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ORIGINAL RESEARCH

Effects of 5 Hz Auditory Beat Stimulation on Mind Wandering and Sustained Attention in an Online Experiment

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Abstract

Mind wandering (MW) can undermine productivity, affect mood, and even pose potential dangers. Selectively reducing MW during specific tasks would therefore be desirable. This study explored auditory beat stimulation (ABS) to reduce MW and increase sustained attention. In an online experiment with 541 participants, we applied ABS (binaural or monaural presentation, pure tones at 437.5 Hz and 442.5 Hz) during the sustained attention to response task (SART) while employing experience sampling probes to monitor MW. We used two control conditions: no sound and uniform pure tone at 440 Hz. Additionally, we implemented three experimental manipulations aiming at increasing the MW frequency during the SART (length of SART inter-stimulus interval, sequence of SART stimuli in ascending or random order, and expectancy of a creativity task after the SART). ABS did not significantly impact the frequency of reported MW or SART % NOGO success. Of the three additional manipulations only the sequence of SART stimuli led to a significant difference in reported MW and SART % NOGO success. We found no substantial evidence for 5 Hz ABS as a universal strategy to reduce MW or increase sustained attention during the SART.

Keywords Self-generated thought · Daydreaming · Auditory beat stimulation · Binaural beats · Monaural beats · Mind wandering · Attention

Introduction

Have you ever read a paragraph only to realize you can't recall its contents because your mind had wandered off and entertained itself with something else? Our minds are prone to occasionally veer off course instead of focusing on the task at hand. In fact, when asked at random times during the day, people report mind wandering (MW) in a third to half of all cases (Kane et al., 2007; Killingsworth & Gilbert, 2010). While MW is a natural part of our cognitive processing, excessive MW can compromise task performance and is even associated with negative mood states. This study explores the potential use of auditory beat stimulation (ABS)—a non-invasive cognitive intervention that has been reported to affect cognition and mood—to regulate MW in an online experiment.

MW (also related to the terms daydreaming, attentional lapses, self-generated thoughts, and task-unrelated thoughts) was defined as "a shift in the contents of thought away from an ongoing task and/or from events in the external environment to self-generated thoughts and feelings" (Smallwood and Schooler 2015, p. 488) We are thus mind wandering whenever we divert our conscious attention away from the task at hand and events in our surroundings. Our minds can wander to the past by remembering, or to a possible future by concocting plans and imagining potential scenarios.

Mindfulness, in contrast, seems to lie on the opposing side of a spectrum of attention (Belardi et al., 2022; Smilek et al., 2010). While MW steers our attention away from the present moment, mindfulness practice aims to keep it there. In a common form of mindfulness practice, the idea is to point our attention to an object of focus in the present moment, e.g., the physical perceptions of our breath. In line with this idea, Jon Kabat-Zinn, who brought mindfulness practice to a growing audience in the western world with his Mindfulness-Based Stress Reduction (MBSR) program, described mindfulness

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as "awareness that arises by paying attention on purpose, in the present moment, and non-judgmentally" (Kabat-Zinn 2013, loc. 395)

Considering this dichotomy between MW and mindfulness, attention in the field often centers on the detriments of MW and the benefits of mindfulness. This focus is understandable due to the huge negative consequences MW can have when occurring in the wrong situation. It can impair our productivity when we require focused attention (Smallwood & Andrews-Hanna, 2013), decrease our mood (Killingsworth & Gilbert, 2010), or influence our caring behavior (Jazaieri et al., 2016). In the worst case, MW can be downright dangerous, e.g., when driving (Yanko & Spalek, 2014), operating heavy machinery (Di Nocera et al., 2018), or working in any other environment where small mistakes due to inattention can be fatal, such as in medical professions (Smallwood et al., 2011).

However, MW should not be viewed solely as a source of negative outcomes. Creativity and future problem-solving skills have been positively associated with MW (Leszczynski et al., 2017; Smallwood & Andrews-Hanna, 2013). Furthermore, considering the common tendency of our minds to engage in MW over staying in the present, this phenomenon may also provide evolutionary benefits (Smallwood & Andrews-Hanna, 2013). Despite these benefits, the potential harms of MW cannot be overlooked.

Therefore, it becomes crucial to explore strategies that can help us achieve a balance: staying present when needed, yet allowing our minds to wander when beneficial. Smallwood and Schooler (2015) proposed three methods to mitigate the negative effects of MW: mindfulness training, cultivating meta-awareness, and task engagement. Although these strategies hold promise, they require conscious cognitive effort and potentially extensive training before being effective. Therefore, immediate, more passive methods that could help reduce MW would be especially desirable.

Auditory beat stimulation (ABS) is a non-invasive cognitive intervention which was suggested for neuroenhancement in general, but also particularly to decrease MW (Chaieb & Fell, 2017; Chaieb et al., 2015; Fell, 2018). Participants hear two tones at different frequencies, either one on the left and the other on the right ear (binaural), or both on both ears simultaneously (monaural). The two tones are slightly shifted in frequency. This leads to a phenomenon called *binaural beats* or *monaural beats*, because participants perceive a beating sound at the frequency near to the difference between the two shifted frequencies they hear (Fritze, 1985).

The underlying neurophysiological processes behind these two differ. Binaural beats are assumed to originate in the superior olivary nuclei, where neurons sensitive to phase shifts between signals from both ears start to fire depending on the phase differences. Monaural beats in contrast are created by a composite signal of two frequencies and were explained to originate more peripherally, since they are detected at the cochlear level (Chaieb et al., 2015; Draganova et al., 2008). The predominant mechanism to explain how binaural beats could elicit psychological effects is the *brainwave entrainment hypothesis*, which posits that auditory stimulation at a specific frequency in turn lets the electrocortical activity to oscillate at the same frequency (Huang & Charyton, 2008). Since certain frequency bands in the EEG are associated with different psychological states and cognitive processes, ABS lends itself as a procedure to target such states and processes (for a recent review, see Ingendoh et al. 2023).

ABS has consequently been the subject of extensive research that has examined its effects on various aspects of cognition and mood. While the findings are rather mixed, comprehensive reviews by Chaieb et al. (2015) and Garcia-Argibay et al. (2019) reported the promising potential of ABS to influence verbal memory, creativity, attention and sustained attention, and mood states. This supports the potential applicability of ABS in mitigating MW.

However, when it comes to the specific exploration of ABS in relation to MW, only a few studies have been published. In particular, for the combination of ABS and a *direct* measure of MW by experience sampling or thought probes, we identified only three studies: A pilot study by Chaieb et al. (2020), another one by the same research group (Chaieb et al., 2022), and one experiment in the study by Robison et al. (2022).

