Improving Attention Using Wearables via Haptic and Multimodal Rhythmic Stimuli

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Figure 1: *Left*: Study 1 setup where participants received combinations of rhythmic light, sound, and haptic stimuli at 10 and 40 Hz from an audiovisual glasses device and haptic wristband. *Right*: In Study 2, participants tested the variable and fixed frequency haptic stimulation and no stimulation condition in-the-wild with the Fitbit smartwatches.

ABSTRACT

Rhythmic light, sound and haptic stimuli can improve cognition through neural entrainment and by modifying autonomic nervous system function. However, the effects and user experience of using wearables for inducing such rhythmic stimuli have been under-investigated. We conducted a study with 20 participants to understand the effects of rhythmic stimulation wearables on attention. We found that combined sound and light stimuli from a glasses device provided the strongest improvement to attention but were the least usable and socially acceptable. Haptic vibration stimuli from a wristband also improved attention and were the most usable and socially acceptable. Our field study (N=12) with haptic stimuli from a smartwatch showed that such systems can be easy to use and were used frequently in a range of contexts but more exploration is needed to improve the comfort. Our work contributes to developing future wearables to support attention and cognition.

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CCS CONCEPTS

• **Applied computing** → *Consumer health*; *Psychology*; • **Human-centered computing** → **Ubiquitous and mobile computing**; **Ubiquitous and mobile computing systems and tools**; **Empirical studies in ubiquitous and mobile computing**; **Haptic devices**; *Sound-based input / output*; **Empirical studies in HCI**.

KEYWORDS

haptics, entrainment, brainwave entrainment, attention, smartwatch, audio-visual entrainment, sustained attention to response task, user study, field study, cognitive enhancement, attention enhancement, neuroscience, cognitive psychology

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1 INTRODUCTION

Rhythmic stimuli like light, sound and haptics can modulate brain function and improve cognitive processes like attention [3, 12, 48, 63]. While existing approaches have mostly used non-wearable or highly specialized devices, wearable devices like smartwatches and smart glasses could potentially be used to deliver rhythmic stimuli, and modulate brain function.

This approach offers a number of exciting possibilities: first, commercial wearables that are already widely deployed and socially acceptable [16, 53] could be used to deliver cognitive enhancement interventions with a simple software download, allowing easy distribution of these interventions. Second, because they are almost always present on the user's body, wearables can be easily activated to provide cognitive enhancement whenever the user needs it, and can potentially even automatically detect when stimulation is needed.

In this study, we opted to focus on improving attention with rhythmic stimulation wearables. Attention can be defined as the ability to selectively allocate cognitive resources to a particular internal or external entity [43], and it is a critical cognitive function in everyday life [11]. While many approaches have been developed to improve attention, failures of attention still represent a major burden on society; for example the majority of traffic accidents involve attention failures [64]. Wearable devices which are built to be safe, unobtrusive, and usable in many different situations are a promising potential way to address some of these unmet needs.

A successful device must be effective, easy to use, socially acceptable, and comfortable. To date, the effectiveness and user experience of wearable rhythmic stimulation for attention has not been well investigated. As such, this work aims to answer two research questions as follows.

- **RQ1**: What are the effects of different combinations of light, sound, and haptic rhythmic stimuli on attention and user experience?
- **RQ2**: What are the user perceptions of various haptic stimulation protocols from smartwatches and their effects on the perceived effectiveness in improving attention in-the-wild?

For RQ1 we aimed to investigate the effects of a wide range of stimuli and modalities, while RQ2 focused on haptic stimulation (which we considered most promising after the results of Study 1).

To investigate RQ1, we conducted a study with 20 participants who wore an audiovisual glasses device and a haptic wristband that provided various combinations of stimuli while doing a computerized attention task. The findings from this first study indicated that auditory, audiovisual, and haptic stimuli improved attention and haptic stimulation was the most usable and socially acceptable of the combinations tested. To further study haptic stimulation and to develop a practical way to implement the technique in-the-wild, we conducted a follow-up field study that investigated RQ2. The study showed that haptic stimulation from smartwatches was easy to use and users used the system frequently in a range of contexts. The results suggest the need for further exploration into improving comfort in rhythmic stimulation.

In summary, this paper contributes with empirical findings, in lab and real-world settings, to how multimodal rhythmic stimulation from wearables affects attention as well as the associated usability ratings, comfort levels, and social acceptability of using such devices. This work also contributes with implementation details of rhythmic stimulation protocols on head-worn and wrist-worn devices for enhancing attention.

2 RELATED WORKS

Our work builds upon previous studies on the effects of rhythmic stimuli and wearable interfaces on cognition and user experience. A large amount of previous work has focused on using rhythmic stimuli to improve cognitive function. However, only a few have focused on attention, especially in the form of a wearable device that can be used while performing an attention-demanding task.

2.1 Measuring attention

Attention involves a number of distinct processes which can be measured separately [31]. However, it is also possible to describe overall attention function, often referred to as vigilance–the ability to perform a task while avoiding lapses and failures of attention [51].

Vigilance is most commonly measured in a practical sense using continuous performance tasks (CPTs) — extended duration tasks which require the participant to perform a simple task like pressing a button when a particular letter appears on the screen over an extended time span (typically around 10 minutes) [10]. These tasks are sensitive to overall attention function because lapses of attention lead participants to respond erroneously and/or slowly. Therefore, the ability to continue performing the task accurately over an extended time is used as a measure of overall attention function. A number of continuous performance tasks are currently in use, ranging from simple reaction time tasks which measure the time to respond to a light [41] to more complex tasks such as driving simulations [15] which track deviations from the lane.

The claim that continuous performance tasks measure a useful form of overall attention function has been substantiated by data that CPT performance is correlated with everyday cognitive function. Poor performance on the Test of Variables of Attention is used to diagnose ADHD [20], and other continuous performance tasks like the Sustained Attention to Response Task correlate with everyday cognitive failures [58]. Continuous performance tasks have also been used to demonstrate the impact of various manipulations, such as sleep deprivation [66], psychostimulant drugs [22], and activities like chewing gum [29] on attention function.

Good performance on these tasks is also highly related to electrical oscillations detectable in EEG. Good performance is associated with high frequency, low amplitude oscillations, while failures of attention are associated with low-frequency, high amplitude oscillations [44].

The link between physiology and vigilance has inspired the development of systems like AttentivU [35] and driver drowsiness monitoring systems [52], which attempt to detect lapses of attention from physiological signals and warn the user. Such systems can improve safety [21] but are subject to some limitations: they require complex sensors, interrupt the task the user is performing, and may be ineffective if the user is not able to voluntarily increase their vigilance.

In this study, we explored an alternate way to increase vigilance using rhythmic stimuli. Our approach aimed to harness the known effects of rhythmic stimuli on brain physiology to induce high-frequency brain rhythms associated with good vigilance.

