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Impact of Binaural Beat Technology on Vigilance Task Performance, Psychological Stress and Mental Workload

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THE IMPACT OF BINAURAL BEAT TECHNOLOGY ON VIGILANCE TASK PERFORMANCE, PSYCHOLOGICAL STRESS, AND MENTAL WORKLOAD

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science

By

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GRADUATE SCHOOL

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Elizabeth A. Shoda ENTITLED Impact of Binaural Beat Technology on Vigilance Task Performance, Psychological Stress, and Mental Workload BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science.

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ABSTRACT

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Impact of Binaural Beat Technology on Vigilance Task Performance, Psychological Stress, and Mental Workload.

Currently, there is only one published study examining the impact of binaural beats on the performance of a laboratory vigilance task, however this study had mixed results and left many questions unanswered. I further examined this phenomenon by using a successive vigilance task, between-subjects design, and a control condition to determine whether beta frequency binaural beats could affect vigilance performance over time and across conditions. I hypothesized that participants listening to beta binaural beats would have more hits and fewer misses on the vigilance task than participants in the control condition. In addition, I hypothesized that participants listening to beta binaural beats would have lower levels of psychological stress and mental workload while completing the task than participants in the control condition. The participants underwent a 30-minute vigil, in which they were required to monitor a computer monitor and hit a button on a keyboard whenever a critical target was present. Results partially supported the hypothesis that beta binaural beats would improve vigilance performance; however no significant stress or workload differences existed between the control and binaural beat conditions. Although only partial support was found, this study provides important information about a little-researched phenomenon and opens the door to much needed future research in this field.

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I. INTRODUCTION

The Vigilance Problem

Vigilance is the ability to sustain attention and respond appropriately to changes in the environment (Shaw, Matthews, Warm, Finomore, & Silverman, 2010). Some important jobs, such as air traffic control, military surveillance, seaboard navigation, and airport baggage screening, require high degrees of vigilance (Warm, Parasuraman, & Matthews, 2008). However, this is often problematic because research and practice have consistently revealed that as time on task increases, vigilance performance decreases. This phenomenon is known as the vigilance decrement and has been a problem for researchers and practitioners for decades (Wiener, 1987). Failures of vigilance have been responsible for, among other things, errors in air traffic control, major and minor on the job accidents, and fratricide incidents in the Iraq War (Molloy & Parasuraman, 1996; Hawley, 2006). Compounding this problem has been a widely embraced shift towards work that requires automation. More and more jobs are now requiring humans to act as observers of automated processes and perform fail-safe roles in which action is only necessary in the event of accidents or failures of automation (Parasuraman, 1987).

One of the earliest and most notable vigilance studies was conducted during World War II to investigate the decreasing efficiency of radar operators over time. After about 30 minutes on the job, radar operators began missing “blips” on the screen that allowed German U-boats to slip into British waters undetected. The Royal Air Force commissioned Norman Mackworth to investigate why these failures of detection were occurring (Warm, Dember, & Hancock, 1996). Mackworth (1948) created an experiment in which participants monitored a blank face clock apparatus and had to report when the “clock” hand performed a double jump and moved a distance twice as long as the normal distance. He found that as time went on, the observers had less correct detections and more false alarms in determining the target movement. Mackworth’s research coined the term “vigilance decrement”, or decrement function, to refer to the decreasing efficiency of vigilance performance over time.

An important factor affecting the interpretations and conclusions drawn from vigilance data, is research on attentional resource theory. Under attentional resource theory, the vigilance decrement is the result of a depletion of attentional resources caused by the mentally demanding nature of vigilance tasks (Grier et al., 2003). This view of vigilance as mentally demanding is supported by research that shows that vigilance tasks are stressful and require high levels of workload (Warm et al., 2008). Self-report measures indicate that vigilance tasks can induce negative mood shifts, fatigue, sleepiness, and stress (Hancock & Warm, 1989; Matthews, 2001; Warm, 1993). A number of studies have directly and indirectly demonstrated the utility of attentional resource theory to explain changes in vigilance task performance over time (Hitchcock et al. 2003; Szlama, Warm, Matthews, Dember, & Weiler, 2004). For example, Warm et al. (1996) conducted a series of experiments that showed that the vigilance decrement is accompanied by a linear increase in overall workload, as measured by the NASA-TLX. Matthews and Davies (2001) found that when difficulty components, such as degraded visual signals and added secondary tasks, were introduced to the experiment, vigilance performance declined accordingly. The more taxing the task was on the participants' attentional system, the worse they performed.

These observations have been verified by using neuroimmaging studies to document changes in the brain during vigilance tasks. For example, studies using Transcranial Doppler Sonography have shown that the vigilance decrement is paralleled by a temporal decline in blood flow only when observers are actively engaged in the task (Warm & Parasuraman, 2007; Warm, Matthews, & Parasuraman, 2009). A considerable amount of research has linked cerebral blood flow to neural activity in the performance of mental tasks (Raichle, 1998; Risberg, 1986; Reinerman et al., 2006), such that this decreased blood flow indicates an increase in the use of cognitive resources. When observers were asked to view the task passively in a manner that might be considered understimulating, blood flow remained stable throughout the session (Warm & Parasuraman, 2007; Warm, Matthews, & Parasuraman, 2009). Because of these detrimental effects to performance and resultant neurological changes, the attentional resource model of vigilance has become an important research topic over the past few decades.

Determinants of Vigilance Performance

Vigilance is a complicated issue and vigilance performance can be affected by a number of different variables. Endogenous and exogenous determinants are two categories of variables that can affect vigilance performance. Endogenous variables include features and properties within the task itself, as well as motivational factors arising from the participant, while exogenous variables come from the environment or external stimuli. Commonly studied endogenous variables include signal salience, signal modality, and temporal and spatial uncertainty (Warm, Finomore, Vidulich, & Funke, *in press*).

One of the most utilized endogenous determinants in vigilance research has been event rate. Event rate has been studied extensively due to its ability to influence vigilance performance, as well as act as a moderator of vigilance performance (Warm, Finomore, Vidulich, & Funke, *in press*). In vigilance tasks, critical signals are embedded within a series of reoccurring neutral background events. The event rate involves the speed at which background events occur in a vigilance task. Although the background events are neutral in that they don't require a response from the observer, their effects on vigilance task performance are not neutral. Background event rate can affect performance in a number of ways. The more one has to look for critical signals in a study, the less the probability that such signals will be detected. Also, signal detection in vigilance is determined to a degree by what is going on when no signal is present, aka, during background events (Warm & Jerison, 1984).

Several studies have demonstrated that the speed of background event rates is an important factor in determining vigilance task performance. The accuracy of signal detection tends to vary inversely with event rate and participants often detect more signals during a slow event rate versus a fast event rate task (Jerison & Pickett, 1964). Background event rate can also affect the amount of perceived workload and stress present during a task. Several studies have shown that scores on the NASA-TLX were significantly higher during a fast event rate task than a slow event rate task (Galinsky, Rosa, Warm, & Dember, 1993; Grubb, Miller, Nelson, Warm, & Dember, 1994). Background event rate speed has been shown to be a moderator between vigilance performance and several other variables. For example, the effects of signal salience were shown to be greater in a fast event rate task than slow event rate task (Metzger, Warm, & Senter, 1974). In addition, Finemore (2009) found that the Worry subscale of the Dundee Stress State Questionnaire (DSSQ; Matthews et al., 2002) was elevated in a slow event rate condition and then diminished in a fast event rate condition. Also, McGrath (1963) reported that the effects of background noise from music, mechanical noise, and traffic, attenuated the vigilance decrement in a 20 events/min task, but exacerbated the decrement in a 60 event/min task.

