oscillations underly DMN-state changes that give rise to mindwandering, ABT, spontaneous memory replay, and reduced interference through novel encoding.

Taken together with the findings reported for increased delta oscillations, these studies support the appearance of both alpha and delta oscillations alongside memory consolidation. Specifically, high endogenous alpha and delta seem to accompany states facilitative to memory consolidation, while low alpha appears to accompany those related to interference. However, the findings of Brokaw et al. (2016) appear to contradict these conclusions, suggesting that decreased, rather than increased endogenous alpha predicts successful memory consolidation. The rationale underlying this observation appears elusive and further investigations of the interaction between alpha and memory consolidation are required. One way to achieve this is to artificially induce the signature reported by Brokaw et al. (2016), and examine changes in memory performance that reflect memory consolidation.

Modulating Endogenous Rhythms With Binaural Beats

One paradigm by which the neurophysiological signature discussed above can potentially be induced is auditory stimulation through Binaural beats. Similar to other brain stimulation paradigms, this approach works based on entrainment, i.e. modifying endogenous oscillations by exposing similar frequencies (for review see Hanslmayr et al., 2019). This is achieved by presenting a sinusoidal oscillation (e.g. 220hz), referred to as the carrier frequency to one ear, and another oscillation (e.g. 240hz) to the other ear. The difference (here: 20hz) is perceived as a third, so-called beating frequency, and presents the resulting stimulation frequency. Seminal reports about binaural beats came from Oster (1973), and since then binaural beats have successfully been used to entrain naturally occurring rhythmic oscillations in the brain (e.g., Chaieb & Fell, 2017; Jirakittayakorn & Wongsawat, 2018). However, no study to date has assessed the effects of binaural beat stimulation during consolidation on memory performance.

Present Study

The present study investigated whether the findings of Brokaw et al., (2016) could be artificially induced through auditory stimulation. It was examined whether binaural beats are capable of modulating episodic memory consolidation by entraining endogenous rhythms during a nine-minute post-encoding period. Episodic memory performance was assessed with a face recognition task. To assess the capacity of post-encoding auditory stimulation to modulate the memory of faces, a (0.5hz) delta binaural beat stimulus was employed, and the hypothesis was (in line with Brokaw et al., 2016) that it would facilitate consolidation. Additionally, an (8hz) alpha binaural beat stimulus was employed and it was hypothesized (in line with Brokaw et al., 2016) that it would interfere with memory consolidation. Both binaural beat stimuli were compared to performance following an auditory control stimulus that lacked frequency-specific stimulation.

Given the findings by Brokaw et al. (2016) that ABT predicted memory performance, a second aim was to investigate whether the differential occurrence of ABT could predict the differences in memory performance following alpha and delta stimulation, compared to control stimulation. ABT was measured with experience-sampling questionnaires which assessed proportional themes of thought during the consolidation period. It was hypothesized, that if the expected decrease of memory consolidation following alpha stimulation would be observed, this would be mediated by a larger proportion of ABT under control stimulation. Inversely, it was hypothesized that if the expected increase in memory consolidation following delta stimulation would be observed, this would be mediated by a smaller proportion of ABT during the control stimulation.

Implications of findings in support of hypotheses one and two would include establishing a novel paradigm for the manipulation of memory consolidation during wakefulness. Additionally, such findings would aid in disentangling the apparent discrepancy in the current literature regarding alpha oscillations and memory consolidation and furthering the existing body of work regarding external delta stimulation and memory consolidation. Findings in support of hypotheses three and four would extend the current understanding of the influence of autobiographical thinking during post-encoding periods on memory consolidation. Together the results of the present study may find implications for the development of an intervention utilizing binaural beat stimulation as a general learning aid in the future.

Methods

Participants

The study was advertised to participants online and through personal contacts. Most participants signed up through the SONA research participation system, which ensured that they were familiar with the exclusion criteria. Recruits via personal contacts also met the exclusion criteria. Participants were excluded if they reported visual impairments or any form of hearing impairment. Further exclusion criteria were put in place by the Safety, Health and Environment Department (VGM) of Leiden University, as the experiment was conducted in times of the global COVID-19 pandemic. A symptom screening call was in place 24h before participation and only symptom-free participants were invited to the lab. Upon arrival, the same screening was conducted again. Participants were excluded from participation and access to the lab if they reported having any COVID-19 symptoms.

Based on previous studies (Varma et al., 2018) it was calculated that 34 participants were required to reach reliable power levels. To fully counterbalance the within-subjects factor of the data set 36 participants had to be recruited. The initial sample consisted of 5 male, and 27 female participants, ranging from 19 to 31 years of age (*M* = 22.81; *SD* = 2.99). After being informed about the study in written form and orally, all participants gave written informed consent. Participation was compensated with the standard rate (€ 3.50 per 30 mins) or received course credits according to the standard rate (1 credit per 30 mins).

Materials

The experimental paradigm comprised three different types of auditory stimulation. It also comprised a behavioral task, for which participants encoded faces and rated them on their perceived friendliness and that concluded in a recognition test. Finally, participants had to fill several forms throughout the experiment. The behavioral task and exposure to the auditory stimuli commenced in cubicles with computers. Additionally, protocols to enable research in times of the COVID-19 pandemic were put in place for the experiment. The required materials are discussed in the following sections.

Binaural Beats and Control Stimulus

The auditory stimuli consisted of two binaural beats (alpha and delta) as the experimental conditions, and the carrier frequency without a binaural beat served as the active control stimulus. Each stimulus was nine minutes long. The stimuli were created in Ableton Live 10 (Ableton AG, 2018)) by using two instances of Operator with a single sinus-wave oscillator to create the two tones. To ensure uncompromised binaural stimulation the tones were panned to one side each and Beyerdynamic DT 770 Pro 250 Ohm headphones (Beyerdynamics GmbH & Co. KG, 2015) were employed to administer the binaural beats without crossover (both tones being heard in the same ear).

All stimuli were centered on 440hz, which was always projected to the left ear. For the alpha binaural beat, the 440hz carrier frequency was accompanied by a 448hz sinus tone in the right ear. Thus, the resulting beating frequency was 8hz. The delta binaural beat was created by supplying 440.5hz to the right ear, which resulted in a beating frequency of 0.5hz. To achieve the 0.5hz increment (which Operator is not capable of by itself), Ableton's frequency shifter (set to +0.5hz) was employed, in addition to the Operator plugin. The control stimulation comprised projecting the 440hz carrier frequency into both ears, and thus entailed no beating frequency.

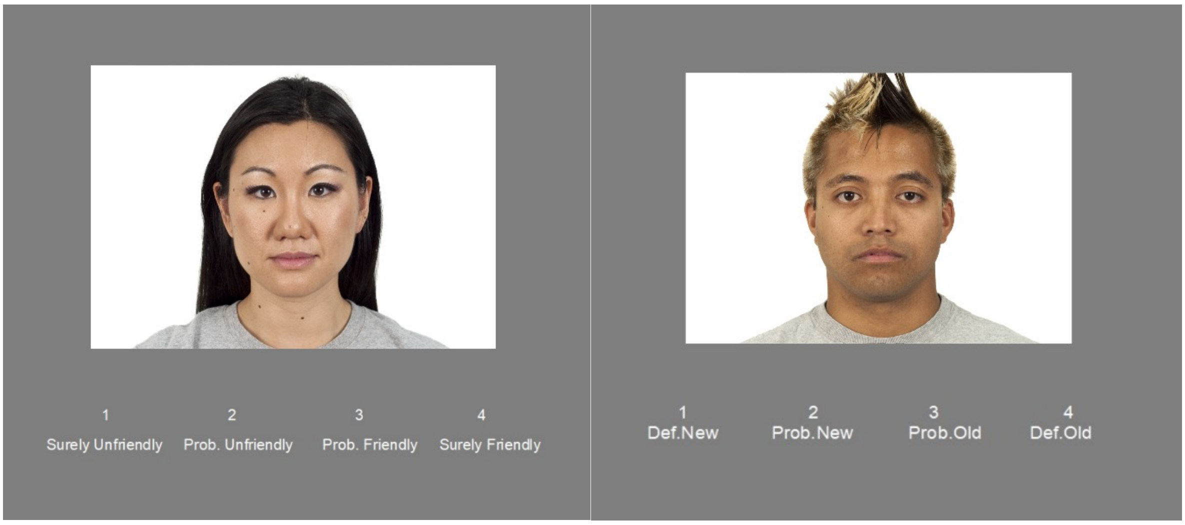
To reduce the discomfort of participants, all auditory stimuli were accompanied by white noise for the entire duration. The white noise was derivative of a Moog Mother32 (Moog Music inc., 2015) and was projected at a relative level of -15db. The noise was high pass filtered at 100hz to prevent undesired interactions with the binaural beats. To further decrease the potential for discomfort, the white noise was slowly introduced by opening the Mother32's low pass filter throughout the first 15 seconds. Additionally, the tones comprising the binaural and monaural beats were faded in over the first ten seconds of the 9 minutes by employing volume automation. The reverse pattern was employed at the end of the nine minutes for a fade-out of 15 seconds on both sounds comprising the stimuli (tones and noise).

Behavioral Task

The behavioral task was adapted from Varma et al., (2017), and comprised encoding several face stimuli and rating them on their perceived friendliness. The face stimuli employed in the behavioral task were taken from the Chicago Face Database (Ma, et al., 2015). Excluding the ten face stimuli used in the practice block (B0, Fig. 2) participants were tested on 288 faces with neutral expression in the recognition test (B4, Fig. 2). Half of these were female, and the other half were male (144 each). For female and male faces alike, an equal proportion of White, Latino, and Asian faces were present (48 of each gender). Participants were shown 192 faces throughout the three encoding blocks (B1-3, Fig. 2), and 96 previously unseen faces were added in the recognition test. Examples of the faces can be seen below (Fig. 1).

Figure 1

Encoding with Friendliness Rating and Memory Test Component of the Behavioral Task



Note. The image on the left shows an example of the face stimuli and the perceived friendliness rating presented during encoding. The image on the right shows an example of the face stimuli during the recognition test with a confidence rating.