2.2 Influence of rhythmic stimuli on cognition and physiology

Rhythmic sensory stimuli can influence cognition and physiology through multiple mechanisms, including entrainment of neural oscillations within the brain [3], and modulations of overall arousal by activating specific nerves such as somatosensory afferent fibers or the vagus nerve [63]. Because both neural oscillations and arousal are key to maintaining vigilant attention, there is a strong potential to improve attention with rhythmic stimulation wearables.

2.3 Neural entrainment methods for cognitive enhancement

Neural entrainment is a phenomenon in which rhythmic sensory stimuli – such as sounds, lights, or touch can produce brainwaves at the frequency of the stimulus. Neural entrainment can be detected through spectral analysis of the EEG, where presenting a rhythmic stimulus increases EEG power at the frequency of the stimulus [49, 69].

Importantly, the brainwaves produced by neural entrainment can affect brain function. For example example, flashing light at 5 Hz (theta frequency, which is associated with memory function) improves performance in memory tasks, suggesting that the brain waves induced by flashes of light promoted better memory encoding [36, 50].

Many studies have leveraged neural entrainment as a strategy for improving cognition. Entrainment modalities including light, sound, and binaural beats have been applied to a wide variety of tasks to improve performance, with varying results [3]. However, very little research has examined the effect of entrainment on attention specifically. Furthermore, most entrainment systems have been conducted using non-wearable systems, such as lights placed in a room or sounds generated by a computer. Some wearable devices known as "mind machines" have been developed for entrainment [65], but they typically block visual and auditory input and are thus difficult to use while performing a task.

The widespread adoption of wearables like smartwatches and smartglasses with actuators like speakers and vibration motors raises the possibility that these devices could be used for entrainment. Combining entrainment stimuli with smart devices that are almost always present on the body offers many new possibilities for using entrainment to enhance cognition in varied real-life situations.

2.4 Non-entrainment methods

In addition to neural entrainment, sensory stimulation can modulate cognition and physiology by activation of specific sensory nerve systems. A number of wearable systems have been developed which use rhythmic haptic [70] or electrical nerve stimulation to induce specific states. Most prominent among these are transcutaneous electrical nerve stimulation devices which rhythmically stimulate sensory nerves in the skin with electricity to relieve pain [57]. Repetitive electrical stimulation has also been shown to affect sensory processing beyond pain; for example stimulating the balance-sensing vestibular nerves can improve balance, likely because the stimulation of the nerves increases the sensitivity of neural systems for maintaining balance [27].

Other devices are designed to manipulate affective state and autonomic nervous system function; the Apollo Neuro device modulates autonomic nervous system function by specific vibration patterns and the company has shown that the device can modulate heart rate variability [24] and improve performance under stress [48]. The Sensate device is designed to stimulate the vagus nerve via bone conduction through the rib cage [42]. Systems have also been developed to improve sleep onset via rhythmic rocking (either using a motorized bed [45] or simulated by rhythmic stimulation of the vestibular nerves [23]). The BoostMeUp device was shown to improve cognition by regulating autonomic nervous system function [16]. Vibration applied to the outer ear was shown to activate the auricular branch of the vagus nerve and reduce inflammation due to rheumatoid arthritis [1].

Other devices have been developed to improve attention by presenting reminders, such as vibration or audio notifications, to re-engage attention when it lapses. AttentivU [34, 35], which uses electroencephalography (EEG) neurofeedback to detect lapses, improved user engagement levels in preliminary studies. Other devices, which present reminders at intervals or when inattentive behavior is detected have demonstrated some efficacy in treating ADHD symptoms [38, 56, 62].

Other investigators have studied the effects of sensory stimulation using non-wearable systems. For example, whole-body vibration in a laboratory environment has been shown to both increase [47] and decrease vigilance [6], depending on the vibration parameters and task. Particularly relevant to this work, Zhang et al. [70] found that performance on a test of attention was improved after 15 minutes of hand vibration using a Phantom Omni tabletop haptics device. The stimulation led to changes in EEG power (increased 15 Hz sensorimotor rhythm activity) which were associated with the degree of attention improvement suggesting that improvement occurred due to brainwave entrainment or changes to neural circuits that occurred as a result of stimulation.

While many of these systems have demonstrated impressive effects, a limitation is that they rely on hardware that is stationary (such as the Phantom Omni platform), or technically complex (EEG sensors in the AttentivU). There is to date little evidence on the effectiveness and acceptability of simple wearable devices for improving attention.

Despite robust evidence suggesting that rhythmic sensory stimulation can produce beneficial changes in cognition, little research has focused on wearable devices that can be used while performing a task to improve attention. To address this goal, we designed an experiment evaluating several types of wearable rhythmic stimulation strategies.

2.5 User Experience of Rhythmic Stimuli

While there is extensive research on the physiological and cognitive effects of *rhythmic stimuli* [3, 6, 16, 47, 57, 70], relatively little has focused on the user experience of these stimuli and optimizing devices for daily use.

In a qualitative analysis of the user experience of brainwave entrainment for faster sleep onset [25], the researchers compared impressions of rhythmic audio (through an audio headband) and rhythmic visual stimulation using a smartphone VR headset. Participants found both the audio and visual stimulation to be acceptable for use in daily life. Rhythmic audio stimulation was easy to use. However, eight of the 28 participants found the audio tones unpleasant or distracting; others reported adverse effects included dizziness, restlessness, and sick feelings. Audio stimulation was preferred to visual stimulation (wearing the headset), which was considered uncomfortable and cumbersome by some users. Five participants experienced headaches.

Research on gamma-frequency audio and visual entrainment for dementia treatment found that daily combined audio/visual stimulation for several weeks was free of major side effects, but associated with minor side effects, particularly headache, eye irritation, and tinnitus [14, 26]. The relatively high rate of side effects from this technique has motivated efforts to entrain brainwaves with less irritating stimuli; for example, a method called "invisible spectral flicker", which uses imperceptible changes in color to entrain 40 Hz activity [2]. However, no studies have directly compared the effectiveness and user experience of this approach to conventional entrainment.

The existing literature on user experience also has a number of significant gaps. Very few studies have focused specifically on the comfort and ease of use of rhythmic stimulation devices, and almost no research has directly compared different stimulation protocols to optimize their effectiveness and usability. Existing data suggests that devices currently used are often perceived as bulky and cumbersome [25] or irritating [14]. Little research has focused on wrist-based stimulation devices, which is significant as wrist wearables are seen as more socially acceptable than devices placed on other parts of the body like the head or the trunk [53, 54].

More research should focus on wearable devices that are optimized for comfort, usability, and social acceptability. We sought to address these gaps through this work in which we directly compared multiple modalities of rhythmic stimuli, and compared their effectiveness and associated user experience.

3 STUDY 1: EFFECT OF RHYTHMIC STIMULI ON ATTENTION AND USER EXPERIENCE

Our first study aimed to test multiple wearable stimulation modalities for their effects on attention, comfort, usability, and social acceptability. We tested effects on attention while participants received each type of stimulation and compared it to attention performance while receiving no stimulation.