External or environmental factors can also have effects on vigilance task performance. Some of these variables include light, odor, noise, and binaural beats. An abrupt change in luminance contrast is one of the strongest forms of exogenous cueing (Warm, Finomore, Vidulich, & Funke, *in press*). Also, exposure to a brief whiff of Peppermint can enhance the frequency of signal detections (Warm, Dember, & Parasuraman, 1991). Noise can affect performance in several ways. Listening to music has been shown to bolster vigilance performance (Alikonis, Warm, Matthews, Dember, & Kellaris, 2002). In addition, exposure to low levels of white noise can abolish the vigilance decrement in a cognitive vigilance task (Noonan, Ash, Loeb, & Warm, 1984) and exposure to jet engine noise can elevate signal detection during short vigilance tasks (Helton, Matthews, & Warm, 2009). However, under longer duration tasks, listening to jet noise or other acoustic noise can actually degrade performance (Becker, Warm, Dember, & Hancock, 1995; Szalma & Hancock, 2011). In a similar vein, listening to binaural beats may also have the ability to increase vigilance performance.

Binaural Beats and Vigilance Performance

Binaural beats are a type of brainwave entrainment technology that use rhythmic stimuli to produce a frequency following response in the brain. Specifically, binaural beats are an auditory phenomenon produced when two similar but slightly different frequencies are presented separately and simultaneously to each ear. The phase interference between these two waveforms produces "a composite signal with a frequency midway between the upper and lower frequencies and an amplitude modulation that occurs with a frequency equal to the difference between the two original frequencies" (Lane, Kasian, Owens, & Marsh, 1998, p. 249). For example, if 300 Hz are presented to the left ear and 310 Hz are presented to the right ear, the listener will perceive a composite tone of 305 Hz and a 10 Hz binaural beat. In this scenario, the listener will have increased brainwave activity at the 10 Hz frequency (Wahbeh, Calabrese, & Zwickey, 2007).

Depending on the frequency of the binaural beat, different psychological and physiological effects are believed to occur. When frequency differences are below 2 Hz, the sound is perceived as moving from right to left across the head. For higher frequency differences, sound appears to fluctuate in loudness (Moore, 2012). The most commonly studied frequency ranges are delta frequencies (1-4 Hz) that are associated with deep sleep; theta frequencies (4-8 Hz) that are associated with light sleep and creativity; and beta frequencies (13-28 Hz) that are associated with a thinking, focused state and increased arousal (Foster, 1990).

Theoretically, binaural beats may have the ability improve vigilance performance by increasing arousal and thus increasing the availability of general cognitive resources.

The influence of binaural beats on various psychological, physiological, and neurological systems has been demonstrated by past research (Atwater, 2009; Stevens et al., 2003). For example, Wahbeh et al. (2007) used a 60-minute binaural beat CD with a proprietary blend of beats developed by the Centerpointe Research Institute to assess changes in depression, anxiety, mood, and quality of life (as measured by the World Health Organization-Quality of Life Inventory). Pre to post measurement scores showed a significant decrease in trait anxiety and an increase in quality of life. When looking at the Profile of Mood States assessment, pre to post measurements showed a decrease in the tension/anxiety, confusion, and fatigue subscales, and an increase in the depression and vigor subscales. Physiologically, dopamine showed a significant pre to post decrease after the binaural beat intervention.

Although binaural beats have been used to alter various psychological and physiological states (Huang & Charyton, 2008), only one study looking at the impact of binaural beats on vigilance performance has ever been published. This makes for an interesting storyline because this article, which was published in a major journal, has never been replicated in a published study and has rarely been cited by vigilance researchers.

Lane, Kasian, Owens, and Marsh (1998) published a study examining the impact of two binaural beat audio tracks on vigilance task performance. In one condition, a track of theta and delta binaural beats of 1.5 and 4 Hz was used. In the other condition, a track of beta binaural beats of 16 and 24 Hz was used. The authors hypothesized that listening to the beta binaural beats would significantly increase the number of correct detections compared to the theta/delta condition. Results indicated that over the course of a 30 minute vigilance task, participants listening to beta binaural beats had significantly more correct detections, while participants listening to the theta and delta beats had significantly more false alarms.

The Lane et al. (1998) study, however, contained several methodological problems. Most notable was the absence of a control condition to determine whether binaural beats affected vigilance performance compared to a baseline of no binaural beats. The Lane et al. (1998) study demonstrated that vigilance performance can be decreased by using beats artificially designed to reduce performance, and similarly, that performance can be increased by using beats designed to improve performance. Without a baseline control group, however, these results have no practical implications. However, if binaural beats can be shown to improve vigilance performance compared to a baseline, this technology may be able to be utilized in occupational settings to improve work task performance and reduce errors. Although in its current form, this technology may not be implemented very practically, future advances in audio technology may diminish some of these design concerns.

II. CURRENT STUDY

Purpose and Hypotheses

The purpose of this study was to examine whether binaural beats have significant effects on vigilance task performance, psychological stress, and workload. This study replicated and expanded upon Lane et al. (1998) by using a larger sample size and a between-subjects design. This study also utilized “homemade” binaural beats, rather than beats purchased from outside institutions. All previous binaural beat studies encountered in the literature review have used beats created by either the Monroe Institute or the Centerpoint Research Institute. Using beats created internally could demonstrate that this technology can be cost efficient and accessible to a wider range of individuals. It also ensured that the audio tracks were not confounded with unwanted frequencies since all aspects of creating the audio tracks were controlled by the researchers, whereas the compositions from the Monroe Institute and Centerpointe Research Institute could contain proprietary information and unwanted frequencies.

In addition to testing the effects of binaural beats on vigilance performance, the present study extended this query by examining the effects of this technology on perceived workload and stress. Based on past research showing that binaural beats can entrain brainwaves to achieve various psychological effects, it was hypothesized that participants listening to beta binaural beats would have increased focus and attention and thus better scores on the vigilance task as measured by hit rates and false alarms.

Because of this increased level of focus and attention, it was also hypothesized that the beta binaural beats would also result in lower scores on measures of psychological stress and mental workload when compared to the control group. Hypothesis 1 states that participants listening to binaural beats will have overall higher hit rates than participants listening to the pink noise alone. Hypothesis 2 states that participants listening to binaural beats will have a lower overall false alarm rate than those listening to only pink noise. Hypothesis 3 states that participants listening to binaural beats will have overall lower scores on the NASA-TLX than those listening to only pink noise.

For the SSSQ and the SAS, I plan on examining change from the beginning of the task to the end. Hypothesis 4a states that participants listening to binaural beats will show less decrease on the Engagement subscale of the SSSQ than participants listening to pink noise only; hypothesis 4b states participants listening to binaural beats will have a larger decrease on the Worry subscale of the SSSQ; and hypothesis 4c states participants listening to binaural beats will have a larger decrease on the Distress subscale of the SSSQ compare to those listening to only pink noise. Hypothesis 5 states that participants listening to binaural beats will report larger decreases in stress appraisals as measured by the SAS.

Expanding beyond Lane et al. (1998), it was also expected that differences between groups would be reflected in the signal detection measures of perceptual sensitivity (*d')* and response bias (*c*). These measures are useful because they provide additional information about how the participant responded; *d'* measures whether the participant's sensitivity, or ability to distinguish signal from noise, is increasing or decreasing, while *c* measures response bias, or whether the criteria the participant is using to make decisions about signal or noise is changing (See, Warm, Dember, & Howe, 1997). For example, if a participant becomes fatigued during the course of a task, they might not be as sensitive to differences between signal and noise. As a result, their *d*' would decrease over time; alternatively, if the beta binaural beats increased their alertness, then *d'* would be higher in the experimental condition than in the control condition. If a participant gained more confidence during the task and decided to respond in a more liberal manner, their *c* would decrease. Values of *c* less than 1 indicate liberal responding, whereas values greater than 1 indicate conservative responding. These measures will not only indicate whether the binaural beat intervention had an effect on vigilance performance, but also whether the effects were due to changes in sensitivity or response bias.