Experience-Sampling Questionnaire

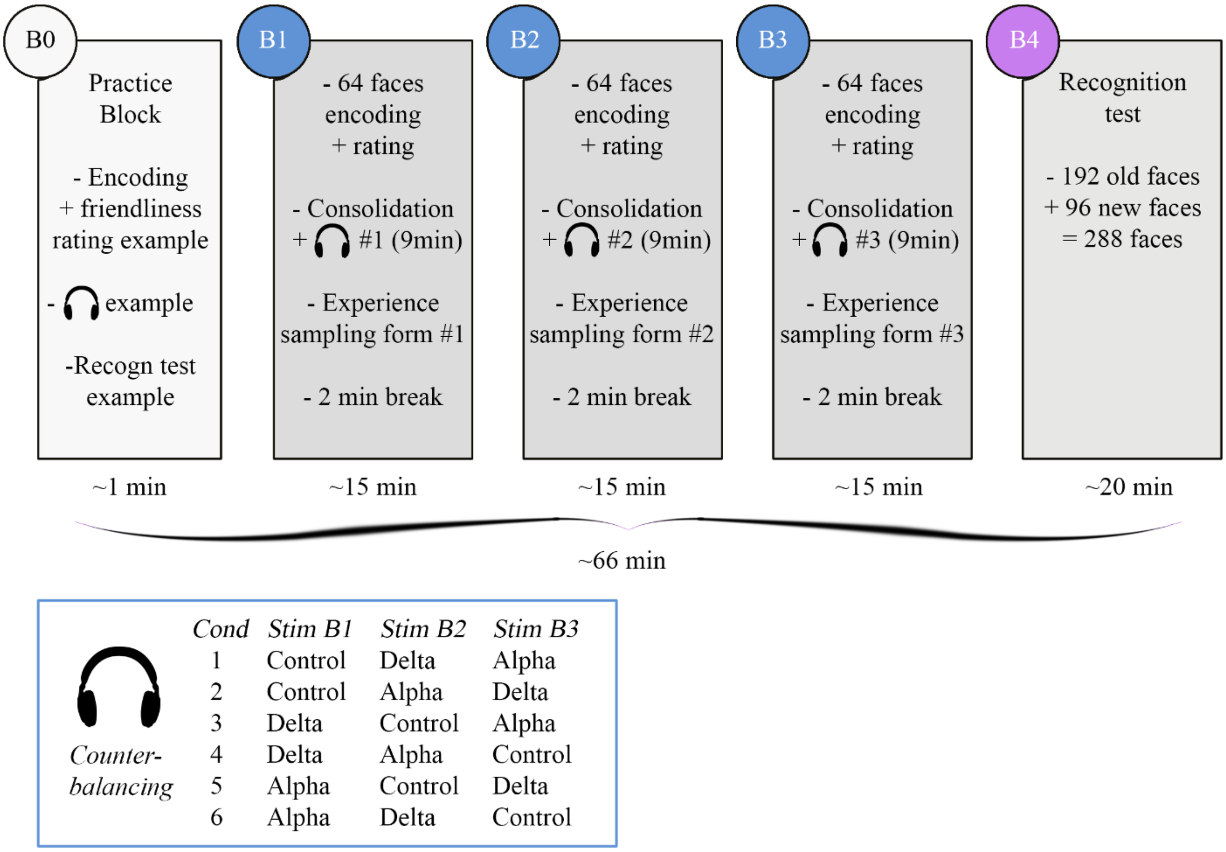
Three experience sampling questionnaires were placed next to the computer screen in the cubicles. These forms assessed participant's thought content during the consolidation period with auditory stimulation and were based on the questionnaire used in Varma et al. (2018). For each of the three auditory stimuli, a uniquely labeled form (letters A to C) was present. After the consolidation/delay phase in each of the first three blocks (B1-3, Fig. 2), an on-screen message called participants to fill in the form with the respective letter. The questionnaire contained six questions inquiring about proportional themes of thought (e.g., percentage of thoughts about the previously learned faces, autobiographical thought) which participants had to answer in percentages. It also contained sub-questions, which assessed scales regarding the intensity and qualia of the proportional themes of thought (e.g., richness or vividness of the autobiographical thoughts) that were assessed on a seven-point scale. See Appendix I, Table 1 for the full questionnaire.

Procedure

The study was approved under the ethics committee approval code 2020-11-24-S. Varma-V3-2683. A behavioral protocol (e.g., the requirement of masks, disinfecting hands, and 1.5m distance) was put in place by the VGM, to enable research during the global COVID-19 pandemic (See Appendix II, Table 1). Further, a special research protocol (including cleaning and ventilation routines) for the study had been approved by SOLO, and adherence was checked through a research checklist (see Appendix II, Table 2). Participants that fulfilled the necessary criteria were seated at a table, where they received the information letter and the additional COVID-19 information letter, which summarized the COVID-19 measures and had previously been sent to them per email, a second time. Afterward, participants were briefed on the details of the study and filled in the consent form to resume with the experiment. This process took approximately ten minutes. For the experiment itself, participants were exposed to a computer task in a cubicle with a pair of headphones present. Upon being seated in the cubicle, the researcher explained the following tasks.

Figure 2

Experimental Design Procedure



Cond	*Stim B1*	*Stim B2*	*Stim B3*
1	Control	Delta	Alpha
2	Control	Alpha	Delta
3	Delta	Control	Alpha
4	Delta	Alpha	Control
5	Alpha	Control	Delta
6	Alpha	Delta	Control

Note. The image depicts the experimental procedure employed in this study, which comprised a practice block and four experimental blocks, and took approximately 66 minutes in total.

The face stimuli for the task, as well as the instructions, were presented to the participants on the computer screen (see Fig. 1). Each component in the experiment was preceded by an information and instruction screen, and user input (pressing the space or enter key) was required to proceed. Consistently throughout the experiment, participants responded to the task by pressing the number keys 1-4, and the corresponding meaning of the keys was shown below the face stimuli.

Under the observation of the researcher, participants first underwent a practice block (B0), where they experienced an example of rating five faces (~15 seconds). Each face stimulus was preceded by displaying a fixation cross for 0.5 seconds, followed by a face stimulus displayed for 2.5 seconds. The friendliness rating for each face was given on four levels (surely unfriendly, probably unfriendly, probably friendly, surely friendly; see Figure 1). After each face was shown for the full duration, the screen displayed feedback on the recorded (or missed) input. Thereafter, the next fixation cross and face stimuli were shown. This was followed by an example of the auditory (binaural beat) stimulus (~15 seconds), and an example of the recognition test (~30 seconds). The familiarity and confidence rating had four levels (surely unfriendly, probably unfriendly, probably friendly, surely friendly; see Figure 1). Contrary to the encoding example, the face stimuli were not necessarily shown for the entire duration during the recognition test, as feedback on correct or incorrect classification was given as soon as a valid response had been recorded.

Then the participants proceeded to the first experimental Block (B1, ~15 minutes), in which they encoded 64 faces and rated them on their friendliness. The face stimuli and the instructions were shown on-screen for 3.5 seconds, and each face was again preceded by a 0.5-second fixation cross. Contrary to the practice block, no feedback was given. Encoding was followed by a 9-minute consolidation period accompanied by one of three auditory stimuli, depending on the random order they were allocated to, as shown in Fig. 2 above. Thereafter, they filled in the post-consolidation experience sampling form and took a two-minute break. Blocks two and three (B2, B3) were equal to B1, in which the remaining binaural beats or control auditory stimuli followed.

The experiment ended with a recognition test that consisted of the 192 previously seen faces (64 each in B1-3), as well as 96 new faces. The test lasted approximately 20 minutes and formed the main dependent variable (d-prime; Stanislaw, 1999). After the experimental procedure was completed, participants could put their masks back on and rejoin the researcher outside of the cubicle. Participants were seated back at the table and were asked to describe each stimulus in order, including related sensations, and the overall experience. Then, the participants were debriefed and encouraged to ask questions. The experiment took approximately 120 minutes in total.

Analysis

Analysis of the Memory Performance

The present study employed a within-subjects design. The main independent variable was auditory stimulation with three levels (8hz alpha binaural beat, 0.5hz delta binaural beat, and no beating frequency as the control condition). Every participant underwent each of the three stimulations in an order defined by random assignment to one out of six conditions. The main direct variable of this experiment was the participants' memory scores, as commonly measured by their sensitivity index (d-prime). The second dependent variable comprised self-reported thought content during the consolidation period with auditory stimulation and was measured through the experience sampling questionnaires.

All analyses were undertaken in SPSS 22. Encoding trials for which the participant failed to provide a friendliness rating were removed from the recognition trials. Trials to which no response was received to the old/new judgment were also excluded. The remaining face scores were grouped by stimulation condition (control, delta, alpha). For each participant, hit rates and false alarm rates were calculated. This was done once based on the highly confident responses only ('definitely sure'), and once including both highly confident and non-confident scores ('definite sure' and 'probably sure'). The confident hit rate and false alarm rate were then normalized through z-score transformations (Stanislaw, 1999), and scores too close to floor or ceiling levels of these variables were adjusted. For rates that were zero, the formula was $1/(2*(a + b))$, and for rates that were one, the formula was $1-(1/(2*(a + b)))$, where a was the hit rate (highly confident responses) and b was the miss rate (highly confident responses), for adjusting hit rates; where a was the false alarm rate (highly confident responses) and *b* was the correct rejection rate (highly confident responses), for adjusting false alarm rates. Based on a large variability in the number of confident responses between participants across the old/new responses, confidence ratings were ignored and d-prime scores from both highly confident and non-confident responses were combined.

To test H1, which predicted significantly higher memory scores following delta stimulation compared to control stimulation, and H2, which predicted significantly lower memory scores following alpha as opposed to control stimulation, repeated measures (RM)-ANOVAs were employed. Outliers, sphericity, and normality were assessed beforehand, to ensure fulfillment of the required assumptions. Hypotheses one and two were investigated by means of paired-samples t-tests. Normality of these variables had been assessed before employing the ANOVA, and thus, fulfillment of all relevant assumptions for the t-tests had already been verified.

Analysis of the Experience Sampling Questionnaires

The experience-sampling questionnaires yielded two types of data about the consolidation period for each auditory stimulus: proportions and scales. The proportions resulted from the questions regarding participants' proportional themes of thought during the consolidation period, related to the face stimuli, autobiographical thoughts (ABT), experience of the sound, rest, blank, and ‘other’. In the case of thoughts categories as ‘other’, participants were asked to provide examples. This proportion was sometimes added to the ABT proportion if they referred to personal thoughts unrelated to the experiment, to rest if they referred to meditation or restful thoughts, or to another new category referred to as distraction when participants provided examples having thoughts about their surroundings.

The effect of ABT on memory performance in each condition was calculated using just ABT scores at first and then combined with distraction to yield an ‘overall ABT’ score. The scales originated from additional questions assessing the strength or qualia of the subjective experience related to the thought categories like vividness of ABTs, negative or positive ABTs, pleasure or displeasure from the sounds, and sleepiness or excitement resulting from the sounds. These were indicated on 7-point scales, as shown in Appendix I, Table 1.

To assess H3, which proposed that decreases in memory scores following (8hz) alpha binaural beat stimulation, when compared with the control stimulation will be explained by respectively higher proportions of autobiographical thought exhibited during the consolidation period, and H4, that increases in memory scores following (0.5hz) delta binaural beat stimulation compared to the control stimulation will be explained by respectively lower proportions of autobiographical thought exhibited during the consolidation period, the differences in ABT across all stimulation conditions, as well as differences in d-prime scores between the conditions, were calculated. To check the relevant assumptions, normality and linearity for all difference variables were assessed. As many outliers were present in the data (see Results section), correlations between proportional differences in ABT and differences in memory scores between alpha and control (H3), as well as for delta and control (H4) were assessed by Spearman’s r test.