3.1 Tasks and Stimuli

3.1.1 Sensory stimulation. The stimuli were delivered using two devices. Sound and light stimuli were delivered using the Captivates smart glasses (Figure 2 *left*) [13]. The Captivates contain red LEDs in the inner frame, which we used for light stimulation. We also mounted a speaker on the left temple to provide auditory stimulation (pulsed tone).

The Vibrotactile Haptics Platform (VHP) [18] is a wrist-mounted array of 8 to 12 linear resonant actuators (Figure 2 *right*) which can exert pressure on the skin, allowing the delivery of arbitrary vibration frequencies and waveforms. We chose to use this device over a smartwatch or similar device because the actuators have a better high-frequency response, allowing faithful delivery of 40 Hz vibrations that is not possible with more common vibration motors. We delivered the same waveform to all actuators to that they acted in synchrony.

All stimuli were square waves (in order to maximize the response of sensory systems sensitive to sharp peaks) with a 50% duty cycle. We used these two devices for presenting the different stimulus modalities as we wanted to use the optimal device for each modality; light and sound stimuli can be more consistently presented with a head-worn device, while vibration can be consistently presented on both head-worn and wrist-worn but people prefer wrist-worn devices [54].

We performed sensory stimulation using four modalities:

- *Light*: using red LEDs embedded in the frame of the Captivates smart glasses, which provided diffuse illumination (intensity approximately 14 lux) of the entire visual field. We used red light to match previous visual stimulation protocols which were conducted with the eyes closed, resulting in a red stimulus [50].
- *Sound*: pulses of a 7500 Hz tone are played using a speaker mounted on the left temple of the Captivates glasses. Intensity is approximately 41.1 db(A) at the left ear position. The intensity and frequency were chosen to be audible but not painful or dangerous, lying in the middle of the human hearing range and at an intensity that is perceptible but not painful for most subjects.
- *Combined sound and light*: where both the speakers and LEDs were activated in phase.
- *Vibration*: using the VHP placed on the wrist, and programmed to deliver square wave vibrations with the phase synchronized across all of the actuators. The VHP was placed on the dominant wrist in order to avoid inducing artifacts in a heart rate sensor, which was placed on the non-dominant index finger to minimize motion artifacts.

We also varied the stimulation frequency, so that each modality was used at both 10 Hz and 40 Hz.

Additionally, we presented a no-stimulation condition in which all devices were turned off. This resulted in 9 total conditions, each of which was presented twice in the experiment. Each period of stimulation lasted approximately two minutes.

We selected 10 and 40 Hz as stimulation frequencies because EEG activity at these frequencies is associated with divergent mental states: 10 Hz activity is increased with inattention [44], and entrainment of 10 Hz results has sedative effects [67], while 40 Hz activity is associated with active mental states [28] and 40 Hz entrainment has been reported to improve task performance [55]. Thus, we predicted that if the effects of rhythmic stimulation relied on brainwave entrainment, 40 Hz would improve performance more than 10 Hz. By contrast, similar attention improvement for both frequencies would suggest that the mechanism did not rely on neural entrainment.

Figure 2: Captivates smart glasses. Vibrotactile Haptics Platform (VHP) wristband.

3.1.2 Attention task. Participants were given the Sustained Attention to Response Task (SART) [58] to perform during each condition. The SART is highly predictive of everyday attentional failures [58]. In our SART task, digits 1-9 were pseudo-randomly presented at intervals ranging between 0.6-1.8 seconds (*mean*=1.2*s*). Participants were instructed to press the spacebar as fast as possible when a digit appeared unless the digit was a "3", in which case they were to make no response.

3.2 Measures

Our primary measure of attention performance was the percentage of incorrect responses in the SART where the participant pressed the spacebar when the number "3" appeared (referred to as the "error rate"). This is the typical measure used to evaluate attention on the SART.

We also measured reaction time to the SART stimuli in which the participant correctly pressed the spacebar in order to test if the rhythmic stimulation altered reaction times. Changes in reaction time can aid in interpreting changes in accuracy. For example, an increase in accuracy and lengthening of response time suggests a switch to a more careful and deliberative strategy, while increased accuracy alongside unchanged or decreased reaction time indicates improvement in focused attention [17].

We measured the comfort of each type of stimulation using a 7-point scale,reverse-scored (i.e. "On a scale of 1 to 7, how uncomfortable was the sound/light/vibration you got during the last test?", 1=completely comfortable, 7=very uncomfortable).

At the end of the experiment, we briefly re-presented each stimulus and asked participants to rate the usability and social acceptability of that device (glasses or wristband) and stimulation frequency (10 or 40 Hz). Usability was assessed using two questions adapted from the System Usability Scale [8] ("I think I would like to use this kind of stimulation frequently to help me pay attention" and "I think this device and stimulation is easy to use."). We used only two questions from this scale because in pilot testing the full scale was found too time consuming and many of the questions were found to be confusing in the context of this study. Social acceptability was measured using two questions about using the stimulation in public ("I would be comfortable using this device and stimulation in public." and "It would be socially acceptable to use this device and stimulation in public.") which are standard items for assessing social acceptability [32, 33]. All questions were 7-point Likert scales. The usability and social acceptability ratings were calculated by adding the ratings for the two questions in each measure (e.g., overall usability rating was calculated by adding the rating for Likert questions 1 and 2, resulting in a maximum possible rating of 14). Because the questions refer to a device, we did not measure comfort and acceptability for the no-stimulation condition. Participants were also asked to type in their qualitative feedback on their experience with the stimulus.

3.3 Participants

We included 20 participants who ranged in age from 20-35 years old (*mean*=26.6 years), 10 male and 10 female. We excluded participants who reported a current psychological or neurological condition, were taking any prescribed medication that acts on the brain, and participants who responded "yes" or "possible" to any questions on a standardized epilepsy screening questionnaire [46]. Ethics approval was received prior to the start of the study.

3.4 Procedure

Participants visited our lab for the experiment. After participants gave consent to participate, we explained the attention task and equipped the participant with the two stimulation devices: the VHP wristband on the dominant arm and the Captivates glasses on the face. Participants practiced 30 trials of the SART task before beginning the experiment.

The experiment consisted of 18 blocks. Each block was about 2.5 minutes and contained a 30-second baseline period followed by 57 trials (2 minutes) of the SART task, during which, one of the stimulation conditions or no stimulation was presented. At the end of each block, the participant was asked to rate the comfort of the stimulation. Participants completed two blocks of each stimulus type, counterbalanced so that the mean time from start of experiment to stimulus was equivalent for all stimulus conditions (e.g., if the first block was 10 Hz sound, the last block would also be 10 Hz sound). We also inverted the order of blocks between successive participants so that there were no systematic differences between when each condition was presented.

Following the completion of all blocks, we briefly re-presented each of the 8 stimulation conditions and asked participants to answer the questions about usability and social acceptability described in the Measures section. We also asked participants for general input on the their experiences with each type of sensory stimulus.

3.5 Data Analysis

3.5.1 Quantitative Analysis. To understand the effects of different stimulation conditions on attention and comfort variables, we used two-way ANOVA repeated measures ANOVA or a non-parametric Friedman test with factors stimulation frequency (10 Hz or 40 Hz) and stimulation modality (sound, light, light+sound, or vibration).