The binaural beat and control conditions were further separated by a vigilance task that either had a fast event rate or a slow event rate. The purpose of this was to determine whether event rate moderated the relationship between audio condition and perceived workload and stress. Previous literature has shown event rate to be an important variable in the study of vigilance, effecting performance singlehandedly, as well as moderating the relationship between performance and other variables. Event rate will be an important variable to look at because it will provide information as to how robust the audio manipulation is in affecting performance.

III. METHOD

Participants

One hundred and thirty individuals participated in the experiment: 44.5% of participants were male and 55.5% were female. The mean age for participants in this study was 20.87 years. All participants were enrolled at Wright State University and completed the experiment for partial course credit. Participants were required to have normal or corrected-to-normal hearing and vision.

Design

This experiment utilized a 2x2x6 mixed design with repeated measures to examine vigilance performance across time and between conditions. Three independent variables were tested: audio condition, event rate, and period. Audio condition was a between-subjects factor with two levels: a control condition with pink noise coupled with no binaural beats and an experimental condition with pink noise coupled with beta binaural beats. Event rate was also a between subjects factor with two speeds of event rate. Participants were assigned at random to one of four conditions: no binaural beats and slow event rate, no binaural beats and fast event rate, beta binaural beats and slow event rate, and beta binaural beats and fast event rate. Period was a within subjects factor with each subject completing six continuous 5-minute periods of watch. Because sample size was not consistent within each condition Type 3 sums of squares was used (Kirk, 1995).

Stimuli

Audio Tracks. The two audio tracks used in this study were created using MATLAB (The MathWorks Inc., 2010). Following procedures used in similar studies (Lane et al., 1998; Wahbeh et al., 2007), the tracks contained a background of pink noise. Pink noise is a type of signal commonly used to create sound masking programs. It contains all the frequencies that fall within the range of human hearing and resembles the sound of running water or a fan (Ward & Greenwald, 2007). Unlike white noise, which is static and has the same energy at every frequency, pink noise contains equal energy per octave, not per frequency, which results in a more natural and discerning sound. Participants in the control condition received a track which only contained pink noise, whereas participants in the experimental binaural beat condition listened to a track containing the pink noise coupled with binaural beats. Consistent with Lane et al. (1998), the beta condition track included binaural beats at 16 and 24 Hz with amplitudes 15 db above the amplitude of the pink noise; unlike Lane et al. only one carrier tone (300 Hz) was used to present both beats. The tracks were played using stereo headphones and the intensity was set to a comfortable level, as determined by the participant.

Vigilance Task. All experiments were conducted using HP Pavillion Desktop computers. The vigilance task was created using MATLAB (The MathWorks Inc., 2010). The task involved participants watching the computer monitor and responding when a target was present. Participants sat approximately two feet from the computer monitor and the room was lit with four overhead fluorescent light bulbs. The room contained two windows which had shades covering them. Similar to Lane et al. (1998), individual capital letters were presented on the screen from a list of twenty six. The target occurred whenever a letter was repeated. For example, if the letter “M” was presented and followed again by the letter “M”, the second “M” would be the target. The participants responded to experimental stimuli by pressing the spacebar on the keyboard.

The experimental vigilance task included six continuous periods lasting five minutes each for a total of 30 minutes. The luminance of the stimuli was measured by means of a Minolta Luminance Meter. The luminance of the letters was 35 cd/m^2, while the luminance of the background was 106 cd/m^2. The Michelson contrast ratio was calculated from these readings to yield a ratio of .50 (Michelson, 1995).

Extensive pilot testing was conducted to evaluate the design of the Lane et al. (1998) study and to determine the appropriate rate to present stimuli for the current experiment. Lane et al. (1998) presented stimuli at a rate of 60 events/minute, displayed the stimuli for 100ms, and programmed a 10% chance of a signal being presented. Pilot testing revealed that this was a relatively easy task resulting in high levels of performance and little vigilance decrement. To increase the vigilance decrement the rate of presentation was increased to 75 events/minute and the signal probability was reduced to 6%.

The event rate in this experiment is slightly higher than in the Lane et al. (1998) study (75 events/minute versus 60 events/minute). During pilot testing, this event rate made the task difficult enough for a more pronounced vigilance decrement to be observed. Several articles have reported that a higher event rate increases the vigilance decrement and, thus, makes the task more difficult (Parasuraman, 1979; Krulewitz, Warm, & Wohl, 1975; Loeb & Binford, 1968).

For the current study, a difficulty component was introduced to the task by including another event rate. The two different event rates constituted two levels of task difficulties. The fast 75 events/minute event rate represented the hard task, while the easy task used a much slower 20 events/minute event rate. Both the fast and slow event rate tasks used a 100ms display rate and 6% critical signal rate with the rule that two critical signals could not occur back to back. For the fast task this resulted in a total of 2,250 stimuli, of which 135 were critical signals. This resulted in 375 stimuli per period, of which either 22 or 23 were critical signals. For the slow task this resulted in a total of 600 stimuli, of which 36 were critical signals. This resulted in 60 stimuli per period, of which 6 were critical signals. The easy task represents a significantly slower event rate than the Lane et al. (1998) study, but more similarly mirrors event rates seen in typical vigilance studies.

Vigilance Performance Data

Vigilance performance was measured as the proportion of correct responses to critical signals (hits), and incorrect responses to noise signals (false alarms). Hits were determined by whether a participant responded to the critical signal within the allowed time (800ms). Responses to critical signals outside of the allowed time frame were coded as misses. Responses in the absence of critical signals were coded as false alarms. Each participant had 800ms to respond to an event, regardless of which condition they were in. Although participants in the slow event rate condition had additional time between events, response times were kept consistent to rule out any confounds from differing response time lengths. The data collected from the vigilance task also allowed computation of the signal detection measures of *d*', a sensitivity index that provides the separation between the means of the signal and the noise distribution, and *c*, the participant's response bias (See et al., 1997). The signal detection measure of *c* was used instead of the more traditional *β* because it has been shown to be more sensitive to changes in vigilance tasks (See et al., 1997).

Psychological Outcome Measures

Mental workload was measured immediately after the vigilance task using a computerized version of the NASA Task Load Index (TLX; Hart & Staveland, 1988). The TLX is a multi-dimensional rating procedure that provides an overall workload score based on an average of ratings on six subscales: Mental Demand, Physical Demand, Temporal Demand, Own Performance, Effort, and Frustration (Hart & Staveland, 1988). Mental Demand assesses how much mental and perceptual activity was required. Physical Demand evaluates how much physical activity was required. Temporal Demand assesses how much time pressure was felt due to the rate or pace at which the task was presented. Own Performance looks at how successful raters felt they were in accomplishing the goals of the task. Effort evaluates how hard the rater had to work to accomplish their level of performance. Frustration level assesses how insecure, discouraged, irritated, and annoyed the rater felt during the task. Overall workload scores are determined by responses to the six rating scales either averaged across ratings or weighted by pair-wise comparisons among these six factors. In this study a computerized version of the TLX was used to ensure ease of use and efficiency when scoring the tests. The computerized version is highly correlated with other methods of administration (computer vs. verbal = .98, computer vs. paper/pencil = .94; Hart & Staveland, 1988).

Participants rated the perceived workload of the vigilance task on each TLX dimension by sliding a bar between 0, “Low”, and 100, “High”. Unweighted averages of the slider scores were used as measures of the global scores. This is consistent with previous research that demonstrates similar results with both weighted and unweighted approaches to scoring (Nygren, 1991; Rubio, Diaz, Martin, & Puente, 2004; Wiebe, Roberts, & Behrend, 2010).