As an exploratory post hoc test, the differences in ABT were correlated with the differences in memory scores following alpha and delta stimulation through Spearman’s r, followed by linear regression of these variables. Further, paired t-tests between the proportions and scales that adhered to normality and Wilcoxon signed rank sum tests for proportions and scales where normality could not be assumed were explored. Finally, differences between all remaining proportions and scales, as well as their correlations with the memory scores were examined through paired samples t-tests and Pearson’s r tests whenever the assumptions were met, and Wilcoxon signed rank sum tests, as well as Spearman’s r tests when not.

Results

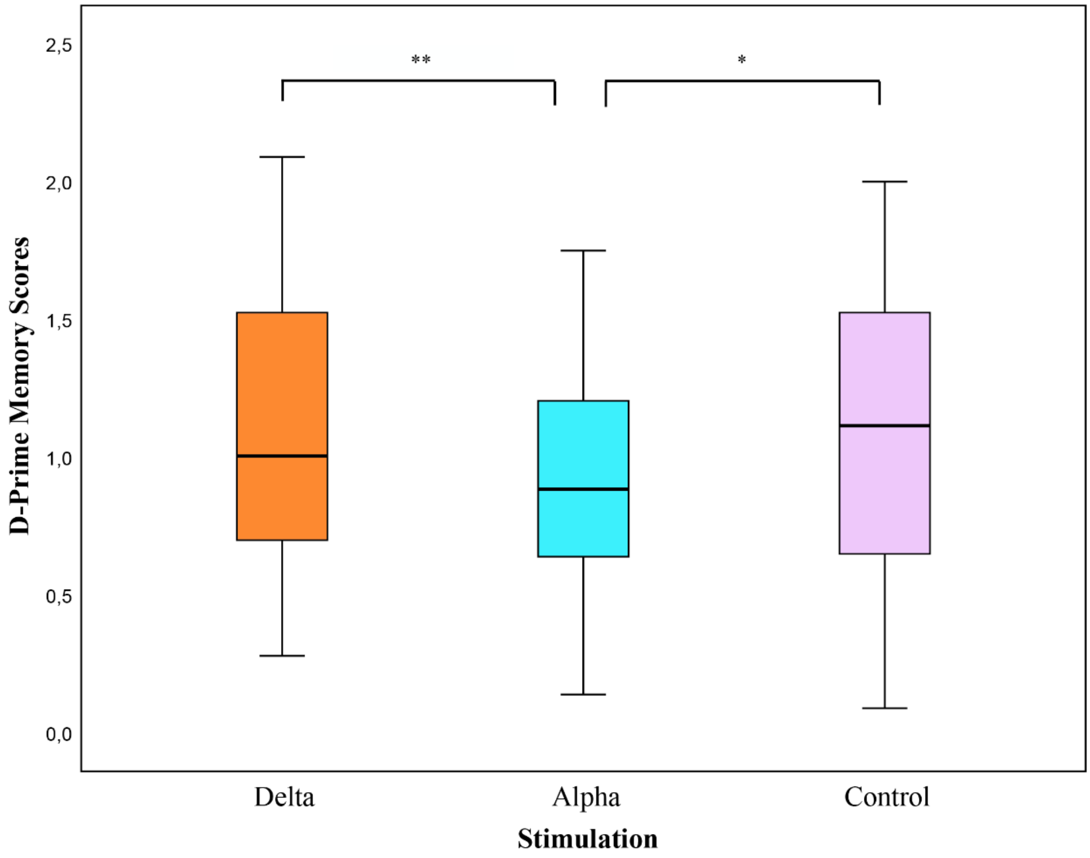
Memory Scores

Initially, six participants were excluded based on observed protocol violations and oral reports thereof (e.g., filling out the wrong forms, falling asleep), as well as technical issues (e.g., audio stimuli not playing through the headphones). To maintain a counterbalanced set of data, the two most recently collected participants were excluded. This left the valid data of 24 participants comprising four counterbalanced sets. Within this data, all required assumptions to test H1, which predicted significantly higher memory scores following delta stimulation compared to control stimulation, and H2, which predicted significantly lower memory scores following alpha as opposed to control stimulation were fulfilled.

The exposure to delta stimulation yielded the highest average d-prime scores (*M* = 1.09, *SD* = .52), followed by the mean d-prime scores proceeding the control stimulation (*M* = 1.07, *SD* = .52). Finally, the lowest mean d-prime score was observed proceeding alpha stimulation (*M* = .93, *SD* = .45). To assess, whether the observed differences in line with hypotheses one and two were significant, a within-subjects repeated measures (RM)-ANOVA was employed. The analysis showed a mild trend in the main effect of binaural beat stimulation on mean d-prime scores, *F*(2, 36) = 3.31, *p* = .06. There was no significant interaction between memory performance and the order group to which the participant belonged, *F*(2, 36) = 1.113, *p* = .38, indicating that no order effects were present. Therefore, simple effects were tested by means of paired samples t-tests.

Figure 4

Binaural Beat Stimulation Effects on Memory Scores: Delta vs. Alpha vs. Control



Note. The image above shows the comparison of d-prime scores between three stimulation conditions using paired t-tests. Comparing the memory scores following delta with those following the control stimulation did not show a significant difference, *t*(23) = -.282, *p* = .78. However, the alpha condition showed a marginal decline in memory scores when compared to the control condition at the one-tailed (*) level *t*(23) = 1.690, *p* = .05. Additionally, memory performance following the delta condition was significantly higher than the alpha condition at a two-tailed (**) level, *t*(23) = 2.591, *p* = .02.

Proportional Differences

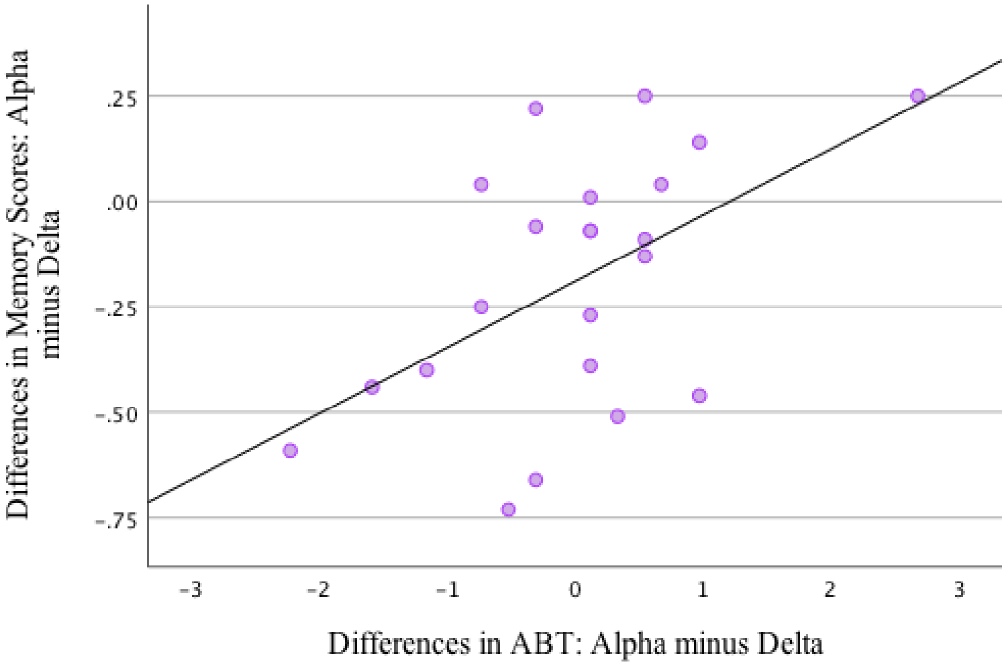
To examine H3, which proposed that decreases in memory scores following (8hz) alpha binaural beat stimulation, when compared with the control stimulation will be explained by respectively higher proportions of autobiographical thought exhibited during the consolidation period, and H4, that increases in memory scores following (0.5hz) delta binaural beat stimulation compared to the control stimulation will be explained by respectively lower proportions of autobiographical thought exhibited during the consolidation period, the required assumptions of the newly created difference variables were assessed. Normality was assumed for all difference variables except for the difference in ABT between the control and delta conditions, $W(22) = .848$, $p < .01$. Outliers existed in the difference in memory scores between the control and alpha conditions, as well as between control and delta. Further outliers existed in the differences in ABT between control and alpha, as well as alpha and delta. Removing outliers did not result in the fulfillment of the normality assumption. Yet, linearity was assumed for all combinations.

Spearman's r tests showed, that the positive correlation between differences in d-prime scores and differences in ABT in the control and alpha condition was not significant, $r(20) = .024$, $p = .916$, indicating that larger differences in ABT did not predict larger differences in memory scores. Further, the negative correlation between differences in ABT and differences in d-prime scores between the control and delta condition was also not significant, $r(20) = -.218$, $p = .33$, indicating that larger differences in ABT scores did not predict fewer differences in memory scores between the two conditions.

For further exploratory analysis, a Spearman's r correlation comparing the differences in ABT with the differences in memory scores between the alpha and delta stimulation condition was conducted. It revealed a positive significant correlation between the difference in ABT and the difference in d-prime scores for the alpha and delta condition, $r(20) = .409$, $p = .03$, indicating that larger differences in ABT between the two conditions predicted larger differences in memory scores. Thereafter, a linear regression between the two variables was conducted.