To assess the current state of findings regarding ABS in relation to MW, we thus looked a little further at ABS effects on sustained attention in general. To synthesize earlier research on the interplay of ABS and sustained attention, measures of which have sometimes been interpreted as *indirect* measures of MW, we performed a systematic review and meta-analysis of the literature. This encompassed previous publications that employed ABS and assessed its effects on sustained attention in between-subjects designs (Axelsen et al., 2020; Kennel et al., 2010; Kirk et al., 2019; Robison et al., 2022). We employed a fixed-effects model using a Restricted Maximum Likelihood (REML) algorithm. All effects were coded in the positive direction: an improvement in the attention task performance (e.g., faster reaction times, more correct trials) under the ABS condition compared to the control condition was interpreted as a positive effect. Our meta-analysis showed a small statistically significant effect of ABS on sustained attention but also revealed the large variance and mixed findings in previous studies (Cohen's d = 0.24, $95\% CI$ = [0.07; 0.40], $p = 0.0054$, 5 experiments in 4 studies, N = 594 participants, I^2 = 94%, indicating very high heterogeneity, see also Fig. 1).

Regarding these mixed findings in the previous literature, we investigated the potential effects of ABS on MW and sustained attention in a considerably large sample by conducting

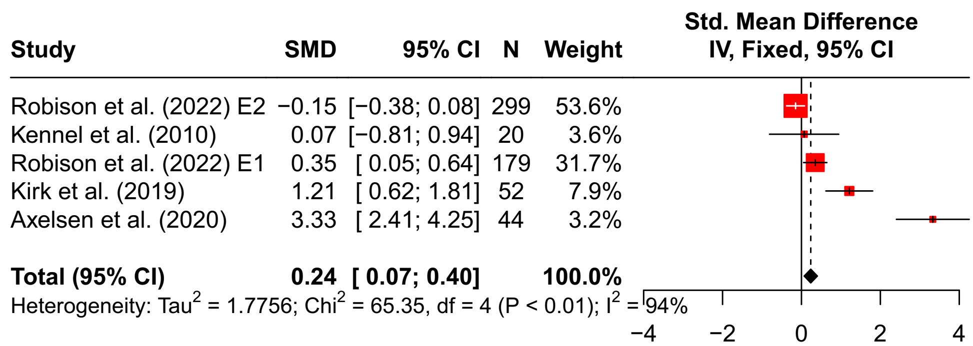


Fig. 1 Meta-analysis results for ABS effects on sustained attention. *Note.* SMD = Standardized mean difference; SE = Standard error

an online study in which participants performed the sustained attention to response task (SART) for 20 minutes while being exposed to ABS or a control condition. We used 5 Hz binaural or monaural beats (frequency pair: 437.5 and 442.5 Hz), a uniform sound control (440 Hz), and a no sound control. Our reasoning to use 5 Hz ABS was that stimulation with 5 Hz monaural beats was previously found to reduce intracranial EEG power and phase synchronization in the hippocampus and rhinal cortex (Becher et al., 2015) and the hippocampus has been associated with MW (Ellamil et al., 2016; O'Callaghan et al., 2019). Based on the finding that ABS was effective only for participants with high MW during baseline (Chaieb et al., 2020), we here thought to explore experimental manipulations to increase MW and by this conceptually generalize the findings of Chaieb et al. (2020). We therefore added three experimental factors intended to manipulate the frequency of MW occurrence, two which aimed at making the SART task more monotonous (longer SART ISI, ascending stimuli presentation in SART) and one which increased the urge to MW (expectancy of another creative task after the SART, which the participants already knew). We hypothesized that 5 Hz ABS decreases the frequency of self-reported MW and increases sustained attention measures and, in line with Chaieb et al. (2020), that this is even more pronounced in those conditions with increased MW due to our additional manipulations, leading to interactions of these manipulations with the ABS effect.

Methods

Participants

Participants were recruited from different sources for a German and English version of the experiment. A subset of the English-speaking participants were recruited through MTurk (mturk.com) and were hence paid for participation. All other participants were either not compensated or received course credits.

From an initial sample of 715, we removed participants before analysis due to our exclusion criteria as follows: Repeated participation (n = 11), incomplete data (n = 1), incomplete or very long duration of participation (experiment duration below 23 min or above 120 min [n = 59]), too few correct SART trials (proportion of correct GO trials below $\frac{2}{3}$ [n = 51], or proportion of correct NOGO trials below $\frac{1}{2}$ [n = 22]), and outliers in time to answer the ES probes (n = 30). For the outlier detection, we defined a cutoff based on the interquartile range (IQR), because the distribution of these values was highly skewed. The cutoff was set to 75th percentile plus three times the IQR. Data analyses were then based on the remaining sample of 541 participants (217 English-speaking, 324 German-speaking). Compensation for participation was not tied to whether a participant's data was included in the analyses, but solely on their participation in the experiment. These data were also used for a different publication that assessed questions related to validity and reliability of the SART as well as associations of MW measures derived from the SART with scores from a mindfulness trait questionnaire (Belardi et al., 2022).

We ran a sensitivity analysis to estimate the minimal detectable effect size for the two-way interactions of interest, given our design and sample size with 90% power and $\alpha = .05$) using G*Power (Faul et al., 2007, 2009). The estimation led to a minimal detectable effect size of $f = 0.162$ ($\eta^2 = 0.026$), which corresponds to medium to small effects sizes according to Cohen (1988).

The study was approved by the Ethics Commission of the Faculty of Psychology of UniDistance Suisse (https://unidistance.ch/en/research/ethics).

Research Design

We ran an experiment in a 4 × 2 × 2 × 2 between-subjects design with the four independent variables *Auditory Stimulation* (5 Hz binaural, 5 Hz monaural, 440 Hz pure tone, no sound), *SART inter-stimulus interval* (ISI, 1 or 2 s), *Sequence of Stimuli* (random or ascending), and *UUT Expectancy* (expected or unexpected). Participants were randomly allocated into one of the resulting 32 factor-level combinations (see Table 1. Our main interest was the assessment of two-

Table 1 Participant allocation to conditions

Auditory stimulation	*SART ISI*	*UUT expectancy*	*Sequence of stimuli*	*n*
Monaural 5 Hz	1 s	Not expected	Ascending	21
			Random	14
		Expected	Ascending	18
			Random	16
	2 s	Not expected	Ascending	17
			Random	15
		Expected	Ascending	17
			Random	15
Binaural 5 Hz	1 s	Not expected	Ascending	18
			Random	18
		Expected	Ascending	14
			Random	17
	2 s	Not expected	Ascending	20
			Random	16
		Expected	Ascending	20
			Random	16
No sound	1 s	Not expected	Ascending	18
			Random	16
		Expected	Ascending	19
			Random	20
	2 s	Not expected	Ascending	15
			Random	18
		Expected	Ascending	17
			Random	15
Uniform 440 Hz	1 s	Not expected	Ascending	16
			Random	17
		Expected	Ascending	17
			Random	19
	2 s	Not expected	Ascending	15
			Random	15
		Expected	Ascending	15
			Random	17

way interactions of ABS with the three other factors that were hypothesized to increase MW (Sequence of Stimuli, UUT Expectancy, ISI). By focusing only on main effects and two-way interactions our sample was large enough to detect medium-sized effects in a between-subjects ANOVA.