Psychological stress was measured before and after the vigilance task using the Short Stress State Questionnaire (SSSQ; Helton, 2004). The SSSQ is a 24-item multidimensional questionnaire based on the Dundee Stress State Questionnaire (DSSQ; Matthews, Joyner, Gilliland, Huggins, & Falconer, 1999). The SSSQ factors include Distress, Engagement, and Worry. They are meant to closely reflect the concept of a mental trilogy composed of affect, conation, and cognition (Matthews et al., 2002). The Distress factor appears to be a measure of negative affect (“I am depressed”), the Engagement factor is predominantly a motivation factor (“I want to succeed today”), and the Worry factor appears to reflect cognition (“I feel concerned about the impression I will make”; Helton, Fields, & Thorton, 2005).

Stress was also measured before and after the vigilance task using the Stressor Appraisal Scale (SAS; Schneider, 2008). The SAS is a ten-item scale representing primary and secondary stress appraisals. Primary appraisals are evaluations of how personally significant and relevant the situation is and items ask about situational threat, demand, stressfulness, exertion, effort, importance, and uncertainty. Secondary appraisals are evaluations of the amount of resources one has to cope with the situation and measures manageability, ability, and performance.

Procedure

Participants were told that they were testing a new computerized vigilance task to assess its usefulness. They were not informed about hearing binaural beats and were told that the purpose of the audio track and headphones was simply to block out background noise. Before starting the vigilance task, participants completed pre-measures of the SSSQ followed by the SAS. These tests were administered on the computer through a webpage created using Qualtrics. After the participants were finished with both pre-measures, they completed a short practice vigilance task in which no audio was present. This practice task was 5 minutes in length and participants were trained in this short vigil until they had at least an 80% hit rate and, at most, a 6% false alarm rate. Participants had three tries to reach these performance criteria during the task. If participants could not reach these standards in three tries or less, they were directed to continue on to the experiment, but their data was not included in the final analysis. Allowing them to continue regardless of practice performance ensured that participants were not simply failing on purpose to get their course credit without having to participate in the experiment. Nineteen participants failed to meet these criteria.

Each participant was assigned randomly to one of four conditions. Participants either listened to an audio track containing only pink noise or a track containing pink noise with beta binaural beats. In addition, participants either completed the slow or fast event rate version of the vigilance task. Participants were unaware of what condition they were in. There was also no information present in the vigilance task which could have indicated what condition they were in or how conditions varied.

The experimental vigil involved participants sitting at a computer, pressing the spacebar as quickly as possible when the target was presented. Once the vigilance task was completed, the stress measures were administered for a second time, along with the workload measure. The order of administration was NASA-TLX, SSSQ, and SAS. Like the pre-measures, the post-measures were also administered by computer. After completion of the measures, participants were debriefed by the experimenter and given the chance to ask any questions about the study.

IV. RESULTS

Manipulation Check

Of the 130 participants in this study, data from 82 of them were analyzed, while 48 were excluded. The participants were asked at the end of the experiment if they heard a “wobbly” or “beat” noise in their headphones. This “wobbly” noise was indicative of the presence of binaural beats. Participants in the binaural beat condition who did *not* report hearing this noise were excluded from analyses. In addition, data from participants in the pink noise condition were randomly selected to be included in the analyses to achieve equal *n*’s between event rate conditions. Using these selection criteria, near equal *n*’s were obtained (PN, Slow: *n* = 20; BB, slow: *n* = 20; PN, fast: *n* = 21; BB, fast: *n* = 21). In addition to the 130 participants, nineteen participants were excluded prior to data analysis for failing the training portion of the task.

Vigilance Performance

Correct Detections. Mean percentages of correct detections and their associated standard deviations are presented in Table 1 for all combinations of event rate, audio manipulation, and periods of watch.

Table 1

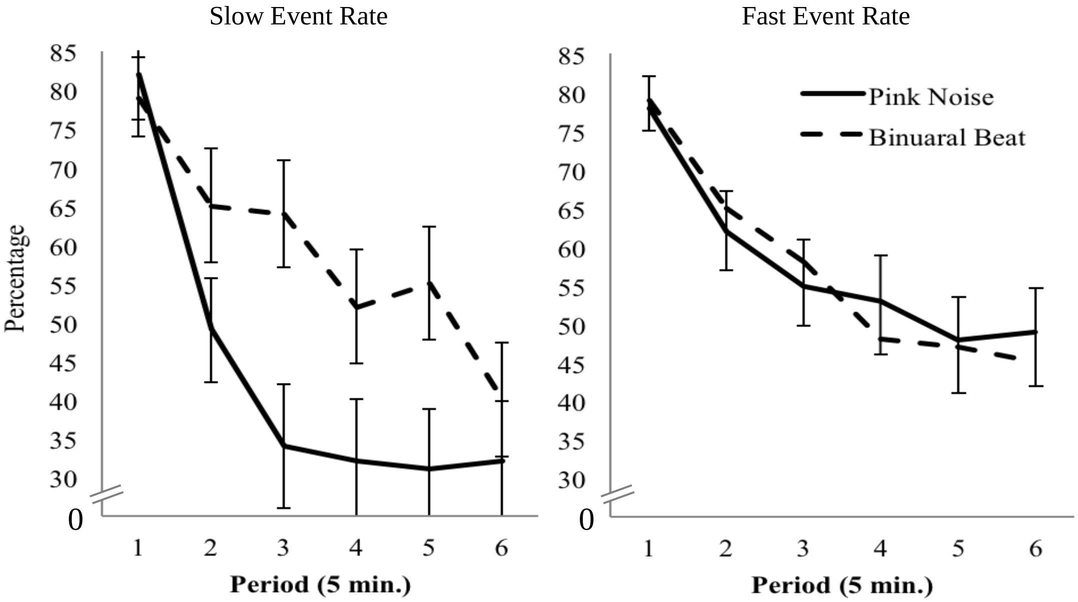
Mean percentages of correct detections for all combinations of event rate, audio manipulation, and periods of watch. Standard deviations are in parentheses.

		Periods (5 minutes)						
Event Rate	Audio	1	2	3	4	5	6	Mean
20 events/min	PN	81.55	49.17	33.93	32.26	30.83	31.67	43.23
	(*n* = 20)	(25.63)	(29.85)	(35.68)	(35.25)	(35.16)	(34.58)	(26.26)
	BB	79.17	64.88	64.40	51.67	55.21	40.36	59.28
	(*n* = 20)	(22.86)	(32.59)	(31.23)	(33.29)	(32.80)	(32.78)	(26.02)
75 events/min	PN	77.78	61.98	55.23	52.58	48.11	48.80	57.41
	(*n* = 21)	(19.14)	(23.52)	(27.08)	(26.95)	(24.92)	(25.50)	(22.31)
	BB	79.57	64.66	58.20	48.12	47.08	44.52	57.03
	(*n* = 21)	(13.72)	(22.96)	(24.04)	(31.62)	(31.50)	(33.06)	(23.19)
	Mean	79.50	60.25	53.03	46.26	45.36	41.47	54.31
		(20.38)	(27.68)	(31.35)	(32.32)	(31.93)	(31.93)	(24.84)

Examination of Table 1 reveals that the amount of correct detections decreased consistently with time on task. A 2 (event rate) x 2 (audio condition) x 6 (periods of watch) mixed-ANOVA was performed on the arcsines of the percentages. This transformation was used to normalize the percentage data (Kirk, 1995). For this, and all subsequent ANOVAs, Box's epsilon was used to correct for violations of sphericity (Field, 2009). Complete summaries of this and all subsequent ANOVAs are presented in the Appendices. Main effects for audio condition, event rate, and their interaction were not significant. Tests of within-subjects effects revealed a significant vigilance decrement ($F(3.71,289.15) = 52.84$, $p < .001$, partial $\eta^2 = .40$) across periods, and significant interactions for period by audio condition ($F(3.71, 289.15) = 3.05$, $p < .05$, partial $\eta^2 = .04$) and period by event rate ($F(3.71, 289.15) = 2.95$, $p < .05$, partial $\eta^2 = .04$). The period by audio condition interaction revealed that participants in the binaural beat condition experienced a significantly less steep vigilance decrement than participants who only listened to pink noise. In addition, a significant period by audio condition by event rate ($F(3.71, 289.15) = 2.60$, $p < .05$, partial $\eta^2 = .03$) interaction was found. This three-way interaction can be seen in Figure 1.