Figure 5

Linear Regression of ABT Differences on Memory Score Differences between Alpha and Delta



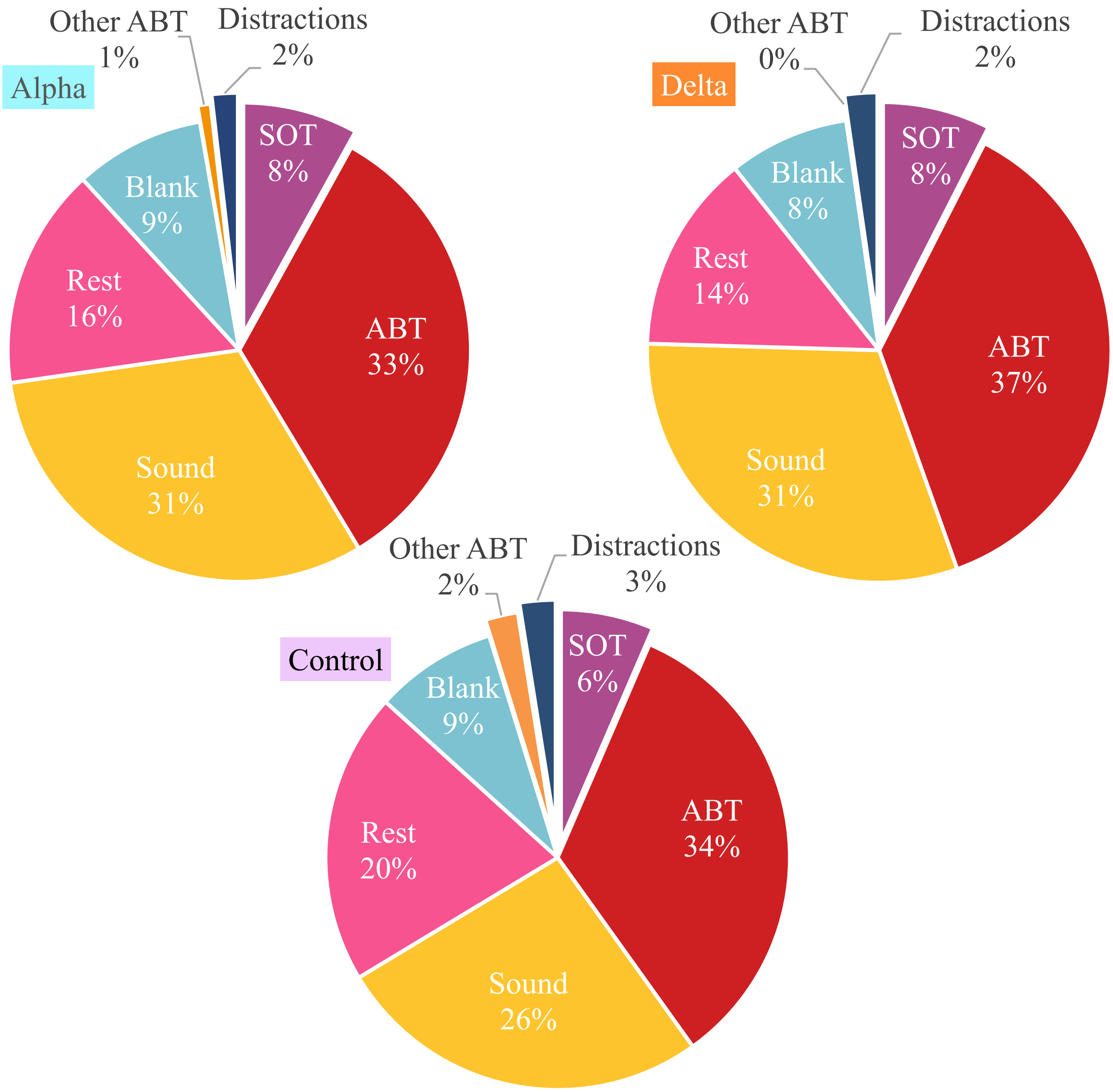
Note. The scatterplot shows the linear regression of the differences in ABT proportions (alpha minus delta) during quiet rest on the differences in memory scores (alpha minus delta), measured by d-prime. The result indicated that larger differences in ABT significantly predicted larger differences in d-prime scores between the alpha and delta conditions, b = .525, $t(20) = 2.76$, $p = .12$, and that the difference in ABT explained a significant proportion of variance in the memory scores $R^2 = .28$, $F(1,20) = 7.62$, $p = .012$.

Proportions

When analyzing the experience-sampling forms, two more participants were excluded based on incomplete data. This left us with the valid data of 22 participants.

Figure 7

Distribution of Proportional Thoughts during Consolidation



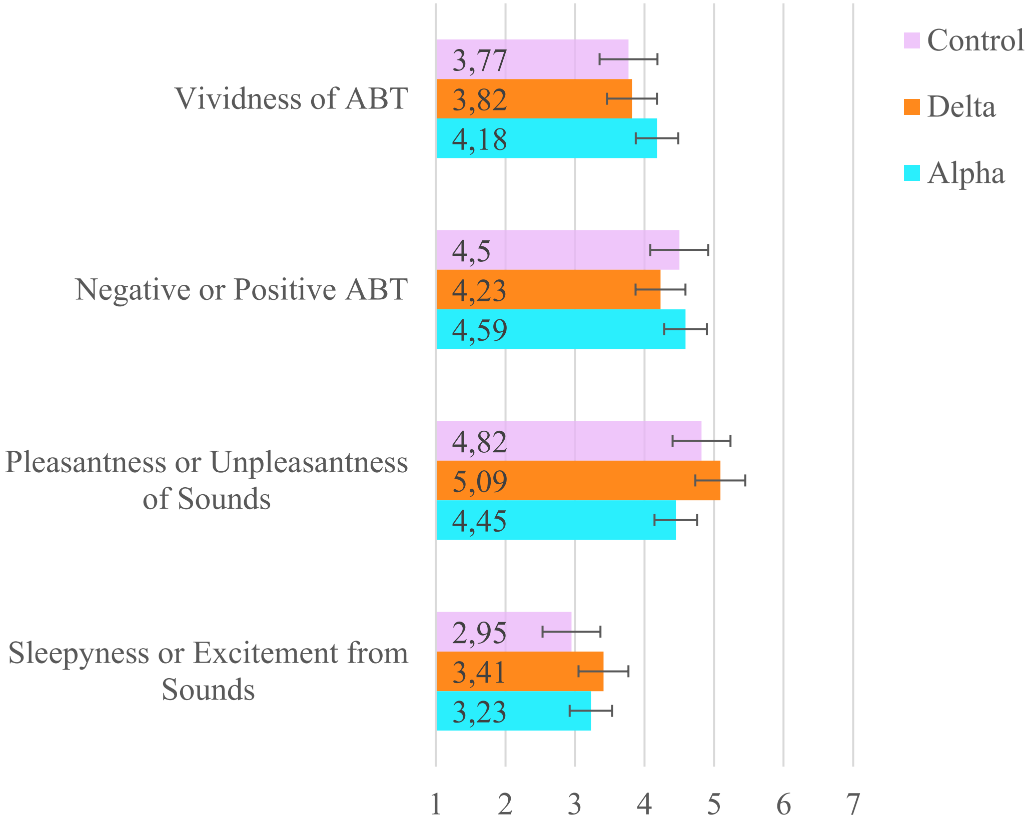
Note. The pie charts display the mean distribution of the proportions of thought during the consolidation period with auditory stimulation for each of the three stimulation conditions.

The Spearman's test revealed a significant positive correlation at the two-tailed level between the proportion of rest and the d-prime scores in the control condition, *r*(20) = .532, *p* = .01, indicating that participant in the control condition that spent a larger proportion of the consolidation period in a state of rest yielded higher memory scores. A negative significant correlation appeared at the two-tail level between other ABT and d-prime scores in the control condition, *r*(20) = -.445, *p* = .04, indicating that participants who reported more ‘other’ thoughts that were assigned to ABT, yielded lower memory scores in the control condition. At the one-tail condition, both of the combined variables displayed a negative significant correlation with the d-prime scores in the control condition. For ABT_ALL, *r*(20) = -.384, *p* = .04. This indicated that participants that spent proportionally fewer thoughts on ABT including other ABT during the control condition yielded higher memory scores. The same held true for ABT_ALL_Distraction, *r*(20) = -.381, *p* = .04, comprising time spent on ABT, other ABT and including the distraction variable. No other correlations were significant and none of the follow-up paired comparisons showed significant differences in proportional thoughts between the three conditions.

Scales

Figure 6

Distribution of the Scales regarding Strength and Qualia



Note. The graph shows the mean distribution of the scales, assessing the strength and qualia (level 1-7) of thoughts during the consolidation period in the three stimulation conditions.

Pearson's r correlations of the scales that did not violate the normality assumption revealed a significant negative correlation at the one-tailed level, between the vividness of ABT and the d-prime scores in the alpha condition $r(20) = -.360$, $p = .05$, indicating that participants with less vivid ABT during Alpha stimulation achieved higher d-prime scores. A second negative correlation, significant at the one-tail level, arose between sleepiness or excitement resulting from the sounds and the memory scores in the control condition, $r(20) = -.384$, $p = .04$, indicating that sleepiness, as opposed to excitedness, predicted higher memory scores. None of the other Pearson's correlations yielded significant results. Turning to Spearman's r tests of the scales that violated the assumptions of the Pearson's r test, we found a significant negative correlation at the one-tailed level, between pleasure or displeasure of the sounds and d-prime scores in the delta condition, $r(20) = -.465$, $p = .03$, indicating that participants who found the delta stimulus more pleasant yielded higher memory scores. No other tests yielded significant results and the follow-up paired samples t-tests (of approximately normally distributed factors) and Wilcoxon signed rank test did also not yield any significant between-group differences on the scales.

Discussion

The aim of the present study was to investigate, whether the findings of Brokaw et al. (2016), which proclaimed an optimal neurophysiological signature for consolidation to be characterized by increased endogenous delta and reduced alpha oscillations, could be artificially induced by external stimulation of 8hz delta and 0.5hz alpha binaural beats. This gave rise to the first two hypotheses:

1. A nine-minute post-encoding consolidation period accompanied by (0.5hz) delta binaural beat stimulation will result in enhanced consolidation of face stimuli, as measured by a recognition test when compared with the memory scores of a comparable control stimulation condition.
2. A nine-minute post-encoding consolidation period accompanied by (8hz) alpha binaural beat stimulation will result in decreased consolidation of face stimuli, as measured by a recognition test when compared with the memory scores of a comparable control stimulation condition.

Memory Scores

The results did not indicate a significant memory improvement following 0.5hz delta binaural beats stimulation during consolidation when compared with the memory scores following the control stimulation. Thus, the hypothesis could not be confirmed. This finding might indicate, that contrary to the reported studies that utilized 0.75hz delta tDCS stimulation during NREM-sleep to successfully facilitate memory consolidation (e.g., Ladenbauer et al., 2016; Ladenbauer et al., 2017), delta binaural beat stimulation does not possess the same facilitative capacities. It is also conceivable, that the binaural beats manipulation suffered from a lack of sufficient intensity or duration (see Limitations and Future Directions section). However, the control condition was set up to be comparable with a wakeful rest condition, which itself has been shown to facilitate memory consolidation (e.g., Dewar et al., 2012). Therefore, this finding does not necessitate, that the stimulation of delta binaural beats encompassed no facilitative effect on memory consolidation. Rather, it could also be interpreted as showing that delta binaural beat stimulation induces effects similarly conducive to memory consolidation than wakeful rest. The comparability of the control condition to a period of wakeful rest based on further findings is discussed below in the section: Proportional themes of thought. Further alternatives are discussed in the Limitations and Future Directions section.