Auditory Stimulation was the main intervention in this experiment with four conditions, two ABS conditions and two control conditions. In the ABS conditions, we used pure sine waves at frequencies 437.5 Hz and 442.5 Hz to create a 5 Hz beat either in a binaural setting (one frequency to either ear) or in a monaural setting (both frequencies played simultaneously to both ears). For the control conditions, we used a pure 440 Hz tone and no sound.

We implemented three additional manipulations that aimed at increasing the frequency of MW by making the SART more monotonous and boring or increasing the urge to MW. First, we set the ISI in the SART stimuli presentation to either 1 or 2 seconds (*SART ISI*). One second is already longer than in the original SART (where it was 900 ms). Second, we presented the SART stimuli either randomly as they are in the original SART, or in ascending numerical order (*Sequence of Stimuli*) as done previously by Smucny et al. (2013). The idea was that the ascending stimuli presentation would make the SART highly predictable and prone to induce more MW, because participants would need less attention to be able to complete the task. Third, we manipulated whether the participants expected the repetition of a creativity task at the end of the experiment or not (*UUT Expectancy*). Before the SART, participants did an Unusual Uses Task (UUT) and depending on the condition, they were either told that they would have to come up with more alternative uses after the SART, or they were not told about a repetition of the task later.

The dependent variable (DV) to assess MW directly comes from experience sampling (ES) probes during the SART, and is defined as the proportion of probes in which a participant answered that their attention had been off task. Several measures from the SART have previously also been used as indirect measurements of MW. Among them are performance measures like the proportion of correct NOGO trials, referred to as *SART % NOGO success* (e.g., Axelsen et al., 2020; Kirk et al., 2019), or the standard deviation (SD) of reaction times (RT) in SART GO trials (e.g., McVay and Kane, 2009, 2012). While our focus was on the direct MW measure, we also ran the same analyses on these two sustained attention measures. We report the results for the SART % NOGO success in this publication as a measure that is directly comparable to those included in our meta-analysis; two of the four studies in our meta-analysis used this measure. The results for the SD of RTs can be found in the supplementary materials.

Materials

We created the experiment as an online experiment with the open-source JavaScript-based experiment builder "lab.js" (https://lab.js.org; Henninger et al., 2019; 2020). All tasks and questionnaires were implemented in this online experiment and all data was collected with it, running and saving data on a server running Linux Debian and Apache HTTP Server.

Sustained Attention to Response Task (SART)

The Sustained Attention to Response Task (SART) is a paradigm to measure sustained attention in a deliberately monotonous task requiring subjects "to self-sustain mindful conscious processing of stimuli whose repetitive non-arousing qualities would otherwise lead to habituation and distraction to other stimuli" (Robertson et al., 1997, p. 474). In this task, participants are asked to press a specific key whenever any digit is presented on the screen (GO trials), with the exception of when a specified target digit is presented (NOGO trials). If the target digit is presented, they should instead not press anything and just wait for the next digit to appear.

We implemented the SART with the following differences from the original: we displayed stimuli for 2 s (instead of 250 ms), had an inter-stimulus interval (ISI) of 1 or 2 s (instead of 900 ms), used a different mask (fixation cross instead of a ring with a diagonal cross), and we had the same font size and position of stimulus presentation instead of randomly different font sizes and varying position. These changes were implemented to make the task even more monotonous and boring, to elicit more MW. Figure 2 illustrates the SART and experience sampling procedures.

Experience Sampling to Assess MW

We assessed self-reported MW with experience sampling probes during the SART task (see also Fig. 2). In intervals randomized between 25 and 35 seconds, participants were asked: "Immediately before this question appeared, was your attention focused ON the task, or OFF task?" and participants had a dichotomous forced-choice option to answer. If participants answered that their focus had been *off* task, a second question assessing meta-awareness was prompted: "Were you aware that your attention was OFF task?". Again, participants had a dichotomous forced-choice answer option (yes or no).

Mindful Attention Awareness Scale (MAAS)

We also applied a measure for dispositional mindfulness, the Mindful Attention Awareness Scale (MAAS), which specifically focuses on everyday experiences (Brown & Ryan, 2003). The MAAS is a widely used self-report measure that consists of 15 items. Higher scores on the MAAS indicate greater mindfulness, characterized by enhanced attention and awareness in daily life. Prior research has established the reliability and validity of the MAAS. We reported the reliability of the MAAS in our two language-based subsamples of this study in a previous publication which also included the associations of MW and sustained attention measures and the MAAS scores (Belardi et al., 2022).

Unusual Uses Task (UUT)

We further included the Unusual Uses Task (UUT), also known as Alternative Uses Task, to assess participants' divergent thinking and creative problem-solving abilities. The UUT is a widely used measure of creativity that requires individuals to generate multiple unique uses for common objects within a limited timeframe (Runco & Acar, 2012). Participants are typically presented with a series of everyday objects and asked to produce as many alternative or unusual uses as possible for each object. We used the UUT only with one object here, "brick", and asked participants to come up with alternatives other than "building a house".

Procedure

In the online experiment, participants first read basic information about the experiment and how their data will be handled and gave their informed consent. They then answered a short demographic questionnaire and the MAAS. Next, they conducted a headphones test and the UUT, followed by 20