For each dependent variable, we determined whether ANOVA was suitable using the Kolmogorov-Smirnov test to check the normality of the ANOVA residuals, and the Mauchly test to check sphericity. The residuals of the response time and social acceptability measures were non-normal, thus we used Friedman tests in place of ANOVA for these variables and performed post-hoc tests using the Wilcoxon signed rank test.

We first analyzed whether either factor had a significant main effect in the ANOVA or Friedman test; if a significant effect was found we then conducted post-hoc tests to determine which conditions differed significantly.

3.5.2 Qualitative Analysis. The qualitative feedback was coded independently by two researchers and analyzed using the thematic analysis method [7] to generate initial themes. Then, the researchers reviewed the coded data and themes to come up with the final themes and analysis. Responses were coded using a scheme that we developed specifically for this study. Attributes coded were perceived effect on attention (positive or negative), sentiment towards the stimulation (positive, e.g., “pleasant”; and negative, e.g., “annoying”), social acceptability (e.g., “I would wear this in public”) and suggested improvements. The experience was coded as a perceived effect on attention if it contained words related to attention such as “distracted”, “alert”, “focus”, “concentration”, and “helpful (to the attention task)”.

3.6 Results

3.6.1 All stimulation modalities except light improved attention (lowered SART error rate), with no effect on reaction time. We tested the effect of stimulation frequency and modality on SART error rate using a two-way repeated measures ANOVA with factors for frequency and modality. We found a main effect for modality ($F(4, 76)$=3.12, p=0.02, partial eta^2=0.14). Post-hoc tests indicated that error rate was significantly lower for the vibration, sound+light, and sound modalities than for the no-stimulation condition (Figure 3, Table 1). Effect sizes (Hedges g) ranged between 0.2 and 0.4 (Table 4). We did not observe any significant differences between the sound, sound+light, and vibration stimulation. Due to non-normal residuals, we used a Friedman test to examine the effect of modality on response time; there was no significant effect ($\chi^2(4)$=9.04, p=0.06, W=0.11).

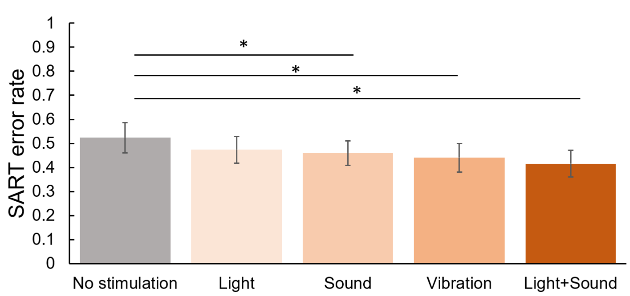

Figure 3: All modalities except light improved SART performance. Modalities were compared using an uncorrected two-tailed paired t test after finding a significant main effect of modality in the ANOVA. Since there was no significant effect of frequency, we combined the 40 Hz and 10 Hz stimulation for each modality in these graphs. * denotes differences with p < 0.05

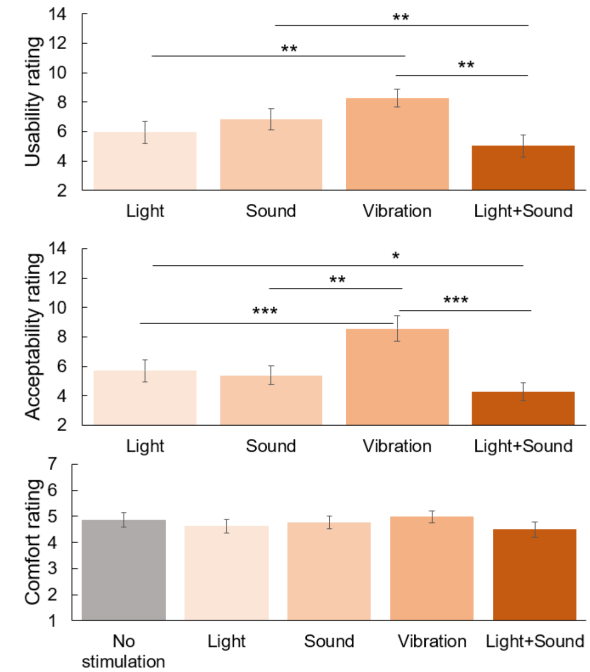

Figure 4: Vibration was ranked as the most useful and socially acceptable modality. Modalities were compared using an uncorrected two-tailed paired t-test after finding a significant main effect of modality. Comfort and usability were tested using parametric tests whereas effects on social acceptability were tested using non-parametric tests as described in methods. * denotes differences with p < 0.05, ** indicates p < 0.01, * indicates p < 0.001. Higher values indicate greater usability/social acceptability/comfort. Usability and social acceptability ratings were not obtained for the no-stimulation condition since these ratings were obtained only when a stimulus was presented.**

	Modality No stimulation	Light	Sound	Vibration	Light+Sound
Mean SART error rate (SD)	0.52 (0.28)	0.47 (0.25)	0.46 (0.23)	0.44 (0.26)	0.42 (0.25)
Mean SART response time (SD)	0.45 (0.08)	0.45 (0.07)	0.45 (0.07)	0.46 (0.08)	0.45 (0.08)

Table 1: SART error rates and response times for each modality. Error rates are a portion of stimuli from 0 to 1, response times are in seconds.

3.6.2 Vibration stimuli were more usable and socially acceptable than other modalities. Participants rated vibration stimuli as the most usable and socially acceptable to use, significantly ahead of other modalities (Figure 4). Vibration also had the highest comfort ratings, ahead of (in order of descending comfort) no stimulation, sound, light+sound, and light (Figure 4, Table 2). However, there were no statistically significant differences in comfort between modalities in a 2-way ANOVA analysis.

	Modality No stimulation	Light	Sound	Vibration	Light+Sound
Mean usability rating (SD)		5.95 (0.77)	6.83 (0.73)	8.28 (0.62)	5.03 (0.74)
Mean acceptability rating (SD)		5.70 (0.73)	5.40 (0.65)	8.58 (0.85)	4.28 (0.63)
Mean comfort rating (SD)	4.88 (0.27)	4.63 (0.26)	4.78 (0.25)	4.99 (0.23)	4.50 (0.29)

Table 2: User experience ratings for each modality. Usability and social acceptability ratings were not obtained for the no-stimulation condition since no stimuli that could be rated were presented in this condition.

3.6.3 Stimulation frequency did not affect SART error rate or response time. Our ANOVA found no significant effect of the factor frequency (Table 3, $F(2, 38)$=3.02, p=0.06, partial eta^2=0.14) on SART error rate, although both 40 Hz stimulation and 10 Hz stimulation were associated with a lower error rate than no stimulation ($t(19)$=2.12,2.14, p=0.048,0.045, g=0.31,0.26) for 10 Hz and 40 Hz vs no stim respectively). There was no significant difference in error rate or response time between the 10 Hz stimulation and 40 Hz stimulation conditions. There was no effect of stimulation frequency on response time.