The results did however indicate, that 8hz alpha binaural beat stimulation during the consolidation period resulted in diminished face recognition when compared with the effect of the control stimulation. Therefore, the second hypothesis was confirmed, although this finding was only marginally significant at the one-tail level. In line with the results of Brokaw et al. (2016), who reported that the decrease of endogenous alpha oscillations was predictive of successful memory consolidation, it is conceivable that the external alpha stimulation artificially increased endogenous alpha, which interfered with the ongoing consolidation, and in turn, accounted for the decreased memory scores. Taken together, these findings contradict the reported body of work that associates increased alpha with states and components that are facilitative to memory consolidation (e.g., Mo et al., 2013 Sharma & Singh, 2016) and decreases in alpha with states and components that interfere with it (e.g., Darby & Sloutsky, 2015; Fatania & Mercer, 2017). This suggests that a mental state or component exists, that facilitates memory consolidation during wakefulness and is accompanied by or interacts with decreased endogenous alpha.

To further explore the differential effect of external delta and alpha stimulation, the resulting memory effects were compared in an exploratory analysis. Post-encoding delta stimulation significantly increased the recognition of faces when compared to post-encoding alpha stimulation. This result is in line with the reports regarding delta in Brokaw et al. (2016). It is further in line with the reviewed literature suggesting that delta is crucially involved with sleep-dependent memory consolidation (e.g., Casey et al., 2016; Westerberg et al., 2012), as well as facilitative periods of wakeful rest (Wamsley & Summer, 2020). Further, this finding adds to the body of work that assesses consolidation effects through the external modulation of delta rhythms (e.g., Ladenbauer et al., 2017; Westerberg et al., 2015).

Together with the findings of alpha interfering with memory consolidation, this suggests that the present paradigm modulated memory consolidation by artificially inducing the signatures reported in the study by Brokaw et al. (2016). Therefore, it could be partially confirmed that binaural beats are capable of modulating episodic memory consolidation by entraining endogenous rhythms during a nine-minute post-encoding period. However, evidence is lacking that the mechanism underlying the differential effect of the alpha and delta stimulation on memory scores is a result of entraining endogenous oscillations through binaural beat stimulation (see Limitations and Future Directions section).

Proportional Differences in ABT

The second aim of this study was to assess, whether the observed differences in memory scores between the binaural beat stimulation conditions compared with the control condition could be (partially) explained by the observed differences in ABT, which predicted increased memory scores in the study by Brokaw et al., (2016). Based on this, we formulated two hypotheses:

3. The observed decrease in memory scores resulting from a nine-minute post-encoding consolidation period accompanied by (8hz) alpha binaural beat stimulation, when compared with a consolidation period accompanied by the

control stimulation, will be explained by respectively higher proportions of autobiographical thought exhibited during the consolidation period.

4. The observed increase in memory scores resulting from a nine-minute post-encoding consolidation period accompanied by (0.5hz) delta binaural beat stimulation, when compared to a consolidation period accompanied by the control stimulation, will be explained by respectively lower proportions of autobiographical thought exhibited during the consolidation period.

As outlined above, the results indicated a (marginal) significant difference in memory scores between the alpha and control stimulation conditions. However, the difference in ABT between the alpha and control stimulation conditions was not significant and could not predict the difference in memory scores. Therefore, the third hypothesis could not be confirmed. Further, the previously elaborated comparison between the effects of delta and control stimulation on memory scores did not differ significantly, and the non-significant difference in ABT was also not a significant predictor of the difference in memory scores. Therefore, the fourth hypothesis could also not be confirmed. This meant that for neither alpha nor delta stimulation, differences in ABT could not predict differences in memory scores when compared to the control stimulation. This also meant that the second research question was refuted.

This finding is not in line with the results of Brokaw et al. (2016), where the decreased alpha and increased delta EEG signature was accompanied by higher ABT proportions, and both were predictive of increased memory scores. It is also not in line with Craig et al. (2014), who reported that (cued) rich ABT interfered with memory consolidation. The lack of findings in the comparison between alpha and control stimulation can potentially be explained in shortcomings of the manipulation (e.g., insufficient strength and duration). The same methodological shortcomings could explain the lack of findings in the comparison of the delta and control stimulation. Alternatively, the lack of findings between the delta and alpha condition could be accounted for by the proposition, that the control stimulation closely resembled a wakeful rest condition (discussed below in the section: Proportional Themes of Thought), and that delta binaural beat stimulation evoked a similar state. This is supported in the absence of differences in memory performance, as well as the absence of differences in ABT proportions present in the data.

The follow-up exploratory analysis of the relationship between the (significant) difference in memory scores between alpha and delta binaural beat stimulation with the difference in proportional ABT suggested, that relatively higher ABT proportions predicted higher memory scores, selectively in the binaural beat stimulation condition in which the proportion of ABT was higher in each participant. Thus, when the within-subject difference in proportional ABT was such, that the proportion of ABT was higher during the delta stimulation compared to during the alpha stimulation, participants yielded higher memory scores following the delta stimulation. Likewise, when the within-subject difference in proportional ABT was such, that the proportion of ABT was higher during alpha stimulation compared to delta stimulation, participants yielded higher memory scores following the alpha stimulation.

Considering the observed lower memory scores following alpha stimulation compared with delta stimulation, it is evident that this effect was mainly driven by significantly higher memory scores under delta stimulation accompanied by relatively higher ABT. Further, the rare case in which participants exhibited higher scores following alpha stimulation compared with delta stimulation was accompanied by relatively higher ABT during alpha stimulation. This could potentially be interpreted as higher ABT during binaural beat stimulation predicting higher memory scores. A pattern in line with this premise can be observed in the scatterplot displaying the results of the linear regression (see Fig. 5). This finding is somewhat in line with the results of Brokaw et al. (2016), where the co-occurrence of high ABT with a state accompanied by low endogenous alpha and high endogenous delta facilitated memory consolidation. This finding would also mean that ABT differentially affected memory scores under the binaural beat and control stimulation. However, the absence of findings involving the control condition, in addition to the fact that ABT lacked predictive ability in both alpha and delta stimulation conditions, as well as the absence of observable difference in ABT between the two conditions warrants caution and permits only tentative interpretations regarding the relationship of ABT and memory scores under binaural beat stimulation.

Proportional Themes of Thought

A further aim of the present study was to investigate the predictive capacities of the proportional themes of thoughts during the consolidation period on the memory scores following each stimulation condition. In the control condition, participants' whose minds were more at rest yielded higher recognition scores, signaling increased memory consolidation. This finding is in line with the literature regarding the facilitative effects of post-encoding wakeful rest periods (e.g., Dewar et al., 2012).

The results also showed that high scores on the ABT-related proportions inversely predicted lower memory consolidation. This finding is not in line with the results of Brokaw et al. (2016), where higher proportions of ABT predicted increased memory consolidation during wakeful rest and the distractor task. It is however in line with the findings by Craig et al. (2014), who reported that (cued) ABT during wakeful rest interfered with memory consolidation. A potential explanation for this interaction could be that states similar to (offline) wakeful rest benefit from decreased ABT, as ABT could comprise novel encoding (future related ABT), as well as require memory reactivations (past ABT), both of which could occupy hippocampal resources currently allocated to memory consolidation and thereby interfere with it (Dewar et al., 2014; Mednick et al., 2013; Wixted, 2004).

Scales

The final aim of the present study was to investigate, whether the supplementary questions assessing the severity or qualia of the proportions of thought on seven-point scales could predict the relative memory scores for each stimulation condition. First, more vivid ABT during consolidation under alpha stimulation predicted lower memory scores. This finding is in line with that of Craig et al. (2014), who reported that the "richness" of (cued) ABT inversely predicted memory scores during wakeful rest. It is unlikely, that the alpha stimulus constituted a familiar sound cue (as employed in the study by Craig et al., 2014) and therefore evoked more vivid ABT. This is corroborated by the lack of differences in ABT vividness between the three conditions. Although an underlying link with ABT vividness and high endogenous alpha is currently not established, ABT itself has previously been linked to high endogenous alpha (Knyazev et al., 2012). Future research will need to establish, whether this link can be extended to the vividness of ABT.

Sleepiness resulting from the sounds, as opposed to excitement, also predicted higher scores in the control condition. This is in line with the findings regarding states of wakeful rest facilitating memory consolidation (e.g., Himmer et al., 2019; Wamsley & Summer, 2020), which is supposed to underly the increased opportunity for neural replay in these states (Giri et al., 2019). Given that the scales for sleepiness from the sounds, as well as the proportions of rest (discussed above in the section: Proportional Themes of Thought) both positively predicted memory scores, it is possible that the control stimulation largely resembled a post-encoding period of wakeful rest, which is understood to be facilitative (e.g., Dewar et al., 2012) and that similar mechanisms were at play. Alternative interpretations are discussed in the Limitations and Future Directions section.

The last finding from the scales showed that participants who found the delta stimulus more pleasant, as opposed to unpleasant, yielded higher memory scores. This finding is in line with multiple studies showing that the valence of the encoded material itself (e.g., Schümann et al., 2018), as well as the valence of the consolidation context (e.g., Beckner et al., 2006; Jiang, et al., 2019), can modulate memory consolidation (for review, see McGaugh et al., 2016). These findings can be accounted for by a modulatory involvement of the amygdala in emotional memory consolidation, in line with the Emotional Synaptic Tagging Hypothesis (Bergado, et al., 2011; McReynolds & McIntyre, 2012). This hypothesis proposes an emotion-induced interaction of neuromodulators (e.g., serotonin) with mechanisms of cellular consolidation, in the presence of emotional valence (e.g., amygdala-driven modulation of LTP in emotional memories; Bergado et al., 2011). Thus, a proportion of the improved face recognition scores following delta stimulation can be attributed to the higher positive valence that several participants associated with it.

General Discussion

In sum, these findings indicate that binaural beat stimulation can facilitate, as well as interfere with episodic memory consolidation. Whilst the participants' neurophysiological signatures were not formally assessed, external alpha stimulation should have steered the participants away from the optimal (low endogenous alpha, high delta) state proposed by Brokaw et al. (2016), whilst external delta stimulation should have steered participants closer to it. This should account for the observed effects of 8hz alpha binaural beat stimulation interfering with memory consolidation, while 0.5hz delta binaural beat stimulation facilitated it. This pattern is observable in the present data under the assumption that the control stimulation resembled a facilitative wakeful rest condition.

An important finding was that the vividness of ABT negatively predicted memory scores under control stimulation, thereby corroborating Craig et al., (2014). Additionally, ABT showed differential effects on memory scores under binaural beat and control stimulation. Whilst combined ABT variables negatively predicted memory scores under the control stimulation, ABT did not predict memory scores in the binaural beat conditions. However, relatively higher ABT proportions during alpha and delta stimulation were predictive of higher memory scores, selectively in the stimulation condition in which the proportion of ABT was higher in each participant. This complex relationship does not suggest that ABT mediates the relationship between binaural beat stimulation and memory consolidation. Neither of the other factors was mediating the relationship between binaural beat stimulation and memory consolidation. Therefore, the underlying mechanism remains elusive.