To follow-up this interaction a 2 (audio condition) x 6 (periods of watch) mixed-ANOVA was conducted for each event rate. For the fast event rate, there were no significant main effects for audio condition, and although the vigilance decrement was present (*F*(3.61, 144.53) = 31.65, $p < .05$, partial $\eta^2 = .44$), it did not vary by audio condition (see right panel, Figure 1). For the slow event rate, the main effect of audio condition approached significance but was not significant (*F*(1, 38) = 3.82, $p < .06$, partial $\eta^2 = .09$). As seen in the left panel of Figure 1, there was a significant vigilance decrement (*F*(3.48, 132.19) = 25.75, $p < .001$, partial $\eta^2 = .40$) and this decline varied as a function of audio condition (*F*(3.48, 132.19) = 3.48, $p < .01$, partial $\eta^2 = .08$), with participants in the binaural beat condition performing better and having a less pronounced vigilance decrement than those who listened only to pink noise. Based on the results, only limited support was found for Hypothesis 1. In this experimental paradigm, binaural beats were only able to affect vigilance performance during the slow event rate task, however the performance differences between binaural beat and pink noise participants in the slow event rate condition were so pronounced that it resulted in a significant overall period by audio condition interaction. More research is needed to confirm or deny the effects of event rate on the period by audio condition interaction.

Figure 1. *Period by event rate by audio condition interaction for correct detections.*



False Alarms. Mean percentages of false alarms and their associated standard deviations are presented in Table 2 for all combinations of audio condition, event rate, and period of watch. No significant main effects or interactions were found for false alarms and the rate of false alarms did not significantly change across periods, *p* > .05 in all cases. These results failed to support Hypothesis 2.

Table 2
Mean percentage of false alarms for all combinations of event rate, audio manipulation, and periods of watch. Standard deviations are in parentheses.

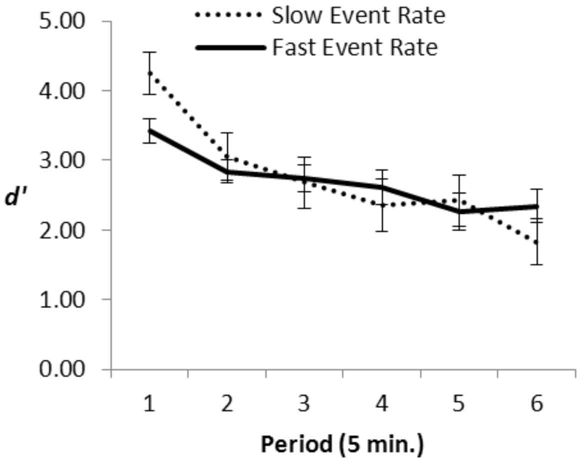
		Periods (5 minutes)						
Event Rate	Audio	1	2	3	4	5	6	Mean
20 events/min	PN	6.49	1.92	1.91	2.29	1.33	3.62	2.93
	(*n* = 20)	(12.66)	(4.28)	(4.71)	(4.99)	(3.45)	(9.79)	(5.04)
	BB	0.85	1.07	0.85	1.17	1.28	1.06	1.05
	(*n* = 20)	(1.78)	(1.95)	(1.58)	(2.44)	(1.97)	(1.42)	(1.52)
75 events/min	PN	1.81	1.09	1.07	1.20	1.93	1.92	1.50
	(*n* = 21)	(3.58)	(0.97)	(0.99)	(1.79)	(3.37)	(4.04)	(1.94)
	BB	1.97	1.11	1.01	1.05	1.90	1.96	1.50
	(*n* = 21)	(5.34)	(1.01)	(0.90)	(1.29)	(2.74)	(2.76)	(1.53)
	Mean	2.76	1.23	1.21	1.42	1.62	2.13	1.74
		(7.30)	(2.41)	(2.53)	(2.95)	(2.91)	(5.45)	(2.92)

Signal Detection Measures. Mean *d*' scores are presented in Table 3 for all combinations of event rate, audio manipulation, and periods of watch. A 2 (event rate) x 2 (audio condition) x 6 (periods of watch) mixed-ANOVA revealed a significant main effect for period ($F(4.03, 314.38) = 28.14$, $p < .01$, partial $\eta^2 = .27$) and a significant period by event rate interaction ($F(4.03, 314.38) = 3.98$, $p < .01$, partial $\eta^2 = .05$). All other sources of variance in the analysis lacked significant, $p > .05$ in all cases. The period by event rate interaction can be seen in Figure 2. The figure shows that *d*' decreased over the course of the task for both event rates, with the slow event rate having a steeper rate of decline than the fast event rate. This indicates that for both event rate conditions, the ability to distinguish signal from noise significantly decreased over the course of the task.

Table 3
Mean scores of d' for all combinations of event rate, audio manipulation, and periods of watch. Standard deviations are in parentheses.

		Periods (5 minutes)						
Event Rate	Audio	1	2	3	4	5	6	Mean
20 events/min	PN	4.10	2.43	1.93	1.63	1.78	1.61	2.25
	(*n* = 20)	(2.15)	(1.98)	(2.47)	(2.53)	(2.45)	(2.27)	(1.98)
	BB	4.41	3.70	3.43	3.08	3.07	2.06	3.29
	(*n* = 20)	(1.75)	(2.19)	(1.94)	(2.06)	(2.15)	(2.00)	(1.74)
75 events/min	PN	3.30	2.66	2.57	2.52	2.12	2.35	2.59
	(*n* = 21)	(0.97)	(.94)	(1.09)	(1.18)	(1.24)	(1.18)	(0.94)
	BB	3.54	3.02	2.91	2.70	2.39	2.33	2.82
	(*n* = 21)	(1.22)	(1.24)	(1.42)	(1.90)	(2.14)	(1.85)	(1.38)
	Mean	3.83	2.95	2.71	2.49	2.34	2.09	2.73
		(1.61)	(1.69)	(1.84)	(2.00)	(2.06)	(1.85)	(1.57)