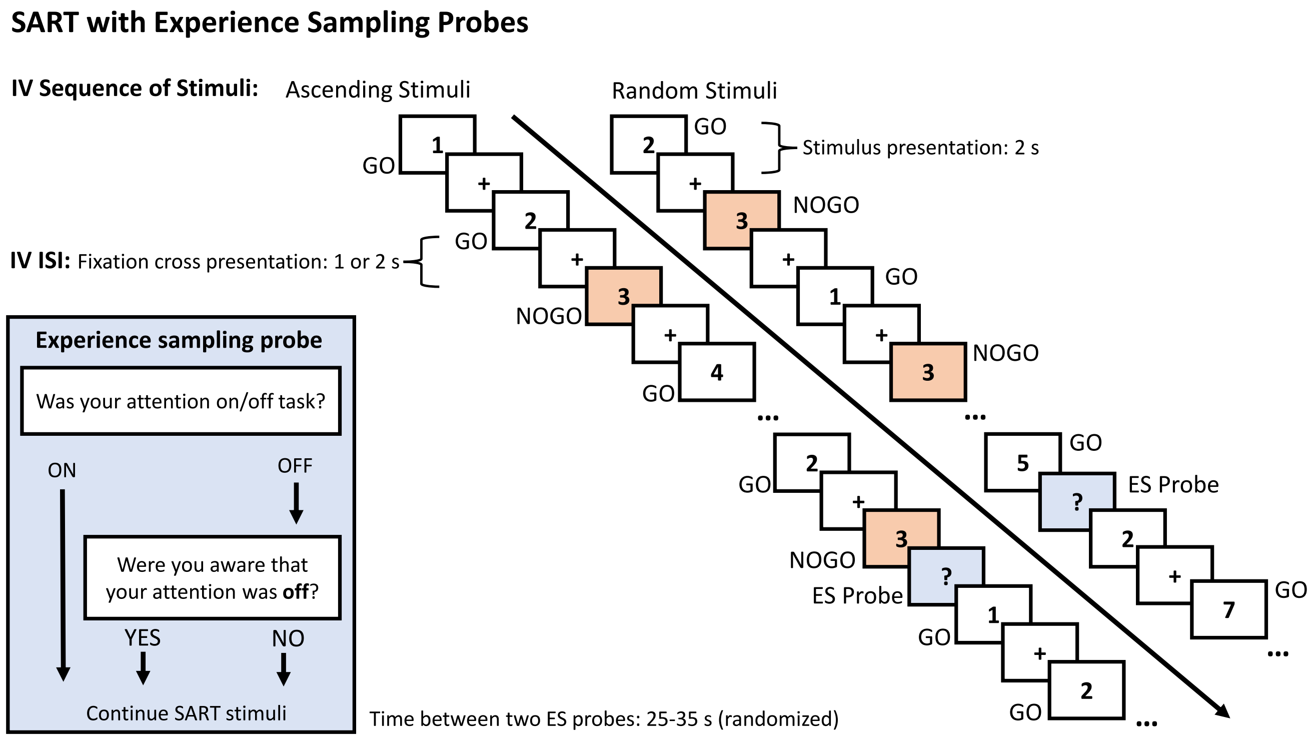


Fig. 2 SART with experience sampling probes. *Note.* Exemplary sequences of stimuli and ES probes during the SART, either with ascending or random stimuli presentation. The window on the left shows the MW ES probe and the additional meta-awareness question in case MW was reported. The target digit indicating NOGO trials is 3

min of the SART with ES. When the SART was finished, the participants repeated the same UUT. Finally, the participants could read more about the aims of the study in the debriefing information.

Data Analysis

We conducted an ANOVA with the four between-subjects IVs (Auditory Stimulation, SART ISI, Sequence of Stimuli, and UUT Expectancy) and the proportion of self-reported MW from the ES probes as DV. We included all main effects and two-way interactions, but left out any three-way interactions due to lack of power. For significant effects, we conducted additional Tukey post hoc tests. For effects from f-tests (ANOVA) we report partial η^2 as effect size measure and for t-tests (post hoc tests) Cohen's d. To account for multiple comparisons, we applied the Benjamini-Hochberg correction (Benjamini & Hochberg, 1995) and report both unadjusted (raw) and adjusted (corrected) p-values in the ANOVAs. For Tukey post hoc tests the reported p-values are adjusted values using the Tukey correction.

We did all data processing, data analysis, and results figure and table creation in R (R Core Team, 2022) using the following additional packages: "esc" (Lüdecke, 2019), "gridExtra" (Auguie, 2017), "jmv" (Selker et al., 2023), "meta" (Balduzzi et al., 2019), "metafor" (Viechtbauer, 2010), and "tidyverse" (Wickham et al., 2019).

Results

Self-reported MW

Overall, the mean proportion of ES probes in which participants reported that they were mind wandering ("off task") was 0.18 ($SD = 0.21$). The mean proportion of meta-awareness of MW was 0.71 ($SD = 0.32$). Figure 3 shows the descriptives of reported MW as distributions for each level of the four IVs.

The results of the ANOVA with self-reported MW as DV and the four between-subjects IVs (Auditory Stimulation, ISI, Sequence of Stimuli, UUT Expectancy), as well as their two-way interactions, are reported in Table 2. The only statistically significant main effect was that of Sequence of Stimuli for which Tukey post hoc tests ($t(522) = 3.76$, $p < 0.001$, $d = 0.32$) and Fig. 3 indicated more reported MW when the stimuli were presented in ascending order ($M = 0.21$, $SD = 0.22$) than in random order ($M = 0.15$, $SD = 0.19$). The interaction between Auditory Stimulation and Sequence was statistically significant in the initial analysis, but not sig-