The results of the present study hold several implications. First, it contributes to the existing body of literature concerning the modulation of memory consolidation. Specifically, evidence for a novel paradigm comprising the manipulating of memory consolidation through binaural beats was presented. Further, contributions to the current discrepancy in the literature regarding alpha oscillations and their interplay with states and mental components underlying memory consolidation were made. Finally, the finding of ABT vividness, as well as combined ABT variables negatively predicting memory scores in the control condition contribute to the existing body of work investigating the influence of ABT on memory consolidation. Beyond the academic literature, the present results may suggest, that post-encoding delta binaural beat stimulation could form the basis for a general learning aid.

Limitations and Future Directions

While the present study reports some remarkable results, there are several limitations to be considered when drawing conclusions from the findings. First, the required sample size ($N = 34$) was not met, calculated based on previous studies employing a similar design (Varma et al., 2018), and this shortcoming has vast implications for the power of the study. Future replications and extensions of the present paradigm should ensure that this criterion is met. Second, even though a paradigm based on neurophysiological signatures is employed, and the rationale rests on various neurological findings, the data in the present study was exclusively behavioral. Thus, future efforts involving neuroimaging will be required to corroborate these results, especially regarding the entrainment resulting from binaural beat stimulation, as well as the ensuing changes in the components that underly memory consolidation.

Further, the interpretation of the results rests on the assumption, that the control stimulation was comparable to a (facilitative) period of wakeful rest, as often employed in consolidation research. However, it is also possible that neither the control nor delta stimulation affected memory consolidation, while alpha stimulation was detrimental. Likewise, it is possible that the control and delta stimulation were detrimental to consolidation, while alpha stimulation was even more detrimental. To assess this relationship, future extensions of this paradigm should include a wakeful rest condition without stimulation in their design. It might also be the case, that the present findings are distorted by missed instances of participants falling asleep, or that microsleeps occurred, as sleep was only assessed in the post-experimental questions. A potential option for measuring sleep is utilizing physical activity and energy expenditure actimeters (Robillard, Lambert, & Rogers, 2012), while microsleeps can be measured non-invasively through video-based measurements (Malla et al., 2010). Further, employing neurological measurements to corroborate the present results would also allow assessment of sleep (e.g., EEG; Ogilvie, 2001). Validated measures of sleep should be employed in future extensions of this paradigm.

Additionally, several drawbacks to this design relate to the timing, especially to that of the delayed recall test. First, a single recognition test following all encoding and consolidation blocks was employed, which varied the consolidation time for each encoded face between nine and 65 minutes. On the one hand, the faces encoded in earlier blocks could be consolidated for a much longer time than those encoded in later blocks, which may have distorted the results. Additionally, face memories encoded in earlier blocks were exposed to multiple stimulation conditions before participants were tested on them. Whilst order effects were accounted for in both the design and analysis, lingering carryover effects may still have been present and distorted the results. Both of these could be accounted for by employing a recognition test after each consolidation period, thereby keeping the time between encoding and (short-) delayed assessment relatively conform. On the other hand, this paradigm does not allow inferences about the long-term effects of the stimulation paradigm on consolidation. Future extensions of this paradigm should include delayed recognition tests at intervals of 24h and 48h. For practicality, the delayed recall tests could potentially be conducted online.

Another drawback stems from the timing of the experience-sampling forms, which were administered post-consolidation and therefore constitute retrospective assessment. This may also have had crucial implications for the results. It may be possible to add situational assessments (e.g., “my mind is currently […]”) right before encoding in addition to the retrospective assessment. Deriving the difference value on each factor assessed by the scales, as it is common practice in the assessment of changes in quality of life accompanying health conditions (Nieuwkerk et al., 2007; Sprangers & Schwartz, 1999), might counteract this.

With further regard to the experience-sampling forms, the fact that the proportions required to add up to 100%, in combination with assessment of these factors on printed forms led to several invalidly filled forms, as well as numerous corrections made by the participants to force their answers to add up to 100%. It is likely, that valuable data may have been lost along this process. Future extensions and replications of this paradigm should consider using digital experience-sampling forms, with the potential addition of a visual representation of the indicated proportions (e.g., a pie chart or a progress bar). On top of that, the experience-sampling scales, and especially the proportions were riddled with outliers and violations of normality and linearity assumptions. This required extensive use of non-parametric tests, that suffer respectively from a lack of power. The above-suggested employment of situational (e.g., “my mind is currently […]”) pre-encoding or pre-consolidation experience sampling forms in addition to those currently employed post-consolidation, and using the differences on the assessed factors as the relevant variables to assess proportions and scales could aid to counteract this issue. Finally, the participant sample was characterized by a very low number of male participants (*N* = 5), and therefore, conclusions can currently only be generalized to the female population.

Conclusion

A recent study by Brokaw et al. (2016) proposed, that the optimal state for memory consolidation is characterized by a neurophysiological state of decreased endogenous alpha and increased endogenous delta oscillations. The findings of the present study suggests that a binaural beats paradigm is capable of modulating memory consolidation. The results indicate that 8hz alpha binaural beat stimulation interferes with memory consolidation, while 0.5hz delta binaural beat stimulation effects memory consolidation equally to the control condition. The findings regarding delta extend the existing body of work. However, the findings regarding alpha constitute an apparent discrepancy with the existing literature, that links high endogenous alpha power to states and components related to memory consolidation (inverse to the demonstrated results). Vivid ABT negatively predicted memory scores in the control condition, corroborating findings by Craig et al., (2014). Additionally, while autobiographical thought (ABT) differentially affected memory scores under binaural beat and control stimulation, it did not mediate the relationship between binaural beat stimulation, as well as control stimulation and memory scores. None of the other assessed mental activities during consolidation appeared to mediate this relationship either. Therefore, the mechanism underlying this effect remains unclear. Further research employing neurological measures is necessary to corroborate these results and assess the underlying mechanism, especially that underlying the contradictory relationship of alpha oscillations and memory consolidation.

References

Ableton AG (2018) *Ableton Live* (Version 10.1.35) [Computer Software]. https://www.ableton.com/

Almeida-Filho, D. G., Queiroz, C. M., & Ribeiro, S. (2018). Memory corticalization triggered by REM sleep: mechanisms of cellular and systems consolidation. *Cellular and Molecular Life Sciences*, *75*(20), 3715–3740. https://doi.org/10.1007/s00018-018-2886-9

Alves, M. V. C., & Bueno, O. F. A. (2017). Retroactive interference: Forgetting as an interruption of memory consolidation. *Trends in Psychology*, *25*(3), 1055–1067. https://doi.org/10.9788/TP2017.3-07En

Andrews-Hanna, J. R. (2012). The brain's default network and its adaptive role in internal mentation. *Neuroscientist*, *18*(3), 251–270. https://doi.org/10.1177/1073858411403316

Andrews-Hanna, J. R., Smallwood, J., & Spreng, R. N. (2014). The default network and self-generated thought: Component processes, dynamic control, and clinical relevance. *Annals of the New York Academy of Sciences*, *1316*(1), 29–52. https://doi.org/10.1111/nyas.12360

Atkinson, R. C., & Shiffrin, R. M. (1968). Human Memory: A Proposed System and its Control Processes. *Psychology of Learning and Motivation - Advances in Research and Theory*, *2*, 89–195. https://doi.org/10.1016/S0079-7421(08)60422-3

Bartsch, U., Simpkin, A. J., Demanuele, C., Wamsley, E., Marston, H. M., & Jones, M. W. (2019). Distributed slow-wave dynamics during sleep predict memory consolidation and its impairment in schizophrenia. *Npj Schizophrenia*, *5*(1), 1–11. https://doi.org/10.1038/s41537-019-0086-8

Baumann, V., Birnbaum, T., Breitling-Ziegler, C., Tegelbeckers, J., Dambacher, J., Edelmann, E., … Krauel, K. (2020). Exploration of a novel virtual environment improves memory consolidation in ADHD. *Scientific Reports*, *10*(1), 1–15. https://doi.org/10.1038/s41598-020-78222-4

Beckner, V. E., Tucker, D. M., Delville, Y., & Mohr, D. C. (2006). Stress facilitates consolidation of verbal memory for a film but does not affect retrieval. *Behavioral Neuroscience*, *120*(3), 518–527. https://doi.org/10.1037/0735-7044.120.3.518

Beyerdynmaic GmbH & Co. KG (2015) DT770 Pro 250 Ohm [Apparatus]. https://europe.beyerdynamic.com/dt-770-pro.html?nosto=headsets_pro_ourtip

Brodbeck, V., Kuhn, A., von Wegner, F., Morzelewski, A., Tagliazucchi, E., Borisov, S., … Laufs, H. (2012). EEG microstates of wakefulness and NREM sleep. *NeuroImage*, *62*(3), 2129–2139. https://doi.org/10.1016/j.neuroimage.2012.05.060

Brokaw, K., Tishler, W., Manceor, S., Hamilton, K., Gaulden, A., Parr, E., & Wamsley, E. J. (2016). Resting state EEG correlates of memory consolidation. *Neurobiology of Learning and Memory*, *130*, 17–25. https://doi.org/10.1016/j.nlm.2016.01.008

Casey, S. J., Solomons, L. C., Steier, J., Kabra, N., Burnside, A., Pengo, M. F., … Kopelman, M. D. (2016). Slow wave and rem sleep deprivation effects on explicit and implicit memory during sleep. *Neuropsychology*, *30*(8), 931–945. https://doi.org/10.1037/neu0000314

Chaieb, L., & Fell, J. (2017). Binaural beat Stimulation. In L. S. Colzato (Ed.), *Theory-Driven Approaches to Cognitive Enhancement* (1st ed., pp. 169–183). Springer International Publishing AG. https://doi.org/10.1007/978-3-319-57505-6

Christoff, K., Gordon, A. M., Smallwood, J., Smith, R., & Schooler, J. W. (2009). Experience sampling during fMRI reveals default network and executive system contributions to mind wandering. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(21), 8719–8724. https://doi.org/10.1073/pnas.0900234106

Compton, R. J., Gearinger, D., & Wild, H. (2019). The wandering mind oscillates: EEG alpha power is enhanced during moments of mind-wandering. *Cognitive, Affective and Behavioral Neuroscience*, *19*(5), 1184–1191. https://doi.org/10.3758/s13415-019-00745-9

Craig, M., Sala, S. Della, & Dewar, M. (2014). Autobiographical thinking interferes with episodic memory consolidation. *PLoS ONE*, *9*(4). https://doi.org/10.1371/journal.pone.0093915

Darby, K. P., & Sloutsky, V. M. (2015). The cost of learning: Interference effects in memory development. *Journal of Experimental Psychology: General*, *144*(2), 410–431. https://doi.org/10.1037/xge0000051