Frequency	10 Hz	40 Hz	No stimulation
Mean SART error rate (SD)	0.44 (0.25)	0.46 (0.24)	0.52 (0.28)
Mean SART response time (SD)	0.45 (0.07)	0.45 (0.07)	0.45 (0.08)

Table 3: SART response times and error rates for each frequency. Error rates are a portion of stimuli from 0 to 1, response times are in seconds.

	Modality Light	Sound	Vibration	Light+Sound
SART error rate	0.19	**0.25**	**0.30**	**0.40**

Table 4: Effect sizes (Hedges g) for each stimulation type compared to no stimulation on SART error rate. Positive values indicate reduced error rates compared to no stimulation. Bold text indicates a significant difference from no stimulation.

3.6.4 Participant experiences using the stimulation. Several themes were generated from participants' feedback. Participants reported that the stimuli had both positive and negative effects on attention. Light and sound (particularly at 10 Hz) and sound-only stimuli (at 40 and 10 Hz) were mainly reported to have positive effects on attention (P2: "(...)red light and sound allows me to pay attention efficiently." and P7 on sound-only: "I could see this helping if I'm doing something tedious at home"). Light-only (mainly at 10 Hz) had negative reported effects on attention (P2:"I [felt] distracted when I got this stimul [*sic*]"). Participants reported mixed effects on attention for the vibration stimuli (P7, positive: "[T]he vibration is less gentle than the previous one and I could see that helping a little bit" and P18, negative: "I did not find the stimulation particularly helpful").

Participants also reported annoyance with and negative sentiment towards the stimuli, particularly the sound and light (On light and sound: P6: "did not like this one the most", P1: "the flashing light is annoying[,] the vibration is fine". On sound-only: P3: "[T]he sound is to [*sic*] high and annoying", P7: "The noise is pretty annoying but I think it kept me more alert." On light-only: P19: "very unpleasant").

By contrast, vibration stimuli elicited positive reports (P7: "it's quite gentle/relaxing", P15: "I can feel this one is like the massage chair vibration. so [*sic*] while I wear this device on my wrist I rather say my body would be relaxed", P17: "[The] stimulus is quite pleasant like a little massage machine.") Only one of the participants (P20) commented that the vibration stimulation was "annoying" at both 40 and 10 Hz.

Light stimuli were associated with reports of eye strain and vision problems (P2:"My eyes felt fatigue [*sic*] a little bit.", P3:"It seems that it will be hard to see properly in different environments", P17:"I had to squint to be able to see anythings [*sic*]"). A few participants (P3, P7, P20) seemed to prefer 40 Hz light stimulation to 10 Hz (P20: "Repeated flashing [10 Hz] is worse than the constant light [40 Hz].")

Participants found light and sound stimuli not socially acceptable because of the discomfort experienced (P1 on 10 Hz sound: "It is nosiy [*sic*] and I don't think it is acceptable in public" and P11 on 10 Hz light: "I really am not willing to use this glasses in public and also in my private place. It completely ruined my concentration ability and also I felt sore eyes.") and also because of how the device looked (P13 on 10 Hz sound: "stimulus it is pretty anno[y]ing and my head starts to ache a little from it. The device is weird[;] looks like toy cosplay glasses"). P11 commented that sound stimulation could be socially acceptable if it were used on earphones: "(...)so it could be used when people are in a public space by using [a] ear plug[-]like apple product". Several participants felt that vibration stimulation would be socially acceptable (P3, P7, P16), potentially because "we are more used to this type of stimulation [from smartwatches]" (P3) but not necessarily helpful for attention (P7: "The vibrating 'watch' is definitely the most socially acceptable one to use in public etc. but I don't feel it really does anything for me as it's quite gentle/relaxing" and P16:"this one is not weird in public but doesn't really help").

Participants also sometimes expressed the desire to increase or decrease the stimulus intensity (P3:"should be a lower sound [volume]", P2:"It [the vibration] is too weak to feel it."), or to use a different sound (P17: "I would rather [have] a sound more similar to white noise"). Participants also reported a few incidental observations about the vibration stimulation (P11 on 40 Hz vibration: "it is getting warm", P15 on 10 Hz vibration:"some times the unexpected change of the rhythm made me lose focus because [I] was thinking about the change more than the simulation but when it was steady it was good").

4 STUDY 2: FIELD STUDY WITH HAPTIC STIMULI

The results from Study 1 suggested that the vibration stimulation was highly promising, being both highly rated for usability and social acceptability, and effective at improving attention. Therefore, we decided to develop and test a smartwatch app for improving attention with vibration in real-world settings.

The goal of this study was to evaluate the perceived effectiveness and user experience of two vibration stimulation modes intended to improve attention. We also evaluated general user impressions of the system, usage patterns, and the situations in which participants used the stimuli.

We recruited 12 participants (none of whom were in Study 1) and provided them with a Fitbit Versa 2 watch, which was programmed to provide haptic stimulation in 3 conditions. The conditions were constant 10 Hz, varying frequency, and a sham condition with no stimulation (which we described to participants as "ultrasonic stimulation"). Stimulation was provided by pulsing the watch's vibration motor (an eccentric rotating mass motor). Participants could turn the stimulation on and off at any time by tapping the screen; we measured the amount of time participants used the stimulation, ratings of comfort and effectiveness for each mode, and asked participants to rate the modes at the end of the study. Ethics approval was received before the start of the study.

4.1 Stimulation Protocols

Stimulation was delivered by the watch and the current vibration mode was indicated by the background color (Figure 5). The watch had three vibration modes, plus an "off" state:

- *Fixed frequency (Yellow mode)*: vibration was presented continuously at 10 Hz
- *Varying frequency (Blue mode)*: vibration frequency was randomly set between 5 and 20 Hz every 10 seconds
- *Sham (Purple mode)*: no vibration, but participants were told that the watch generated imperceptible ultrasound stimulation in this condition.

Unlike Study 1 where the stimulus was a square wave delivered using a linear resonant actuator, the Fitbit has an eccentric rotating mass vibration motor with a measured vibration frequency of approximately 200 Hz. Thus, the stimuli for this experiment consisted of 200-Hz vibration pulsed at a rate of 5-20 Hz. We confirmed that the Fitbit was able to faithfully produce pulses at rates between 5-20 Hz using mechanical recordings of the vibration output. Because the Fitbit was unable to reliably produce pulses above 20 Hz (and we did not observe strong effects of frequency in Study 1), we included 10 Hz and varying frequency conditions but not a 40 Hz condition.

The experiment lasted 5 days. On the first day, participants could switch freely between all of the vibration modes. On days 2-4, the watch was "locked" to allow only one vibration mode on each day. The order of modes on days 2-4 was counterbalanced across participants. On day 5, the watch again allowed the participant to select any mode. On all days, participants could choose when to turn the vibration on and off; participants were encouraged to try using the vibration in a variety of tasks and explore whether it helped. The device also recorded the amount of time spent in each vibration mode.