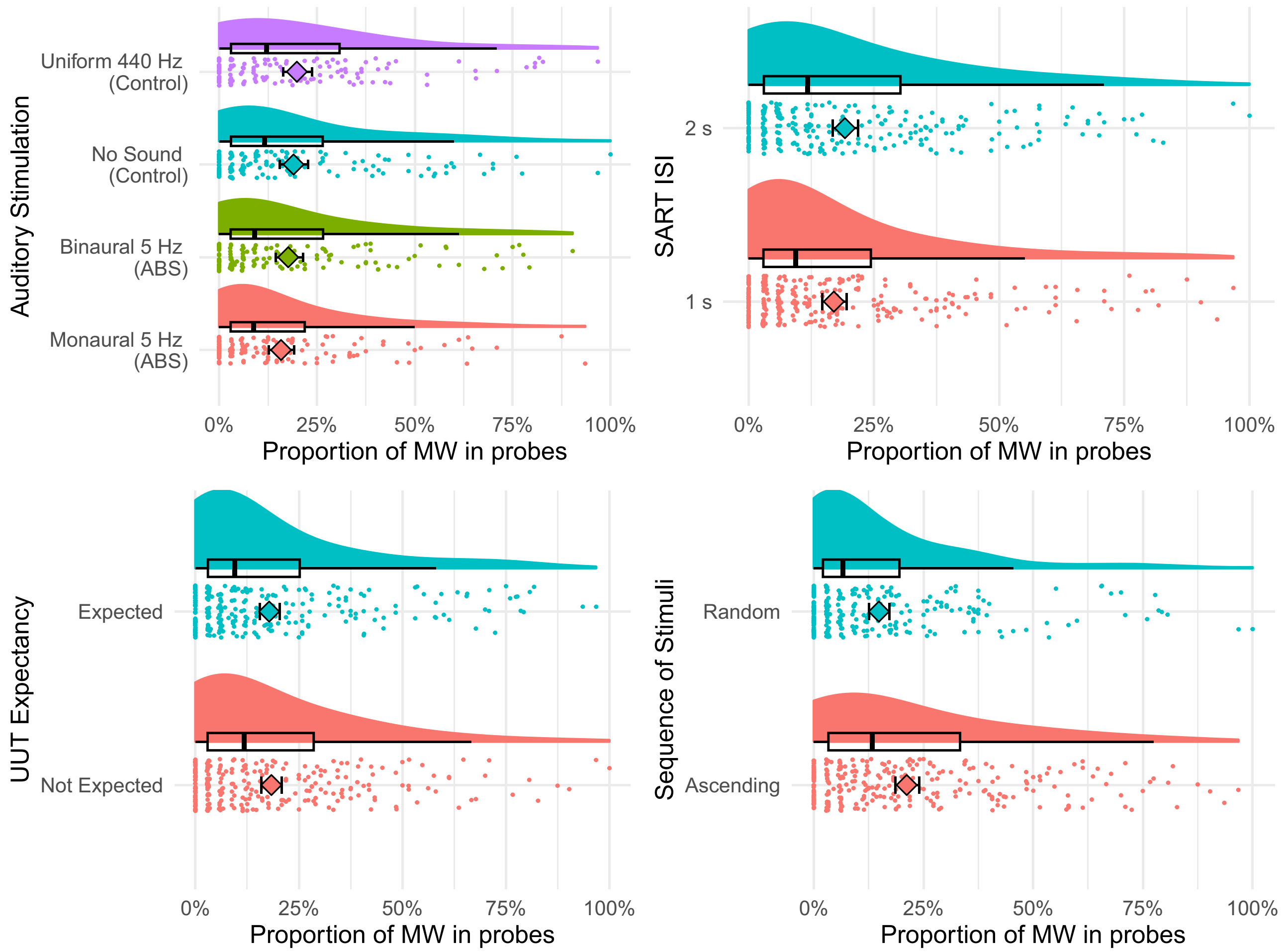


Fig. 3 Main effects of the four IVs on MW. *Note.* Error bars indicate 95% CI

nificant after correcting for multiple comparisons. Tukey post hoc tests indicated that less MW was reported for the two ABS conditions compared to the two control conditions if the Sequence of Stimuli was randomized ($t(530) = -3.243$, $p = 0.0069$, $d = -0.40$) but not when it was in ascending order ($t(530) = 0.77$, $p = 0.87$, $d = 0.092$). The reported MW proportions for the two ABS conditions were $M = 0.22$ ($SD = 0.23$) for the ascending Sequence and $M = 0.11$

Table 2 ANOVA with DV self-reported MW

Factor	*ss*	*df*	*ms*	*F*	*raw p*	*adj. p*[a]		η_p^2
Auditory stimulation	0.170	3	0.057	1.342	0.260	0.371		0.008
ISI	0.064	1	0.064	1.518	0.218	0.364		0.003
UUT expectancy	0.003	1	0.003	0.073	0.788	0.788		0.000
Sequence of stimuli	0.599	1	0.599	14.156	<0.001	0.002	**	0.026
Stimulation × ISI	0.104	3	0.035	0.819	0.484	0.604		0.005
Stimulation × UUT	0.048	3	0.016	0.381	0.767	0.788		0.002
ISI × UUT	0.175	1	0.175	4.128	0.043	0.142		0.008
Stimulation × Sequence	0.367	3	0.122	2.889	0.035	0.142		0.016
ISI × Sequence	0.074	1	0.074	1.754	0.186	0.364		0.003
UUT × Sequence	0.140	1	0.140	3.297	0.070	0.175		0.006
Residuals	22.106	522	0.042					

Note. [a]Adjusted p-values after multiple testing correction using the Benjamini-Hochberg method. η_p^2 = Partial eta squared. Statistical significance indicated as follows: *p<0.05; **p<0.01; ***p<0.001

($SD = 0.14$) for the random Sequence; for the control conditions they were $M = 0.20$ ($SD = 0.21$) for ascending and $M = 0.19$ ($SD = 0.22$) for random Sequence (see Fig. 4).

Because we found clear differences in reported MW in the two language-based subsamples of the study (see Belardi et al. 2022), we also ran the same ANOVA in these two subsamples. We report these in the supplementary materials to this publication. In summary, the main effect Sequence of Stimuli remains statistically significant in the German-speaking subsample, but the interaction effect between Auditory Stimulation and Sequence does not reach statistical significance in any of the subsamples despite the effect sizes of the effect being similar or even larger than in the whole sample. We based our interpretation of the findings on the results of the whole sample as reported above, because in looking at subsamples we halved our sample size and thus ended up with underpowered analyses.

SART % NOGO Success

The mean proportion of correct NOGO trials in the SART was 0.85 ($SD = 0.12$). The descriptives of this NOGO success rate for each level of the four IVs are shown in Fig. 5.

An ANOVA with the same four between-subjects IVs but SART % NOGO success as DV showed a statistically significant main effect of SART ISI and Sequence of Stimuli (see Table 3). The corresponding Tukey post hoc tests (SART ISI: $t(522) = 3.31$, $p < 0.001$, $d = 0.29$, Sequence of Stimuli: $t(522) = 3.21$, $p = 0.001$, $d = 0.28$) and Fig. 5 indicated higher NOGO success rates when the ISI was 2 s ($M = 0.864$, $SD = 0.110$) compared to 1 s ($M = 0.832$, $SD = 0.122$) and when stimuli were presented in ascending order ($M = 0.863$, $SD = 0.103$) compared to random order ($M = 0.832$, $SD = 0.128$). The interaction between Auditory Stimulation and Sequence was statistically significant but the pattern of results did not show a clear differentiation between the two ABS and the two control groups (see Fig. 6).

Discussion

In an online study, we investigated the effect of ABS on self-reported MW and sustained attention during a sustained attention task. Our hypothesis was that ABS would decrease the frequency of MW and increase sustained attention measures. We also examined three experimental manipulations aimed at increasing MW reports during the task. We anticipated that interactions with these manipulations would lead to a larger ABS effect in conditions with more MW.

Our findings, however, revealed no significant main effect of ABS on self-reported MW, in our sample of 541 participants. Across our four conditions of the ABS intervention (binaural beats, monaural beats, pure tone control, no sound control), MW frequency ranged between 15.8% and 19.9% of the experience sampling probes, though they differed hugely between the two subsamples (as reported in Belardi et al. 2022). In comparison, previous studies conducted under laboratory conditions usually reported higher MW frequencies.