Dewar, M., Alber, J., Butler, C., Cowan, N., & Della Sala, S. (2012). Brief Wakeful Resting Boosts New Memories Over the Long Term. *Psychological Science*, *23*(9), 955–960. https://doi.org/10.1177/0956797612441220

Dewar, M., Alber, J., Cowan, N., & Sala, S. Della. (2014). Boosting long-term memory via wakeful rest: Intentional rehearsal is not necessary, consolidation is sufficient. *PLoS ONE*, *9*(10). https://doi.org/10.1371/journal.pone.0109542

Dewar, M. T., Cowan, N., & Sala, S. Della. (2007). Forgetting due to retroactive interference: A fusion of Müller and Pilzecker's (1990) early insights into everyday forgetting and recent research on anterograde amnesia. *Cortex*, *43*(5), 616–634. https://doi.org/10.1016/S0010-9452(08)70492-1

Diekelmann, S., & Born, J. (2010). The memory function of sleep. *Nature Reviews Neuroscience*, *11*(2), 114–126. https://doi.org/10.1038/nrn2762

Farah, M. J., Smith, M. E., Ilieva, I., & Hamilton, R. H. (2014). Cognitive enhancement. *Wiley Interdisciplinary Reviews: Cognitive Science*, *5*(1), 95–103. https://doi.org/10.1002/wcs.1250

Fatania, J., & Mercer, T. (2017). Nonspecific retroactive interference in children and adults. *Advances in Cognitive Psychology*, *13*(4), 314–322. https://doi.org/10.5709/acp-0231-6

Foulkes, D., & Fleisher, S. (1975). Mental activity in relaxed wakefulness. *Journal of Abnormal Psychology*, *84*(1), 66–75. https://doi.org/10.1037/h0076164

Giri, B., Miyawaki, H., Mizuseki, K., Cheng, S., & Diba, K. (2019). Hippocampal reactivation extends for several hours following novel experience. *Journal of Neuroscience*, *39*(5), 866–875. https://doi.org/10.1523/JNEUROSCI.1950-18.2018

Gottselig, J. M., Hofer-Tinguely, G., Borbély, A. A., Regel, S. J., Landolt, H. P., Rétey, J. V., & Achermann, P. (2004). Sleep and rest facilitate auditory learning. *Neuroscience*, *127*(3), 557–561. https://doi.org/10.1016/j.neuroscience.2004.05.053

Gruberger, M., Ben-Simon, E., Levkovitz, Y., Zangen, A., & Hendler, T. (2011). Towards a neuroscience of mind-wandering. *Frontiers in Human Neuroscience*, *5*(JUNE), 1–11. https://doi.org/10.3389/fnhum.2011.00056

Hanslmayr, S., Axmacher, N., & Inman, C. S. (2019). Modulating Human Memory via Entrainment of Brain Oscillations. *Trends in Neurosciences*, *42*(7), 485–499. https://doi.org/10.1016/j.tins.2019.04.004

Hills, T., & Hertwig, R. (2011). Why aren't we smarter already: Evolutionary trade-offs and cognitive enhancements. *Current Directions in Psychological Science*, *20*(6), 373–377. https://doi.org/10.1177/0963721411418300

Himmer, L., Schönauer, M., Heib, D. P. J., Schabus, M., & Gais, S. (2019). Rehearsal initiates systems memory consolidation, sleep makes it last. *Science Advances*, *5*(4), 1–10. https://doi.org/10.1126/sciadv.aav1695

Jackson, A. F., & Bolger, D. J. (2014). The neurophysiological bases of EEG and EEG measurement: A review for the rest of us. *Psychophysiology*, *51*(11), 1061–1071. https://doi.org/10.1111/psyp.12283

Jiang, A., Tran, T. T., Madison, F. N., & Bakker, A. (2019). Acute stress-induced cortisol elevation during memory consolidation enhances pattern separation. *Learning and*

Memory, *26*(4), 121–127. https://doi.org/10.1101/lm.048546.118

Jirakittayakorn, N., & Wongsawat, Y. (2018). A Novel Insight of Effects of a 3-Hz Binaural Beat on Sleep Stages During Sleep. *Frontiers in Human Neuroscience*, *12*(September), 1–15. https://doi.org/10.3389/fnhum.2018.00387

Kirchner, W. K. (1958). Age Differences in Short-Term Retention of Rapidly Changing Infortmation. *Journal of Experimental Psychology*, *55*(4), 352–358.

Knyazev, G. G., Savostyanov, A. N., Volf, N. V., Liou, M., & Bocharov, A. V. (2012). EEG correlates of spontaneous self-referential thoughts: A cross-cultural study. *International Journal of Psychophysiology*, *86*(2), 173–181. https://doi.org/10.1016/j.ijpsycho.2012.09.002

Ladenbauer, J., Külzow, N., Passmann, S., Antonenko, D., Grittner, U., Tamm, S., & Flöel, A. (2016). Brain stimulation during an afternoon nap boosts slow oscillatory activity and memory consolidation in older adults. *NeuroImage*, *142*, 311–323. https://doi.org/10.1016/j.neuroimage.2016.06.057

Ladenbauer, J., Ladenbauer, J., Külzowä, N., De Boor, R., Avramova, E., Grittner, U., & Flöel, A. (2017). Promoting sleep oscillations and their functional coupling by transcranial stimulation enhances memory consolidation in mild cognitive impairment. *Journal of Neuroscience*, *37*(30), 7111–7124. https://doi.org/10.1523/JNEUROSCI.0260-17.2017

Liu, D. L. J., Graham, S., & Zorawski, M. (2008). Enhanced selective memory consolidation following post-learning pleasant and aversive arousal. *Neurobiology of Learning and Memory*, *89*(1), 36–46. https://doi.org/10.1016/j.nlm.2007.09.001

Liu, S., Kuschpel, M. S., Schad, D. J., Heinz, A., & Rapp, M. A. (2015). Differential effects of music and video gaming during breaks on auditory and visual learning. *Cyberpsychology, Behavior, and Social Networking*, *18*(11), 647–653. https://doi.org/10.1089/cyber.2015.0140

Lokhandwala, S., & Spencer, R. M. C. (2021). Slow wave sleep in naps supports episodic memories in early childhood. *Developmental Science*, *24*(2), 1–10. https://doi.org/10.1111/desc.13035

Ma, D. S., Correll, J., & Wittenbrink, B. (2015). The Chicago face database: A free stimulus set of faces and norming data. *Behavior Research Methods*, *47*(4), 1122–1135. https://doi.org/10.3758/s13428-014-0532-5

Malla, A. M., Davidson, P. R., Bones, P. J., Green, R., & Jones, R. D. (2010). Automated video-based measurement of eye closure for detecting behavioral microsleep. *2010 Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBC'10*, 6741–6744. https://doi.org/10.1109/IEMBS.2010.5626013

Marshall, L., Mölle, M., Hallschmid, M., & Born, J. (2004). Transcranial direct current stimulation during sleep improves declarative memory. *Journal of Neuroscience*, *24*(44), 9985–9992. https://doi.org/10.1523/JNEUROSCI.2725-04.2004

McCormick, E. M., & Telzer, E. H. (2018). Contributions of default mode network stability and deactivation to adolescent task engagement. *Scientific Reports*, *8*(1), 1–11. https://doi.org/10.1038/s41598-018-36269-4

McGaugh, J. L., Roozen, B. J. P. G., & Roozendaal, B. (2016). Memory modulation. *The Curated Reference Collection in Neuroscience and Biobehavioral Psychology*, *125*(6), 411–443. https://doi.org/10.1016/B978-0-12-809324-5.21092-4

Mednick, S., Cai, D. J., Shuman, T., Anagnostaras, S., & Wixted, J. (2013). An opportunistic theory of cellular and systems consolidation. *Trends in Neurosciences*, *34*(10), 504–514. https://doi.org/10.1038/mp.2011.182.doi

Metzinger, T., & Hildt, E. (2011). Cognitive Enhancement. In J. Illes & B. J. Sahakian (Eds.), *Oxford Handbook of Neuroethics* (1st ed., pp. 1–24). Oxford: Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199570706.013.0063

Mikutta, C., Feige, B., Maier, J. G., Hertenstein, E., Holz, J., Riemann, D., & Nissen, C.

(2019). Phase-amplitude coupling of sleep slow oscillatory and spindle activity correlates with overnight memory consolidation. *Journal of Sleep Research*, *28*(6). https://doi.org/10.1111/jsr.12835

Mo, J., Liu, Y., Huang, H., & Ding, M. (2013). Coupling between visual alpha oscillations and default mode activity. *NeuroImage*, *68*, 112–118. https://doi.org/10.1016/j.neuroimage.2012.11.058

Moog Music inc. (2015) Moog Mother32 [Apparatus]. https://www.moogmusic.com/products/mother-32

Müller, G. E., & Pilzecker, A. (1900). Experimentelle Beiträge zur Lehre vom Gedächtniss [Experimental contributions to the science of memory]. *Zeitschrift Für Psychologie*, *1*.

Nere, A., Hashmi, A., Cirelli, C., & Tononi, G. (2013). Sleep-dependent synaptic down-selection (I): Modeling the benefits of sleep on memory consolidation and integration. *Frontiers in Neurology*, *4 SEP*(September), 1–17. https://doi.org/10.3389/fneur.2013.00143

Nieuwkerk, P. T., Tollenaar, M. S., Oort, F. J., & Sprangers, M. A. G. (2007). Are retrospective measures of change in quality of life more valid than prospective measures? *Medical Care*, *45*(3), 199–205. https://doi.org/10.1097/01.mlr.0000246613.49214.46

Ogilvie, R. D. (2001). The process of falling asleep. *Sleep Medicine Reviews*, *5*(3), 247–270. https://doi.org/10.1053/smrv.2001.0145

Oster, G. (1973). Auditory beats in the brain. *Scientific American*, *229*(4), 94–102. https://doi.org/10.1038/scientificamerican1073-94

Robillard, R., Lambert, T. J. R., & Rogers, N. L. (2012). Measuring sleep-wake patterns with physical activity and energy expenditure monitors. *Biological Rhythm Research*, *43*(5), 555–562. https://doi.org/10.1080/09291016.2011.614794

Schümann, D., Bayer, J., Talmi, D., & Sommer, T. (2018). Dissociation of immediate and delayed effects of emotional arousal on episodic memory. *Neurobiology of Learning and Memory*, *148*(February 2017), 11–19. https://doi.org/10.1016/j.nlm.2017.12.007

Sekeres, M. J., Winocur, G., & Moscovitch, M. (2018). The hippocampus and related neocortical structures in memory transformation. *Neuroscience Letters*, *680*(May), 39–53. https://doi.org/10.1016/j.neulet.2018.05.006

Sharma, A., & Singh, M. (2016). Assessing alpha activity in attention and relaxed state: An EEG analysis. *Proceedings on 2015 1st International Conference on Next Generation Computing Technologies, NGCT 2015*, (September), 508–513. https://doi.org/10.1109/NGCT.2015.7375171

Sprangers, M. A. ., & Schwartz, C. E. (1999). Integrating response shift into health-related quality of life research: a theoretical model. *Social Science & Medicine*, *48*(11), 1507–1515. https://doi.org/10.1016/S0277-9536(99)00045-3

Staley, K. J., White, A., & Dudek, F. E. (2011). Interictal spikes: Harbingers or causes of epilepsy? *Neuroscience Letters*, *497*(3), 247–250. https://doi.org/10.1016/j.neulet.2011.03.070

Stanislaw, H. (1999). Signal Detection Theory. *Behavior Research Methods, Instruments, & Computers*, *3*(I), 37–149.