Figure 2. *Period by event rate interaction for d'.*



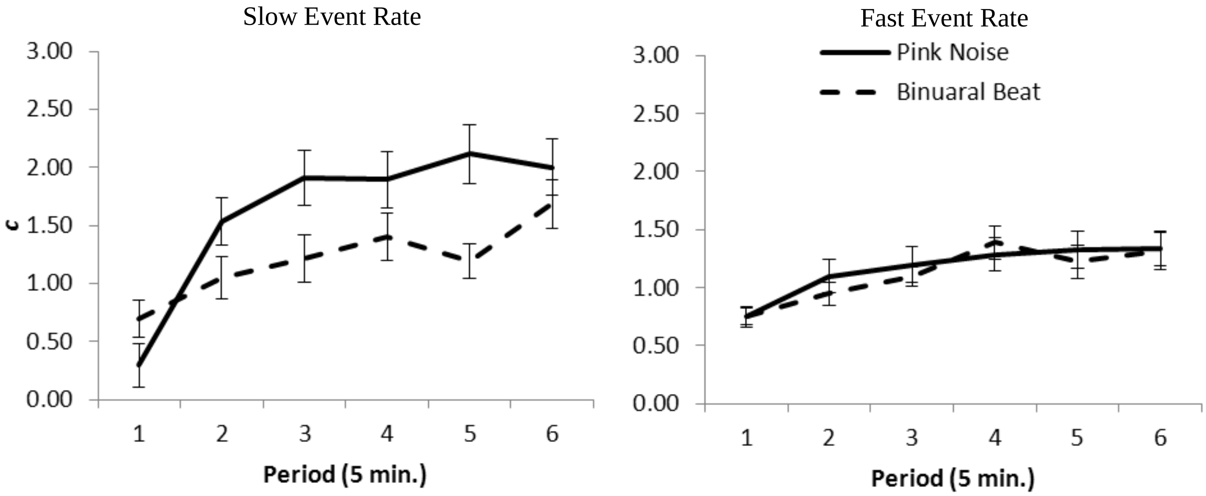
Examination of Table 4 shows that *c* increased with time on task. A 2 (event rate) x 2 (audio condition) x 6 (periods of watch) mixed-ANOVA revealed a significant main effect for event rate ($F(1,78) = 4.02$, $p < .05$ partial $\eta^2 = .05$) and period ($F(3.74, 291.95) = 36.03$, $p < .01$, partial $\eta^2 = .32$), but the main effect for audio condition was not significant. In addition, there were also significant interactions for period by audio condition ($F(3.74, 291.95) = 4.39$, $p<.01$, partial $\eta^2 = .04$), period by event rate ($F(3.74, 291.95) = 5.40$, $p<.01$ partial $\eta^2 = .07$), and period by audio condition by event rate ($F(3.74, 291.95) = 3.27$, $p<.01$ partial $\eta^2 = .04$). This 3-way interaction can be seen in Figure 3.

To follow-up this interaction a 2 (audio condition) x 6 (periods of watch) mixed-ANOVA was conducted for each event rate. For the fast event rate there were no main effects for audio condition and *c* did significantly increase across the experiment ($F(3.83, 153.19) = 17.53$, $p<.001$ partial $\eta^2 = .31$), but this trend did not vary as a function of audio condition. For the slow event rate, the effect of audio condition approached significance but was not significant. As seen in the left panel of Figure 3, *c* did improve ($F(3.54, 134.51) = 20.80$, $p < .001$, partial $\eta^2 = .35$) and this increase varied as a function of audio condition ($F(3.54, 134.51) = 4.49$, $p < .01$, partial $\eta^2 = .11$). For the slow event rate condition, there was a faster initial increase in *c* which stayed more elevated than the fast event rate condition throughout the course of the task.

Table 4.
Mean scores of c for all combinations of event rate, audio manipulation, and periods of watch. Standard deviations are in parentheses.

		Periods (5 minutes)						
Event Rate	Audio	1	2	3	4	5	6	Mean
20 events/min	PN	0.29	1.53	1.91	1.90	2.11	2.00	1.62
	(*n* = 20)	(0.82)	(0.92)	(1.06)	(1.09)	(1.13)	(1.10)	(0.76)
	BB	0.70	1.05	1.21	1.40	1.19	1.68	1.21
	(*n* = 20)	(0.71)	(0.83)	(0.91)	(0.92)	(0.67)	(0.95)	(0.65)
75 events/min	PN	0.75	1.10	1.20	1.28	1.32	1.33	1.17
	(*n* = 21)	(0.32)	(0.67)	(0.70)	(0.67)	(0.75)	(0.68)	(0.59)
	BB	0.75	0.95	1.09	1.39	1.22	1.32	1.12
	(*n* = 21)	(0.40)	(0.45)	(0.38)	(0.66)	(0.66)	(0.74)	(0.44)
	Mean	0.63	1.16	1.35	1.49	1.46	1.58	1.28
		(0.61)	(0.76)	(0.85)	(0.87)	(0.89)	(0.91)	(0.64)

Figure 3. *Period by event rate by audio condition interaction for c.*



Mental Workload

NASA-TLX subscale scores and their associated standard deviations are presented in Table 7 for all combinations of event rate and audio manipulation.

Table 5
Mean NASA-TLX subscale scores for all combinations of event rate and audio manipulation. Standard deviations are in parentheses.

		NASA-TLX Subscale						
Event Rate	Audio	TD	E	FL	MD	PD	P	Mean
20	PN	32.95	35.75	61.85	60.65	55.60	20.30	44.52
events/min	(*n* = 20)	(27.16)	(31.95)	(31.85)	(31.26)	(28.23)	(23.17)	(12.07)
	BB	45.70	52.05	64.55	62.55	67.35	31.05	53.88
	(*n* = 20)	(30.19)	(33.87)	(26.10)	(33.76)	(29.38)	(31.51)	(18.28)
75	PN	59.57	58.52	56.29	65.57	71.48	33.38	57.47
events/min	(*n* = 21)	(22.63)	(29.87)	(23.70)	(26.10)	(25.68)	(28.75)	(15.54)
	BB	55.48	60.33	57.10	64.57	58.38	28.90	54.13
	(*n* = 21)	(27.32)	(32.11)	(25.64)	(28.00)	(29.74)	(24.78)	(15.50)
	Mean	48.65	51.85	59.87	63.38	63.24	28.48	52.58
		(28.35)	(32.83)	(26.65)	(29.36)	(28.51)	(27.18)	(15.96)

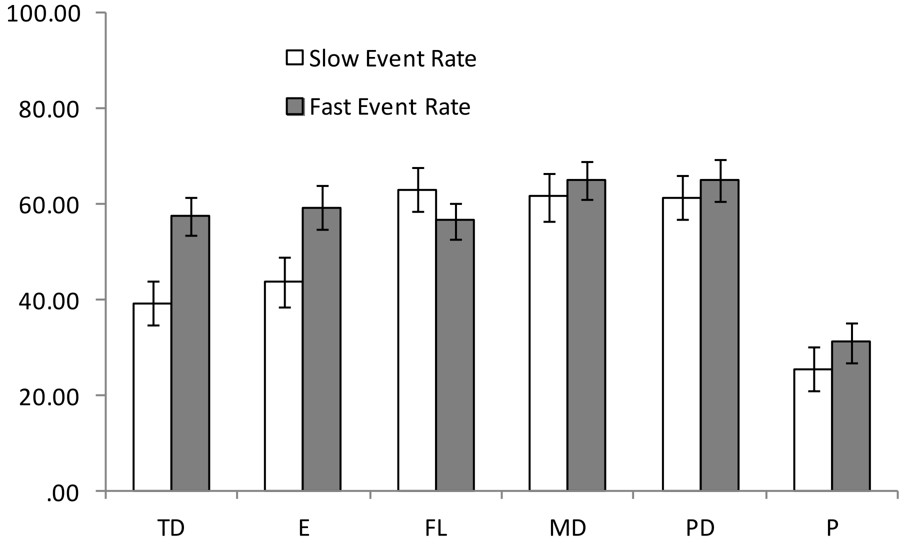
Note. TD = temporal demand, E = effort, FL = frustration level, MD = mental demand. PD = physical demand, P = performance

A 2 (event rate) x 2 (audio condition) x 6 (subscale) mixed-ANOVA conducted on the mean subscale scores revealed a significant main effect for subscale ($F(4.07, 317.58) = 20.95$, $p<.001$, partial $\eta^2 = .21$) and a significant subscale by event rate interaction ($F(4.07, 317.58) = 2.41$, $p<.05$, partial $\eta^2 = .03$). The subscale by event rate interaction can be seen in Figure 4. There were no significant effects for the audio condition. Given the lack of significant audio condition main effects, Hypothesis 3 was not supported.