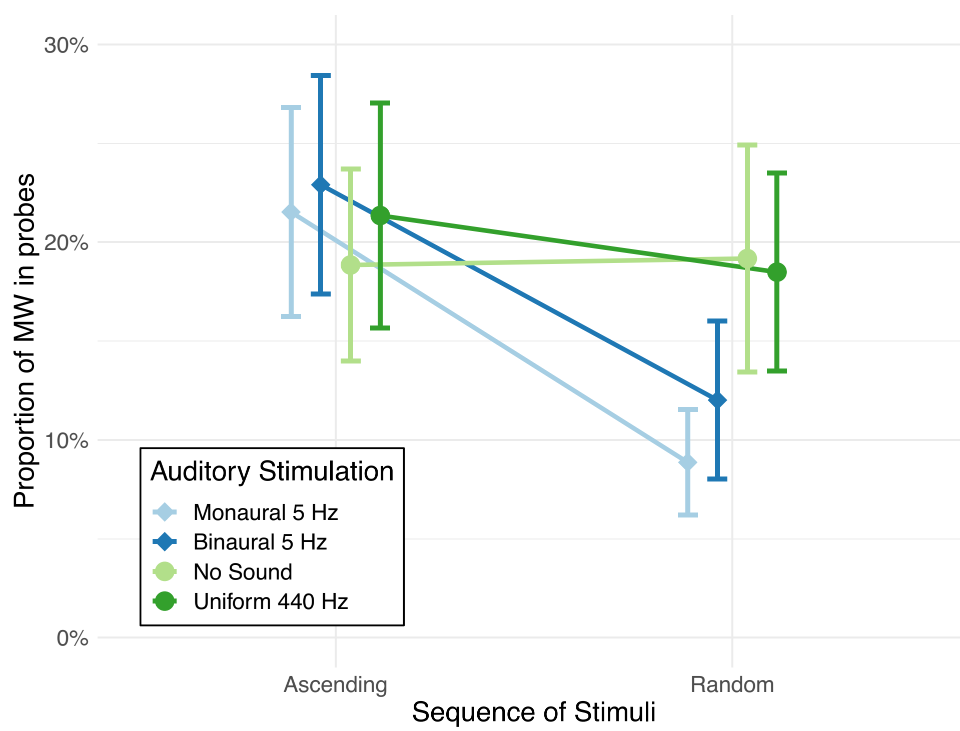


Fig. 4 Interaction of auditory stimulation and sequence of stimuli for MW. *Note.* Error bars indicate 95% CI

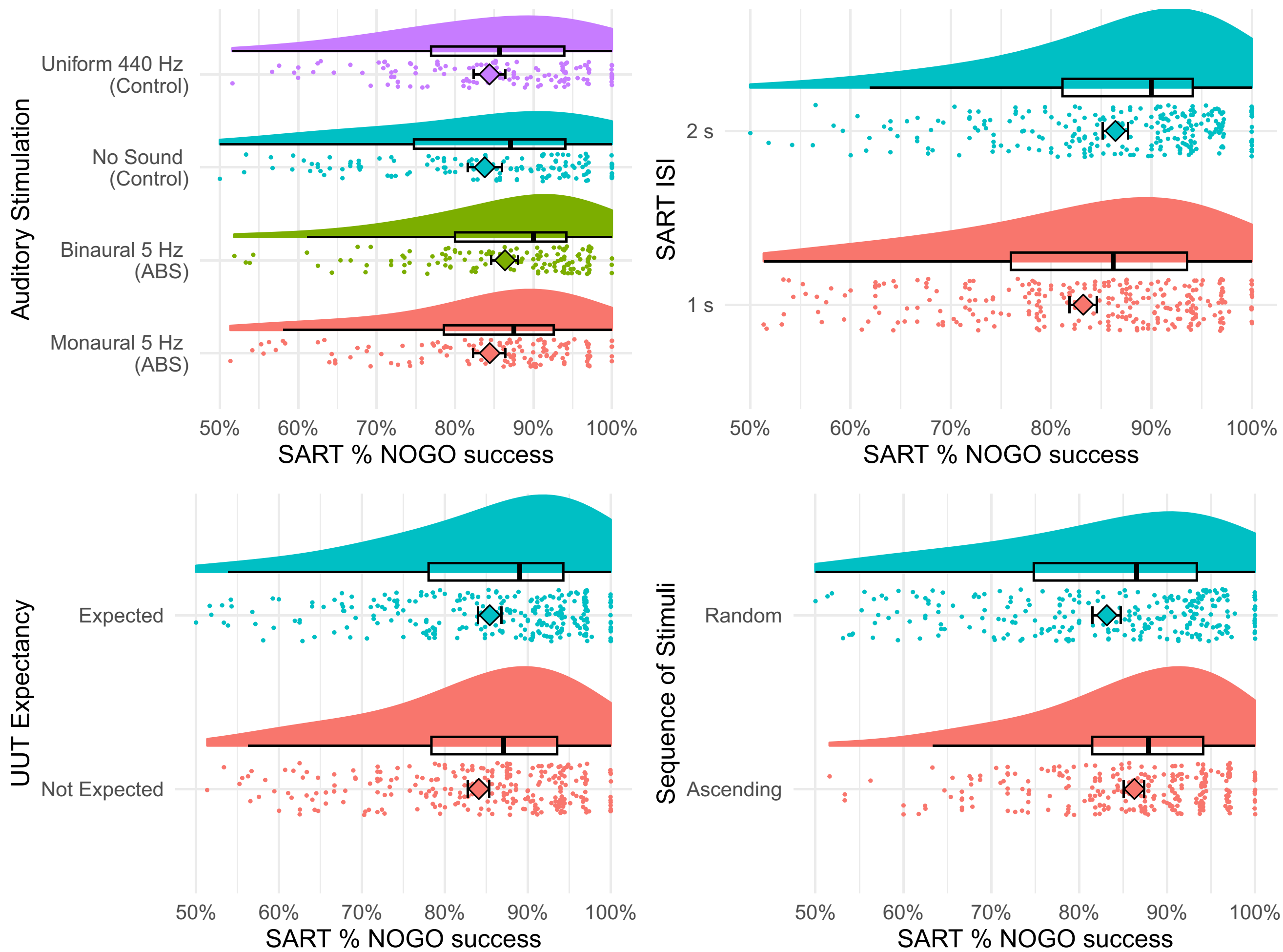


Fig. 5 Main effects of the four IVs on SART % NOGO success. *Note.* Error bars indicate 95% CI