Each mode was associated with a specific color that was displayed on the screen when that mode was active, these colors were used to refer to the different modes (e.g., we asked participants which color modes they preferred). This allowed participants to easily see which mode was active at any given time and provided an easily understandable way to refer to the different modes. Questions about the different modes referred to the color (e.g., we asked participants to rank the blue, purple, and yellow modes in order of how much they preferred them).

Figure 5: Modes on the smartwatch *(from left to right)*: Stimulation Off mode with a blank clockface background; Fixed frequency mode at 10 Hz with a yellow background; Varying frequency mode between 5 and 20 Hz with a blue background; Sham mode with no stimulation with a purple background.

4.2 Participants

The study included 4 male and 8 female participants ranging from 18-38 years old (mean=27 years). Participants were recruited from the local community and any adult over age 18 was eligible.

4.3 Measures

On days 2-4, we measured the comfort of the stimulation that day by taking the average of ratings for three questions on physical comfort (similar to the comfort question in Study 1) and social comfort (social acceptability) inspired by previous works [32, 33]. The perceived effectiveness of the stimulation was measured by taking the average of ratings for three questions on the perceived benefits to attention, usability (adapted from the System Usability Scale [8]), and helpfulness. The questions consisted of:

- How uncomfortable was the vibration that you got from the device today? (comfort, reverse-scored, 7-point scale, 1=completely comfortable, 7=very uncomfortable)
- I would be comfortable using this device and today's vibration mode in public (comfort, 7-point Likert)
- It would be socially acceptable to use this device and today's vibration mode in public (comfort, 7-point Likert)
- I felt more attentive when using this device and today's vibration mode (effectiveness, 7-point Likert)
- I think I would like to use today's vibration mode frequently to help me pay attention (effectiveness, 7-point Likert)
- How helpful do you think today's vibration mode is in helping you pay attention? (effectiveness, 7-point scale, 1=not helpful at all, 7=very helpful)

We also asked users in what situations they used the stimulation and for general comments on the stimulation.

In the end-of-study questionnaire, we asked participants to rank the vibration modes in order of preference, and complete the System Usability Scale [8] to assess the system as a whole. We also solicited general feedback on the watch and experiment. Finally, we measured the amount of time spent using each mode from log files on the watch.

4.4 Procedure

The experiment lasted 5 days; participants were asked to wear the watch each day and charge it at night or when needed. Participants were told that we had found that vibration could improve attention in a laboratory study, and we were testing how people found the experience of using a vibrating watch, as well as what situations they used it in.

On the first day, participants visited the lab and picked up the watch. Participants were told that they were free to turn the vibration on and off whenever they wanted, and we demonstrated how to switch the vibration mode and toggle it on and off. Importantly, we did not require or suggest that participants use the watch for a specific amount of time, rather, we measured the amount of time spent using each mode as a dependent variable.

On days 2-4, the watches allowed only one vibration mode to be used each day, such that all participants had one full day dedicated to each of the three vibration modes (10 Hz, varying, or sham). On these days, we emailed participants a questionnaire on their experiences with and comments on this mode each day at 5 PM. On the fifth day, participants returned the watches to the lab. We then sent a final questionnaire for general feedback on the device and experiment.

4.5 Data analysis

Similar to Study 1, we used a repeated measures ANOVA to test whether comfort and perceived effectiveness of the watch in improving attention differed between the stimulation conditions (constant frequency, varying frequency, and sham). Like in Study 1, we first tested for a main effect of stimulation condition, and then performed post-hoc tests using paired t-tests if a main effect was found. As in Study 1, we used the Kolmogorov-Smirnov and Mauchly tests to confirm that both dependent variables met the requirements for repeated-measures ANOVA.

At the end of the study we asked participants to rank the vibration modes from most preferred to least preferred. To identify whether the stimulation modes were consistently ranked differently from the sham modes, we used a permutation statistics method [5] where we compared the rankings observed to a population of 10,000 random rankings. We then tested whether the differences in ranking between each stimulation condition and sham were larger than that expected by chance.

We also manually coded whether participants reported improved attention in their free text comments and computed the percentage of participants who reported improved attention in each condition. The comments were independently coded by two researchers (intercoder reliability score, Cohen's kappa=91.7%) following the quantitative content analysis method [4, 37]. Comments were coded as a report of improved attention if they contained words and phrases that conveyed a similar meaning such as "paid attention", "increased focus", "concentrate more", and "helpful". After coding, the two coders discussed their responses to arrive at one common agreed-upon result. We used the same approach to analyze what situations they used the stimulation for each day; we coded the responses based on activities, categorized them, and then calculated the percentage of responses within each category. We developed this coding approach specifically for this study.

We tested whether the vibration stimulation elicited more reports of improved attention than the sham condition using a two-tailed McNamar's test in SPSS to compare the rates of improved attention in each condition. Tests were conducted for varying vs sham, constant vs sham, and varying vs constant.

The general feedback on their experiences with vibration stimuli and the system was also coded independently by two researchers (who did the above analyses) and analyzed using the thematic analysis method [7] to generate initial themes. Then, the researchers reviewed the coded data and themes to come up with the final themes and analysis. The feedback was coded according to a coding scheme including the perceived effect on attention (if it contained words such as "distracted", "focus", and "concentration") and attitudes towards the stimulation (positive, e.g., "pleasant"; and negative, e.g., "annoying").

4.6 Results

4.6.1 Participants used the watches frequently . Participants used the stimulation modes (constant and varying frequency) of the watch for a mean of 33 minutes per day (SEM=8.4 minutes).

4.6.2 There was no significant benefit for attention in vibration modes compared to sham mode. We did not observe significant differences between conditions for reported effectiveness ($F(2, 22)$=0.48, p=0.63, eta^2=0.04) or percentage of participants reporting improved attention (McNemar test, $Z(11)$=1.63,1.41, p=0.10,0.16 for varying vs sham and constant vs sham respectively). However, we did observe a trend where varying frequency stimulation was considered more effective and elicited more reports of improved attention than the other modes as shown in Figure 6, Table 5.

4.6.3 Varying frequency stimulation was not significantly preferred to sham stimulation and constant frequency stimulation. We did not observe significant differences between the experimental conditions in the preference rankings (p=0.085, Figure 7, Table 5).

4.6.4 Sham stimulation was considered more comfortable than either vibration mode. In our ANOVA analysis, we found that there was a main effect of vibration mode on comfort ratings ($F(2, 22)$=10.72, p=0.001,eta^2=0.49). Post-hoc tests revealed that the sham mode was rated as significantly more comfortable than either vibration mode (Table 5, $t(11)$=3.16,3.90, p=0.009,0.002 for sham versus random-frequency and 10 Hz modes respectively).

4.6.5 Participants considered the system easy to use. The mean System Usability Scale score was 84.4 (range 62.5-100), which is considered highly usable by conventional criteria [40].

4.6.6 Participant experiences using the watch. Participants reported that the vibration could improve attention (P6:"The vibration made me wary of the activities I did and that I should be paying attention.", P11:"(...) it helped grab my attention"). Participants also reported that the vibration was sometimes distracting (P8:"When I wasn't stressed[,] it was a bit annoying for me", P3:"The vibration setting today was too distracting", P1:"It was a little helpful while writing emails but distracting while engaging in conversational work.")