Although not hypothesized, I followed up on the subscale by event rate interaction to determine where differences exist. Subsequent t-tests using the Bonferroni adjusted *p*-values to correct for family-wise error ($\alpha = .05$, $\alpha/6 = .01$; Kirk, 1995), revealed that the only NASA-TLX significant component contributing to the subscale by event rate interaction was Temporal Demand ($t(80) = -3.05$, $p < .01$, Cohen's $d = -0.14$).

The mean score for Temporal Demand was higher in the fast event rate condition (*M* = 57.53) than the slow event rate condition (*M* = 39.33).

Figure 4. *NASA-TLX Subscales by Event Rate.*



Note. TD = Temporal Demand, E = Effort, FL = Frustration Level, MD = Mental Demand, PD = Physical Demand, P = Performance

Psychological Stress

SSSQ. A 2 (event rate) x 2 (audio condition) between-subjects ANOVA was conducted on the pre-test scores of each SSSQ subscale to determine if any pre-test differences existed between conditions. The ANOVAs revealed that no significant pre-test differences existed between conditions on any of the SSSQ subscales. To test whether the experimental manipulations had any effect on psychological stress, difference scores were computed by subtracting pre-manipulation scores from post-manipulation scores. The mean SSSQ difference scores across conditions and their standard deviations are presented in Table 5. An examination of Table 5 reveals scores on the Engagement subscale (*M* = -0.25 *SD* = 0.47, *t*(81) = -4.77, *p* < .05, *d* = -.53) and the

Worry subscale (*M* = -0.08, *SD* = 0.60, *t*(81) = -1.18, *p* > .05, *d* = .13) decreased while scores on the Distress subscale increased (*M* = 0.10, *SD* = 0.59, *t*(81) = 1.45, *p* > .05, *d* = .17). The SSSQ data were analyzed by a series of 2 (event rate) x 2 (audio condition) between-subjects ANOVAs conducted on the post-pre test difference scores for each subscale. For Engagement, the change scores significantly varied by event rate ($F(1,78) = 10.17$, $p < .01$, partial $\eta^2 = .12$) with participants in the slow event rate (*M* = -0.41, *SD* = 0.50) showing a larger post-pre difference score than participants in the fast event rate (*M* = -0.09, *SD* = 0.40). This indicates that participants in the slow event rate condition were less engaged than those in the in the fast event rate condition. There were no significant differences in change scores across conditions for Distress or Worry. No significant differences existed between audio conditions on any of the SSSQ subscales, therefore Hypotheses 4a-4c were not supported.

Table 6
Mean SSSQ subscale post-pre difference scores for all combinations of event rate and audio manipulation. Standard deviations are in parentheses.

		SSSQ Subscale		
Event Rate	Audio	Engagement	Distress	Worry
20 events/min	PN	-0.47	-0.16	-0.38
	(*n* = 20)	(0.58)	(0.56)	(0.87)
	BB	-0.36	0.21	0.03
	(*n* = 20)	(0.40)	(0.52)	(0.39)
75 events/min	PN	-0.12	0.14	-0.00
	(*n* = 21)	(0.37)	(0.65)	(0.52)
	BB	-0.07	0.18	0.03
	(*n* = 21)	(0.44)	(0.61)	(0.41)
	Mean	-0.25	0.10	-0.08
		(0.47)	(0.59)	(0.60)

SAS. A 2 (event rate) x 2 (audio condition) between-subjects ANOVA was conducted on the pre-test scores of the SAS subscales of primary and secondary appraisals to determine if any pre-test differences existed between conditions. The ANOVAS revealed that no significant pre-test differences existed between conditions on either SAS subscale. To test whether the experimental manipulations had any effect on stress appraisals, I computed difference scores by subtracting pre-manipulation scores from post-manipulation scores. The mean SAS difference scores across conditions and their associated standard deviations are presented in Table 6. An examination of Table 6 will reveal that primary appraisals increased ($M = 0.76$, $SD = 1.14$, $t(81) = 6.03$, $p < .001$, $d = .67$) while secondary appraisals decreased ($M = -0.74$, $SD = 1.61$, $t(81) = -4.19$, $p < .001$, $d = -.46$). A 2 (event rate) x 2 (audio condition) between-subjects ANOVA was then conducted on each subscale difference score. For primary appraisals, results indicated that there were main effects for both the audio condition ($F(1,78) = 5.22$, $p < .05$, partial $\eta^2 = .06$) and the event rate ($F(1,78) = 4.28$, $p < .05$, partial $\eta^2 = .05$) but not their interaction. The mean difference scores were higher in the binaural beat condition ($M = 1.03$, $SD = 0.98$) than the pink noise condition ($M = 0.49$, $SD = 1.22$), and higher in the fast event rate condition ($M = 1.00$, $SD = 1.07$) than the slow event rate condition ($M = 0.50$, $SD = 1.17$). The fact that these scores had positive values indicates that participants in the binaural beat and fast event rate conditions thought that the experimental task was more personally relevant to them than they had originally anticipated. There were no significant differences for secondary appraisals, $p > .05$ in all cases. These results failed to support Hypothesis 5, because primary appraisals are looking at how personally relevant the task is and do not reflect the “stress” component of Hypothesis 5.

Table 7. *Mean SAS subscale post-pre difference scores for all combinations of event rate and audio manipulation. Standard deviations are in parentheses.*

		SAS Subscale	
Event Rate	Audio	Primary Appraisal	Secondary Appraisal
20 events/min	PN	0.07	-0.73
	(*n* = 20)	(1.08)	(1.66)
	BB	0.94	-0.53
	(*n* = 20)	(1.11)	(1.67)
75 events/min	PN	0.88	-0.76
	(*n* = 21)	(1.25)	(1.44)
	BB	1.12	-0.94
	(*n* = 21)	(0.86)	(1.76)
	Mean	0.76	-0.74
		(1.14)	(1.61)

V. DISCUSSION

This study sought to investigate the effects of binaural beat audio technology on vigilance task performance, psychological measures of stress, and mental workload. This study also sought to replicate the vigilance performance results of Lane et al. (1998). Hypotheses 1 and 2 stated that individuals listening to beta binaural beats would have improved vigilance task performance compared to individuals listening only to pink noise. Hypotheses 3-5 stated that individuals listening to beta binaural beats would have reduced levels of workload and stress. Hypotheses, results, and implications are discussed below.

Vigilance Performance.

Hit and false alarm rates were used to examine the effects of binaural beats on vigilance performance. Hypothesis 1, which stated that participants listening to binaural beats would have a higher hit rate, was only partially supported. Although no significant audio condition main effects existed for hit rate, significant period by audio condition and period by audio condition by event rate interactions were found for hit rate. The three-way interaction revealed that the interplay of event rate and audio condition played a role in determining vigilance task performance. For the fast event rate condition, participants listening to binaural beats and those listening to pink noise performed about the same overall on the vigilance task. In contrast, for the slow event rate condition, participants listening to binaural beats did better overall on the vigilance task than those listening to pink noise, although this difference was not significant. The significant difference was the slope of the vigilance decrement. The left panel of Figure 1 reveals that the slow event rate condition participants in the pink noise group showed a steeper vigilance decrement compared to a more gradual vigilance decrement for the binaural beat condition. No significant differences were found for false alarms, therefore hypothesis 2 was not supported.

Signal Detection.