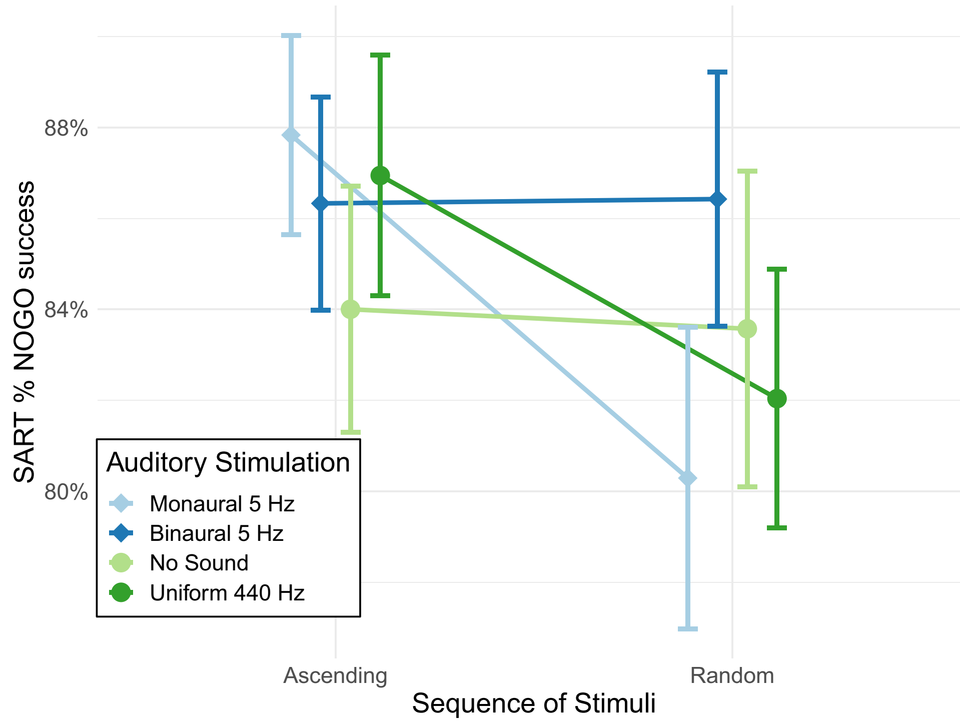
For instance, some found similar or slightly higher frequencies: 18.5% (Nayda & Takarangi, 2021), 21% (Unsworth & McMillan, 2014), 22.4% (Deng et al., 2014). Others reported much higher frequencies: around 40% (Chaieb et al., 2020), 51% (Kane et al., 2016), and 55% (McVay & Kane, 2009).

Table 3 ANOVA with DV SART % NOGO success

Factor	*ss*	*df*	*ms*	*F*	*raw p*	*adj. p*[a]		η_p^2
Auditory stimulation	0.052	3	0.017	1.333	0.263	0.479		0.008
ISI	0.144	1	0.144	10.986	0.001	0.007	**	0.021
UUT expectancy	0.032	1	0.032	2.484	0.116	0.289		0.005
Sequence of stimuli	0.135	1	0.135	10.325	0.001	0.007	**	0.019
Stimulation × ISI	0.017	3	0.006	0.441	0.724	0.724		0.003
Stimulation × UUT	0.034	3	0.011	0.878	0.453	0.503		0.005
ISI × UUT	0.013	1	0.013	0.976	0.324	0.479		0.002
Stimulation × Sequence	0.146	3	0.049	3.737	0.011	0.037	*	0.021
ISI × Sequence	0.012	1	0.012	0.884	0.348	0.479		0.002
UUT × Sequence	0.010	1	0.010	0.761	0.383	0.479		0.001
Residuals	6.819	522	0.013					

Note. [a]Adjusted p-values after multiple testing correction using the Benjamini-Hochberg method. η_p^2 = Partial eta squared. Statistical significance indicated as follows: *p<0.05; **p<0.01; ***p<0.001

Fig. 6 Interaction of auditory stimulation and sequence of stimuli for SART % NOGO success. *Note.* Error bars indicate 95% CI



We also found no significant effects for two of the three additional manipulations aimed at increasing MW frequency during the SART. However, we did find a significant effect for the manipulation Sequence of SART stimuli, with more reported MW when the stimuli sequence was predictable ("ascending") compared to unpredictable ("random").

The effect of Sequence led to a mean difference of 6.7% in MW reports (Tukey post hoc test: $t(522) = 3.76$, $p < 0.001$, $d = 0.32$). The other manipulations that aimed at increasing MW reports did seemingly not work as intended. We found no statistically significant differences in MW reports across the groups with varying ISI or with different expectations about a repetition of the UUT.

The Sequence effect initially showed a significant interaction with ABS that no longer reached significance after correction for multiple comparisons. Despite this, the observed pattern of results from the post hoc tests is noteworthy, because they contradict our hypothesis on such interactions. The group differences of ABS emerged only in the Sequence condition with *less* MW, where stimuli were presented randomly. We had expected to find stronger ABS effects in conditions with more MW, as in Chaieb et al. (2020) where only participants who reported above-median frequencies of MW during silence showed ABS effects. This discrepancy might be related to varying sources for the increased frequency of MW. Chaieb et al. (2020) split their sample on the median of the naturally occurring MW frequency and then found ABS effects in participants who had reported most MW. In our case, we manipulated the task to lead to more MW. The Sequence manipulation, however, also changed the task so that it is not directly comparable to a regular SART anymore. The predictability of the number sequence meant that participants no longer needed to monitor the individual digit stream constantly. Instead, they could just count the number of items presented until they had to withhold a button press again, for every predictable presentation of the NOGO stimulus.

Regarding the sustained attention measure SART % NOGO success, which has been used as an indirect measure for MW, we similarly found no significant main effect of ABS. But regardless of statistical significance, we wanted to know how our data compared to the previously reported effects of ABS on sustained attention. How did our findings compare to those reported in the meta-analysis in the introduction? To explore this, we added the result from the post hoc test for a similar comparison to those included in the meta-analysis and ran the meta-analysis again including our findings. The comparison we used was: both ABS conditions (monaural and binaural) vs. both control conditions (no sound and uniform 440 Hz); Tukey post hoc test results: $t(530) = 1.12$, $p = 0.26$, $d = 0.096$. This resulted in the following new meta-analytic effect of ABS on sustained attention measures: Cohen's $d = 0.17$, $95\% CI = [0.05; 0.29]$, $p = 0.0057$, 6 experiments in 5 studies, $N = 1135$ participants, $I^2 = 93\%$. The initial meta-analytic effect before our study was: Cohen's $d = 0.24$, $95\% CI = [0.07; 0.40]$, $p = 0.0054$, 5 experiments in 4 studies, $N = 594$ participants, $I^2 = 94\%$. Thus, altogether our ABS effect on sustained attention was not far off from previous studies, especially when we focus on those studies with reasonably large sample sizes (>100). However, this comparison only goes so far, because we used ABS with 5 Hz beats (theta) while these other studies used beat frequencies of 14 to 16 Hz (beta frequency band).

Results for the three additional manipulations aimed at increasing MW frequency during the SART, showed a significant effect for the two manipulations SART ISI and Sequence of SART stimuli. Participants showed higher SART % NOGO success when the ISI was 2 s compared to 1 s and when the stimuli were presented in ascending order compared to random order.

The interaction between Sequence and ABS was again significant in the ANOVA, but the pattern of results was inconclusive. There was no clear distinction between the control and ABS conditions in either of the conditions of Sequence.

Our findings add to the growing literature of ABS investigations combined with sustained attention and/or direct MW measures, where previous results have been mixed. Our study benefits from a larger sample size (over 500 participants) compared to earlier studies, almost matching the combined N of the four studies we included in the initially reported meta-analysis. In comparison with these earlier findings, our data delivers further evidence that the effect of ABS in sustained attention tasks or MW might be rather small and thus of little practical use in this form and with the applied frequency pairs. Although our results do not provide robust support for ABS to reduce MW meaningfully, the data suggests potential differences emerging within specific circumstances. Notably, with random SART stimuli—as in the regular SART paradigm—participants in the ABS conditions reported MW in approximately 10% fewer probes than those in the control conditions. However, this finding did not lead to a statistically significant interaction effect after correction for multiple comparisons. Furthermore, even if future research could substantiate such findings in specific circumstances, a 10% decrease in MW frequency might not be enough in situations where MW can be dangerous.