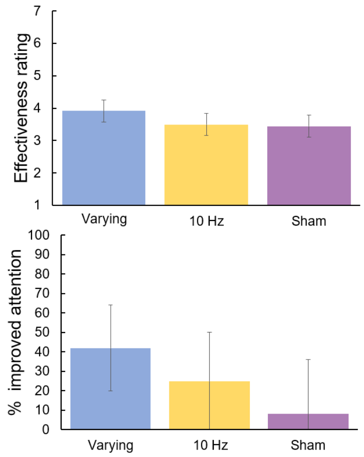

Figure 6: Varying frequency stimulation was rated as the most effective at improving attention, although we did not observe statistically significant differences between conditions.

Mode	Varying	10 Hz	Sham
Mean effectiveness rating (SD)	3.92 (1.23)	3.50 (0.35)	3.44 (0.33)
Percent reporting improved attention	42	25	8
Mean preference ranking (SD)	1.50 (0.78)	2.33 (0.52)	2.17 (0.94)
Mean comfort rating (SD)	3.92 (1.23)	4.47 (0.38)	6.39 (0.32)

Table 5: User experience statistics for each vibration mode. For preference rankings, lower values indicate the mode was more preferred. For effectiveness, comfort, and percent reporting improved attention, higher values indicate better effects.

Mode	Varying	10 Hz
Comfort rating	-1.11	-1.39
Effectiveness rating	0.36	0.04
Preference ranking	0.84	-0.18
Percent improved attention	0.75	0.39

Table 6: Effect sizes (Hedges g) for each vibration mode vs sham. Positive values indicate a higher rating/more favorable ranking than sham.

Some participants also reported that the vibration was calming or reduced anxiety (P8: "I think it has a potential for lowering anxiety", P8: "When i [*sic*] got stressed it helped me to calm down", P11:"It was calming but not too obtrusive.")

Participants also reported that the varying frequency vibration was less noticeable and distracting than the 10 Hz vibration (P1:"I really preferred this vibration mode [varying frequency] compared to the Day 1 [10 Hz] vibration mode. This was much easier for me to have in the background and I was able to keep it on for longer time periods").

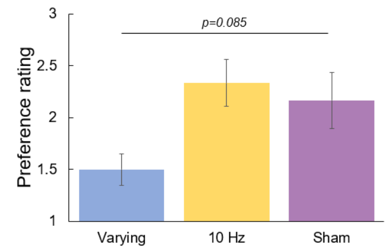

Figure 7: Preference rankings – lower values indicate the mode was more preferred. Varying frequency was most preferred, though there were no significant differences in preferences between modes.

Participants reported using the vibration in a wide range of settings including while working (mentioned in 64% of end-of-day responses), studying and attending lectures (17% of responses), exercising (17% of responses) and during social interactions (5% of responses). Specific tasks mentioned involved coding, academic lectures and tests, presentations, and driving. Participants also reported using the vibration specifically to reduce stress or increase alertness (11% of responses).

5 DISCUSSION

Our study addressed two research questions. First, we investigated the effects of rhythmic sensory stimulation on vigilant attention and the user experience of using different forms of stimulation (**RQ1**). We found that auditory, vibrotactile, and audiovisual rhythmic stimulation were all effective at improving attention and that users preferred vibration stimulation over the other modes and over the no-stimulation condition in terms of usability and social acceptability.

Our second research question focused on how users perceived the effects of vibration stimuli delivered using a smartwatch on attention and comfort, and how they used the devices in daily life (**RQ2**). We found participants considered the overall system easy to use and used the watches frequently, in a variety of contexts. Findings suggested that there were no significant differences in the perceived effects of conditions on attention and the sham stimulation was considered more comfortable than the vibration modes.

We discuss the overall effects on attention and user experience in greater detail below.

5.1 Effect on Attention

Our results in Study 1 demonstrate that rhythmic stimulation with sound, light, and vibration wearables can produce significant improvements in a computerized attention task. When participants used a vibration device in our field study, a few reported in their comments benefits to attention and alertness while engaging in a wide variety of tasks. Our results thus suggest that sensory stimulation devices can meaningfully improve attention.

We did not observe significant benefit of stimulation with the Fitbit in Study 2, though we did observe a non-significant trend where the varying frequency stimulation was rated as more preferred and effective than the sham stimulation (despite poorer comfort ratings). For varying frequency stimulation, the effects on perceived effectiveness and percent of participants reporting improved attention were numerically medium to large (effect sizes ranging from 0.36-0.84, Table 6) and comparable to the effects of vibration on SART performance in Study 1 (Table 4). Thus, a benefit of varying frequency stimulation using that Fitbit may become apparent with a larger sample.

5.2 Mechanisms of Attention Effects

Rhythmic stimuli can influence brain function through entrainment of brain oscillations [3], however, our results suggest that the improvement of attention likely resulted from non-entrainment effects. Entrainment effects are typically frequency-specific, reflecting the organization of the brain where specific oscillations subserve specific functions. However, we did not observe an effect of frequency in Study 1. This result is inconsistent with the idea that improvements in attention from rhythmic stimulation rely on entraining a specific oscillation frequency.

A more promising explanation for the attention improvements we observed is that our stimulation increases general alertness, an effect which has been observed in other studies and tasks. [6, 16, 24, 47]. Notably, Costa et al. [16] found that vibration above 1.75 Hz increased measures of alertness, anxiety,and autonomic arousal; since the stimulation in our study ranged from 10-40 Hz a similar effect may have occurred. A novel aspect of our work compared to previous research which showed that sensory stimulation can modulate alertness is that we show improvement in an attention task (Study 1), which has previously not been demonstrated, and we test with rhythmic stimulation in multiple modalities (i.e. audiovisual and vibration).

The hypothesis that rhythmic stimulation modulates alertness and autonomic arousal can also explain why some participants found that stimulation was helpful, while others found it distracting or distressing: pa. The Yerkes-Dodson Law [68] and Attentional Control Theory [19], predict that an arousal-increasing intervention will increase performance for participants with baseline low arousal, but will decrease performance for participants with baseline high arousal. Future research could confirm these predictions by measuring whether the response to rhythmic stimulation depends on baseline performance, arousal, and mood.

Rhythmic stimuli may alter arousal though several mechanisms such as by simulating a faster heart rate [16] or by activating muscle-tension reflexes [47]. Future studies should directly test whether stimulation with the systems and frequencies we used affects arousal and the mechanisms involved.

While a previous report [70] attributed improvements in attention to neural entrainment, it is also noteworthy that the changes in EEG they detected persisted for several minutes beyond the end of the stimulus. Thus, the changes they detected may not represent neural entrainment, but rather a more general change in neural information processing induced by sensory stimulation such as that observed by Inukai et al. [27]. Further studies measuring EEG and other physiological responses during stimulation may help shed more light on the mechanisms underlying attention improvement.