Tabrizi, F., & Jansson, B. (2016). Reducing involuntary memory by interfering consolidation of stressful auditory information: A pilot study. *Journal of Behavior Therapy and Experimental Psychiatry*, *50*, 238–244. https://doi.org/10.1016/j.jbtep.2015.09.003

Tibi, R., Eviatar, Z., & Karni, A. (2013). Fact retrieval and memory consolidation for a movement sequence: Bidirectional effects of “unrelated” cognitive tasks on procedural memory. *PLoS ONE*, *8*(11), 1–8. https://doi.org/10.1371/journal.pone.0080270

Trammell, J. P., & Clore, G. L. (2015). Does Stress Enhance or Impair Memory Consolidation? *Cogn Emot.*, *28*(2), 361–374. https://doi.org/10.1080/02699931.2013.822346.

Varma, S., Daselaar, S. M., Kessels, R. P. C., & Takashima, A. (2018). Promotion and suppression of autobiographical thinking differentially affect episodic memory consolidation. *PLoS ONE*, *13*(8), 1–15. https://doi.org/10.1371/journal.pone.0201780

Varma, S., Takashima, A., Fu, L., & Kessels, R. P. C. (2019). Mindwandering propensity modulates episodic memory consolidation. *Aging Clinical and Experimental Research*, *31*(11), 1601–1607. https://doi.org/10.1007/s40520-019-01251-1

Varma, S., Takashima, A., Krewinkel, S., van Kooten, M., Fu, L., Medendorp, W. P., … Daselaar, S. M. (2017). Non-interfering effects of active post-encoding tasks on episodic memory consolidation in humans. *Frontiers in Behavioral Neuroscience*, *11*(March), 1–13. https://doi.org/10.3389/fnbeh.2017.00054

Wamsley, E. J. (2019). Memory Consolidation during Waking Rest. *Trends in Cognitive Sciences*, *23*(3), 171–173. https://doi.org/10.1016/j.tics.2018.12.007

Wamsley, E. J., & Stickgold, R. (2019). Dreaming of a learning task is associated with enhanced memory consolidation: Replication in an overnight sleep study. *Journal of Sleep Research*, *28*(1), 1–8. https://doi.org/10.1111/jsr.12749

Wamsley, E. J., & Summer, T. (2020). Spontaneous entry into an “offline” state during wakefulness: A mechanism of memory consolidation? *Journal of Cognitive Neuroscience*, *32*(9), 1714–1734. https://doi.org/10.1162/jocn_a_01587

Wang, B. (2017). Gender difference in effect of positive emotion on consolidation of memory for definitions of English vocabulary. *International Journal of Bilingualism*, *21*(3), 306–316. https://doi.org/10.1177/1367006915625456

Wang, K., Yu, C., Xu, L., Qin, W., Li, K., Xu, L., & Jiang, T. (2009). Offline memory reprocessing: Involvement of the brain’s default network in spontaneous thought processes. *PLoS ONE*, *4*(3). https://doi.org/10.1371/journal.pone.0004867

Westerberg, C. E., Florczak, S. M., Weintraub, S., Mesulam, M. M., Marshall, L., Zee, P. C., & Paller, K. A. (2015). Memory improvement via slow-oscillatory stimulation during sleep in older adults. *Neurobiology of Aging*, *36*(9), 2577–2586. https://doi.org/10.1016/j.neurobiolaging.2015.05.014

Westerberg, C. E., Mander, B. A., Florczak, S. M., Weintraub, S., Mesulam, M.-M., Zee, P. C., & Paller, K. A. (2012). Concurrent Impairments in Sleep and Memory in Amnestic Mild Cognitive Impairment. *J Int Neuropsychol*, *18*(3), 490–500. https://doi.org/10.1017/S135561771200001X.Concurrent

Winocur, G., Moscovitch, M., & Bontempi, B. (2010). Memory formation and long-term retention in humans and animals: Convergence towards a transformation account of hippocampal-neocortical interactions. *Neuropsychologia*, *48*(8), 2339–2356. https://doi.org/10.1016/j.neuropsychologia.2010.04.016

Wixted, J. T. (2004). The psychology and neuroscience of forgetting. *Annual Review of Psychology*, *55*, 235–269. https://doi.org/10.1146/annurev.psych.55.090902.141555

Wixted, J. T., & Cai, D. J. (2013). Chapter: Memory Consolidation. *The Oxford Handbook of Cognitive Neuroscience*, *1*, *Core to*, 436–455.

Wixted, J. T., & Cai, D. J. (2014). Memory Consolidation. In K. Ochsner & S. M. Kosslyn (Eds.), *The Oxford Handbook of Cognitive Neuroscience, Volume 1: Core Topics* (1st ed., pp. 436–455). Oxford: Oxford University Press.

Appendix I

Table 1

Experience Sampling Questionnaire

Question	Answer
During the last delay period, did you think about or repeat the previously learnt faces in your mind?	Y/N
What percentage of your overall thoughts during the rest period was about the previously learnt faces?	%
How many of the 64 faces do you think you successfully recalled or repeated?	0-64
Did you think about personal things unrelated to the experiment?	Y/N
What % of your overall thoughts were about personal past, present concerns or future plans?	%
How rich, vivid or deep were these thoughts on a scale of 1 (not at all) -7 (very much)?	1-7
On a scale of 1(very negative) -7 (very positive) please rate the emotional quality of your thoughts?	1-7
Did you think about the sounds or the experience of the situation during the rest period?	Y/N
What % of your overall thoughts were about the Binaural Beat sounds or the experience of the sounds?	%
How pleasant or annoying was the experience of these sounds: 1 (very pleasant) to 7 (very annoying)?	1-7
Did the sounds make you feel sleepy and bored or excited and focused: 1 (very sleepy) to 7 (very exciting)?	1-7
Was your mind resting during this period?	Y/N

What % of the time were you involved in drowsiness, sleepiness and any other rest-like thoughts?	%
What % of time was your mind blank or you had no particular thoughts?	%
Did you encounter other types thoughts (not listed above) during this period?	Y/N
If yes, what % of time did you have these other thoughts?	%
Give example…	Open
Total %	%

Note. The table shows the post-consolidation experience sampling questionnaire, and the format in which participants could answer each question. General questions about the occurrence of our predefined themes of thought were answered with yes or no (Y/N). A single question assessed the number of recalled faces (0-64). Questions related to proportional presence of these themes of thought were answered in percentages (%). These should add up to 100% in the answer to the last question. Questions for further assessment of the depth and qualia of the proportional themes of thoughts were answered on scales from one to seven (1-7). A single open-ended question allowed participants to give examples for thoughts that fell outside of our pre-defined themes (Open).

Appendix II

Table 1

COVID-19 Behavioral Protocol

Step	Action
1	Researchers will enter the building while wearing a facemask and will keep the mask on (in the hallways, student-rooms, restrooms and laboratory etc.). The experimenter will remove their mask only when either seated in the lab alone, or in the presence of a research participant who is seated separately in a lab cubicle. Upon entering the building, the researcher will disinfect his/her hands and announce him/herself at the reception
2	Researchers will inform the reception about which participant is to be expected at what time
3	Participants will be on time, and announce him/herself at the reception. The experimenter will have informed the participant in advance to wear a facemask upon arrival at the PdlC.
4	The reception will ask the participant to disinfect his/her hands and to wait in the hall, thereby making sure they do not obstruct any pathways.
5	The reception will contact the researcher by phone.
6	The researcher will pick up the participant directly and introduce him-/herself, after which they administer the Questionnaire COVID-19-screening Leiden University.
7	The participant can be taken to the lab only if every question was answered with “NO”.
8	Enroute to the lab and until the participant is seated in a laboratory cubicle, the experimenter will ensure that the participant keeps his/her mask on.
9	After conducting the study, the researcher will accompany the participant to the exit. The participant is signed out at reception.

10	At the end of the study, the researcher will make sure the lab is cleaned properly. He/She will also sign out at the reception upon leaving the PdlC building.

Note. The table shows the steps of the behavioral protocol, put in place by the Safety, Health, and Environment Department (VGM) of Leiden University for research during the global COVID-19 pandemic.

Table 2

COVID-19 Research Checklist

Action	Time	Initials
Before participant is in		
Set sliding sign on door to occupied		
Tidy up the laboratory		
Check the necessary devices, leads, and electrodes for visible damage		
Check the settings and if necessary, the battery life of the device		
Switch on the monitors before switching on the computers		
Open the necessary software and check the communication for all devices		
Place paper towels on the table to collect rubbish and gel		
Ensure all necessary supplies are set out (masks, gloves, disposable electrodes, gel, NuPrep, cotton wool, etc.)		
Ensure that a logbook is available for noting down particulars		
Put out the Informed Consent form ready to be read and signed		
Take your research protocol and follow all instructions step by step		
As soon as you are ready, you can receive the participant and carry out the study		
When participant is in		
Ensure that you continue to work hygienically and safely throughout the study		

After a participant has left
Open all doors and windows to ventilate the room for minimal 10 minutes
Throw away all disposables
Clean the following items in the lab with Wecoline Blauw: Doors and door handles, desks, chairs, headphone, keyboard, mouse, monitor, switches from light/airco/heater and pens.
Close all doors and windows after10 minutes of ventilation
At the end of your research day
Switch off the devices
Tidy up all participant paper-and computer data
Tidy up the lab and control room
Ensure that no personal data is left behind on the computers in the lab
Clean the following items in the control room with Wecoline Blauw: Doors and door handles, desks, chairs, headphone, keyboard, mouse, monitor, switches from light/airco/heater and pens.
Set sliding sign on door to free and clean with Wecoline Blauw
Lock the door

Note. This research checklist was put in place by SOLO to ensure the fulfillment of the COVID-19 research and cleaning protocol. Except for fitting a new pair of hygienic single-use headphone covers before every participation, it comprises all components of the research protocol that took place inside the laboratory. The time and initials of the executing researcher had to be filled in for every step. At the end of every testing day, it had to be handed in at SOLO's office.