Despite these valuable insights from our study, it is important to acknowledge the limitations that may have influenced our results and interpretations. These considerations provide suggestions for improvement in future research. First, to generalize the findings of Chaieb et al. (2020) that ABS only works in participants with high MW, we attempt to induce more frequent MW during the SART with our additional manipulations. Only one of the three manipulations increased MW as expected (Sequence of Stimuli, predictable > unpredictable). This might indicate that our natural tendency to MW is not as easily manipulated, e.g., that simply having more time for individual trials in the SART (ISI length manipulation) does not affect our general attentiveness to a certain task. Other factors like individual differences between the participants might influence the propensity to MW more heavily. The manipulations might also have been too subtle, e.g., in the UUT expectancy manipulation. In this case, participants had already done the UUT task, so they might already have exhausted their answers for this task, and there were no stakes for them to come up with additional answers after the SART. Changing the object for which participants will have to find alternative uses for the expected task after the SART might help because then participants would have a new task to ponder while doing the attention task.

Second, we used a dichotomous selection in our ES ("on task", "off task") to measure MW. This approach comes with certain limitations because the wording and options in the MW ES probes can substantially influence the proportion of reported MW, as discussed in a review on ES in MW experiments (Weinstein et al., 2018). Indeed, framing effects in ES probes can lead to bias in the MW responses. A recent study investigated this framing effect empirically (Weinstein, 2018) and found that the way MW ES probes were framed affected the reported instances of MW. Such framing effects might partially explain the vast differences in MW frequencies reported across studies, as mentioned earlier. Future research might consider using various types of MW ES probes to capture a more nuanced view of MW and mitigate the potential framing effects. It could also be beneficial to test and validate different types of ES probes against objective measures of MW to better understand the relationship between probe type and MW reports. However, objective assessment of MW comes with its own set of challenges. For example, an approach like eye-tracking usually requires specialized equipment and controlled experimental conditions, which are not typically feasible for online studies. Consequently, this restricts the potential sample size and can lead to statistical power issues due to smaller sample sizes. Recent research to use webcams for eye-tracking, however, might be promising to counter this problem. While gaze location is less precise with this approach than when using special equipment, it might be powerful enough to assess MW: Hutt et al. (2023) for example describe their application of the open-source JavaScript tool WebGazer (Papoutsaki et al., 2016) to detect MW in a reading task and report a precision of up to 0.36 ($Kappa = 0.15$, and $F_1 = 0.25$). That is not far off what others found when using commercial eye-tracking, e.g., Bixler et al. (2015) reported a Kappa of 0.19.

Third, since this experiment was conducted online without live monitoring by an experimenter, we had no control over the participants' compliance with the procedure regarding any activity that was not directly recorded in the experiment, e.g., whether they wore the headphones during the whole experiment and kept the volume constant. Participants had to pass a headphones test during the experiment before the

SART task started, to ensure the volume was sufficiently high to identify nuanced sound differences. Repeating such tests during the SART or including an additional auditive monitoring task might help to overcome this issue.

Fourth, other possible control conditions for ABS could further support future investigations. We used a uniform tone at a frequency between the frequency pair of our beat stimulation as an active control condition and a no sound passive control condition. White or pink noise is frequently used as alternative for an active control condition, which can also be used to mask the main ABS experimental conditions, so as to ensure that any potential effects of the noise itself are equally present in all conditions, as discussed in Engelbregt et al. (2019) and Garcia-Argibay et al. (2019). The heterogeneity of control conditions applied in the field and whether or not binaural beats are masked with another signal or presented pure are issues raised in the recent review on binaural beats and brainwave entrainment by Ingendoh et al. (2023).

Future research could further focus on large-scale studies, potentially online, to investigate the specific task characteristics necessary for ABS interventions to influence MW. It could also potentially identify participants' characteristics that make them more or less suitable to profit from such interventions. Eventually, it is also needed to explore the real-world applications for these interventions, which would necessitate going beyond standardized attention tasks and implementing the interventions in more applied settings, e.g., in a driving simulation. This could also include the development of ABS sounds that are more comfortable to listen to than the pure sine tones used in this study. Our own experience and feedback from participants showed us that the ABS intervention in the current experimental form can be rather annoying and is not something most people would voluntarily listen to for a prolonged time. Combining ABS with music could be a promising direction.

In conclusion, we did not find substantive support for the use of ABS to reduce self-reported MW or increase sustained attention measures during a sustained attention task. We observed a noteworthy pattern of results, which was however not confirmed statistically after correcting for multiple testing: Fewer MW reports in the two ABS conditions compared to the two control conditions when stimuli were presented randomly (as in the original SART) but not when presented in a predictable order. It thus might be worth exploring whether under such specific circumstances, 5 Hz ABS still holds the potential to reduce MW. These circumstances might be rather task-specific and the size of the reduction rather limited. For real-world applications, it would then be necessary to pinpoint these circumstances, investigate the transfer to real-world settings and tasks, and develop ABS sounds that are not just effective in lowering MW frequency, but also pleasant enough to be of practical use.

Supplementary Materials

Supplementary materials for this publication are available at: https://osf.io/gfkp6.

Author Contributions Using the CRediT contributor roles taxonomy (casrai.org/credit/). A.B.: conceptualization, data curation, formal analysis, investigation, methodology, project administration, software, validation, visualization, writing—original draft, writing—review and editing. L.C.: conceptualization, resources, writing—review and editing. J.F.: conceptualization, writing—review and editing. N.R.: resources, writing—review and editing. T.P.R.: conceptualization, resources, formal analysis, investigation, methodology, project administration, software, validation, supervision, writing—original draft, writing—review and editing.

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Data Availability The datasets for this study are available at https://osf.io/wg9q5

Declarations

Ethics Approval The study was approved by the Ethics Commission of the Faculty of Psychology of UniDistance Suisse (https://unidistance.ch/en/research/ethics). Procedures involving human participants were carried out in accordance with the 2002 Ethical Principles of Psychologists and Code of Conduct by the American Psychological Association (https://www.apa.org/ethics/code/) and the 1964 Declaration of Helsinki by the World Medical Association and their later amendments.

Consent to Participate All participants gave their informed consent to participate in the study.

Conflict of Interest The authors declare no competing interests.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process During the preparation of this work the authors used generative AI and AI-assisted technologies to improve the readability and language of the manuscript. Particularly, we used Prowritingaid.com and ChatGPT (GPT-4). After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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