5.3 User Experience

Users' impressions of the stimulation were varied and highly dependent on the stimulation modality. From Study 1, vibration stimulation had higher usability and social acceptability ratings than auditory, visual, and audiovisual stimulation, typically because the audio and visual stimuli were experienced as annoying, stressful, or interfered with perception. These experiences were consistent with comments on rhythmic audio and visual stimulation for brainwave entrainment in previous works [14, 25]. The social acceptability ratings were consistent with previous literature that indicate that wrist-worn wearables are considered more socially acceptable than head-worn ones [53, 54].

Due to these findings, we chose to study vibration stimuli only in our field study (Study 2). Users found the vibration device highly usable. Comments on the stimuli showed that a few users preferred the varying frequency vibration over constant frequency. One reason cited by users for this preference was that the varying frequency was "gentler" and less distracting than the constant frequency. This finding may reflect the fact that the varying frequency mode included higher frequencies (ranging up to 20 Hz) which are more attenuated by the vibration motor and skin interface and therefore, perceived as less intense. The sham condition was rated as more comfortable than the two vibration modes. It is possible that the general experience of rhythmic vibration and audiovisual stimuli can be uncomfortable and irritating at times if the induced arousal and anxiety is too much. Many user reports referred to the stimulation intensity in both experiment 1 and 2, suggesting that allowing users to control the stimulation intensity could make it more useful and comfortable.

Similar to the comments on the BoostMeUp system which gave rhythmic vibration from smartwatches [16], several users in both of our studies reported that the vibration stimulation was not distracting, while a few reported feeling distracted and anxious. A few users in our studies also reported feeling calm when experiencing the vibration stimulation, which is similar to the reported calming effect of the Apollo Neuro rhythmic vibration wearable [24].

5.4 Potential Use Cases and Design Space

Our results suggest that a wide range of wearable devices could be augmented to improve attention, often with little to no modification to the hardware, for example, simply by rhythmically pulsing an onboard vibration motor. Devices such as smartglasses and bone-conduction headphones could also be easily used to deliver attention-enhancing audiovisual stimulation. Since millions of users worldwide already own a smartwatch, such as an Apple Watch [61] or Fitbit device [39] or Samsung Watch [9], stimulation from a smartwatch has a greater potential of being deployed and on a large scale [16]. Fitness trackers, in particular, were rated to have the highest WEAR (social acceptability) score of about 4.5, and the highest 'warmth' and 'competence' compared to other forms of wearables [53].

This approach offers many new approaches to cognitive enhancement. Software designed to enhance attention or other cognitive functions could be easily distributed to many of these devices. Further, wearables offer an advantage over the fixed platforms used in studies like Zhang et al. [70] because they can be present with the user almost constantly and easily activated to provide attention enhancement in a wide variety of settings. Participants in Study 2 reported using the device in a wide range of settings, suggesting that a wearable form factor is highly desirable.

We also envision that novel wearable devices could be created specifically for influencing attention and other cognitive processes. Such devices could take forms beyond current smartwatches/glasses, such as earings, rings, or wearable patches with vibration and/or electrical stimulation capability. We crafted our concept wearables using Shapr3D, a 3D CAD tool, and then rendered these models with Keyshot, showcasing both product details and real-life scenarios (Figure 8).

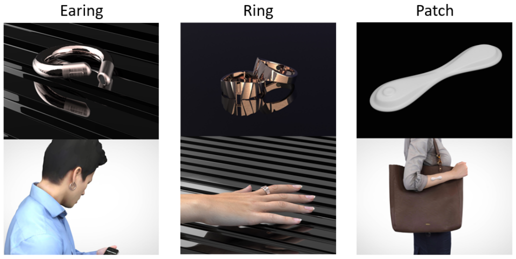

Figure 8: Renderings of the concept models for novel wearables which could deliver vibrotactile stimulation using an integrated vibration motor. Models include an earring (left), ring (middle), and stickable patch (right)

5.5 Limitations and Future Work

Our studies have a number of limitations which we describe below. A significant limitation of both studies is that because the studies involve perceptible sensory stimulation, the control condition was always distinguishable from the active stimulation and thus, the results should be understood as an "open-label" study, with the potential influence of placebo effects. We also acknowledge that participants' prior experience with smartwatches or glasses devices might impact the perceived comfort and usability ratings. Although we did not look at these prior experiences in this work, it might be investigated in future studies. In Study 1, usability was measured using only two questions from the System Usability Scale rather than the entire scale, as this combination of questions has not been validated it should be interpreted as an unvalidated novel scale, not interpreted as a version of the SUS.

For Study 1, while vibration was delivered using a wristband, we delivered sound and light stimuli using a pair of smart glasses. Thus, the differences in acceptability and usability we observed between conditions may reflect not just the stimulus modality, but also the device used to deliver it. We aimed to use the optimal device for each stimulus modality (for example, light and sound stimuli can be more consistently delivered with a head-mounted device) rather than explore all the possible permutations, but future studies may also examine other combinations such as vibration delivered by smart glasses.

A limitation of our field study (Study 2) is that the small sample size limited our ability to draw statistically significant conclusions about the effect on attention. In addition, it is possible that the Fitbit stimulation could be optimized to increase the effect size. For example, by providing an ability to adjust the intensity as several users noted the intensity of vibration stimulation could be too strong or too weak.Future work should explore the utility of rhythmic stimulation in larger field studies with user-controlled parameters.

Future work could explore other ways to improve the comfort of rhythmic stimulation. Apart from enabling users to customize the stimulus intensity and since the effects on attention might depend on the current cognitive-affective state (arousal) of the user, we envision a feedback system that detects these states through physiological signals (e.g., heart rate in BoostMeUp [16], [59, 60]) and optimizes the rhythmic stimuli for optimal arousal, attention and cognitive performance following the Yerkes-Dodson curve [68]. Further investigation with "invisible spectral flicker" [2] could reveal it to be an effective and comfortable way to give rhythmic light stimulation. Social acceptability and social comfort could be improved if the wearable is perceived as helping people and if there is a medical need [30].

Future work should also focus on understanding the long-term effects of stimulation as well as the biological mechanisms by which rhythmic stimuli can improve attention, for example by studying how the stimulation affects EEG. Understanding these effects and mechanisms may enable new, optimized techniques for improving attention, as well as potentially other cognitive functions.

6 CONCLUSION

In this series of experiments, we demonstrated that wearable systems for rhythmic sensory stimulation could produce improvements in objectively measured vigilant attention and potentially provide a useful means of cognitive enhancement in the real world. We also explored the perceived usability, social acceptability, and comfort associated with rhythmic stimulation. Our results from Study 1 suggest that rhythmic stimulation wearables (especially using haptic vibration, sound, and combined sound and light) might be a usable and effective means of improving attention. Our findings from Study 2 suggest that haptic rhythmic stimulation from smartwatches may be easy to use and were frequently used in a variety of contexts. More research is needed to improve the comfort of the rhythmic stimuli in general. Future studies should explore the underlying physiology of these effects, and how other cognitive functions can be enhanced with wearable stimulation devices.

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