Although no hypotheses were made about the signal detection measures of *d'* and *c*, these variables also showed significant differences across experimental conditions. The signal detection variable, *d*', is a measure of perceptual sensitivity. Specifically, it is the quotient of the separation and spread of an occurrence curve. Separation is the distance between the peak of the noise curve and the peak of the signal+noise curve. Spread is the amount of overlap between the two curves. Higher levels of *d*' indicate more separation and spread, and therefore a greater internal probability of correctly detecting a signal. Even though the audio condition differences for *d*' were not significant, an inspection of the means revealed that overall *d*' was greater in the binaural beat condition than the pink noise condition. The only significant difference observed for *d*' was a period by event rate interaction. Overall *d'* was similar in both event rates, but the rate of decline was significantly greater for the slow event rate than for the fast event rate. Conceptually, this verifies the hit rate data, in which participants in the slow event rate condition experienced a greater vigilance decrement. Perhaps this vigilance decrement was greater due to the lower levels of *d*'.

The signal detection measure of *c* was used instead of the more commonly used *B* on the basis of See et al. (1997), who reported that *B* was the least sensitive bias measure to nonperceptual manipulations and to time-dependent changes in vigilance tasks, while *c* was the most sensitive measure. For *c*, significant differences were found for the main effects of event rate and period, as well as for the interaction between period, audio condition, and event rate. The rate of change for *c* varied significantly by audio condition in the slow event rate, but not the fast. In the slow event rate, overall *c* was higher for the binaural beat condition than the pink noise condition (*M* = 2.25). Positive values of *c* indicate a bias towards "*no*" responses, which indicates that participants in the slow binaural beat condition had a greater tendency to respond "no" rather than "yes."

Psychological Outcome Measures.

Hypotheses 3-5 stated that participants listening to beta binaural beats would have less psychological stress and mental workload than those listening to only pink noise. None of my analyses supported these hypotheses. For the NASA-TLX, there was a significant factor by event rate interaction, but no significant differences for audio condition. Subsequent analyses showed that, although overall NASA-TLX scores were not significant, the Temporal Demand subscale was significantly higher in the fast event rate condition. These results provide validation for our event rate manipulation, since the fast event rate resulted in higher temporal demands than the slow event rate.

Results for the SSSQ revealed no significant differences for audio condition on any of the subscales. Only an event rate difference existed for the Engagement subscale, with those in the slow event rate condition experiencing significantly larger decreases in Engagement than those in the fast event rate condition. It is possible that, since the slow event rate was designed to be an easier task, participants felt less interested and invested in the task than they originally thought they would, while, due to the task difficulty, those in the fast event rate condition remained engaged throughout the course of the task. For the SAS, significant difference scores existed for primary appraisals only. For the binaural beat and fast event rate conditions, participants believed that the task was more personally relevant and challenging than they had originally thought, but not necessarily more stressful.

None of the results from the SAS, SSSQ, or NASA-TLX confirm Hypotheses 3-5.. In fact, the results for SAS primary appraisals might be interpreted to indicate that binaural beats could increase the perceived challenge and personal relevance associated with vigilance tasks. This might be a mechanism through which binaural beats could improve performance on vigilance tasks, and future research should investigate this theory in more detail.

Theoretical Implications.

One objective of this study was to provide validation for the Lane et al. (1998) study. Lane found a significant between-subjects difference for theta/delta beats and beta beats on hits and false alarms, but the rate of decrement over time between the conditions was not significant. The current study, however, found a significant period by audio condition difference for hits, but no main effect differences between audio conditions. A possible explanation for this disparity in results could be that participants in the Lane et al. (1998) study already had significant differences between experimental conditions prior to experimentation. If most of the variance between groups existed at period 1 before the binaural beat manipulation took effect, it would produce significant between-subject differences, but no significant changes over the course of the task. However, without more data it is difficult to be certain of the cause of these differences.

Additionally, Lane did not include a control condition in the study, instead focusing on the theta/delta and beta group differences. The theta/delta beats were designed to hinder vigilance performance, while the beta beats were intended to improve performance, so it is not surprising that differences existed between the groups. Finding a significant difference between the control and beta groups would have been a more practical and impressive result, which my study attempted to address.

In addition, one of the more interesting results observed from hit rate data was a reversal of event rate's effects on performance. Typically in vigilance tasks, fast event rates produce noticeable declines in performance and increases in the vigilance decrement (Parasuraman, 1979). This is based on data that suggests that fast event rates increase cognitive workload and strain on attentional resources (Matthews, Davies, & Holley, 1993). This experiment, however, revealed an opposite trend; participants in the fast event rate condition overall performed better on the vigilance task than those in the slow event rate condition. At first glance this may appear to be a flaw in the study or design of the vigilance tasks, but all other tests of method, such as a significant vigilance decrement over time, indicate that this was a properly designed task. This effect may be due to the type of task used and speed of event rate. The task used in this experiment was an *n*-back memory task, in which participants were required to retain in their working memory information from *n* events back. In the case of the present experiment, the task was a 1-back memory task, where participants had to remember information from the stimuli one event previously. Due to the speed of event rates, participants in the slow condition actually had a more difficult task because they were required to keep the information in their working memory much longer than those in the fast event rate task. This reversal in event rate effect is a surprising and significant result. With more research, perhaps these findings can be expressed in display or task designs that minimize fatigue and workload on human systems.

Practical Implications.

The reversal of event rate effect may have important industrial and military applications. This study revealed that the vigilance decrement was significantly reduced in a 75 event/minute task. Although more research is needed to confirm this result, designing tasks at a faster event rate may be the key to reducing the deleterious effects of errors in vigilance. This result may be useful for careers such as cyber operations and airport baggage screening, where information must be analyzed and compared quickly against some kind of standard. Additionally, this study demonstrated that during a 20 event/minute task, binaural beats significantly reduced the vigilance decrement over the course of a 30 minute vigil. If audio technology develops to a level where binaural beats can be utilized efficiently and unobtrusively, this technology may be able to be implemented in workplace environments where failures of vigilance regularly occur.

Limitations.

One limitation of this study was that it was not a perfect replication of Lane et al. (1998) but rather a conceptual one. Although most procedures were replicated, several factors such as frequency of carrier tones, event rates, and psychological outcome variables were slightly different in this current study. Despite, and perhaps because of, these differences, this experiment is still useful in confirming the results of Lane et al.

(1998). Conceptual replication can often be more helpful in confirming past results than perfect replication. Psychology, unlike disciplines such as physics or biology, often deals with variables that are difficult to define objectively and vary considerably from laboratory work to practical application. For example, conceptual replications of a 1975 study on helping behaviors (Levin & Isen, 1975) proved to be more useful than perfect replications (Nussbaum, 2012). The original study found that people were more likely to help others after they found a dime in a phone booth. Subsequent research has confirmed these results by conceptually replicating them in other situations, like when, instead of finding money, people thought about happy memories, did well on a test, or received cookies. Finding money in a phone booth is a very specific, and outdated, scenario. By replicating the results in different environments, it shows that the theory is valid in more than one experimental and situational paradigm. This idea is particularly important to the concept of vigilance, which, in the real world, varies significantly by industry, situation, and environmental factors.

This current study also used a between-subjects design to eliminate carry over effects, which differed from the design used in Lane et al. (1998). This between-subjects design may have negatively affected the results of the current study. After screening participants, the sample size for this study was small, perhaps too small to detect significant differences. For example, based on the hit rate difference, binaural beat performance was .31 SDs higher than pink noise performance. The lack of significance for this small effect size is probably due to the fact that the current study is under powered. The power to find this effect with 41 people per group is only .40. To obtain a power of .80 for these results, 115 participants would have been needed in each condition.

Although this would be a large undertaking, future studies should attempt to replicate this study with larger sample sizes.

Another limitation of this study is the lack of EEG, TCD, or other neurological measures to determine if audio conditions were altering mechanistic functioning during this vigilance task. Instead, a self-report question was used to determine if participants were “hearing” binaural beats, and previous research was used to establish the link between listening to binaural beats and subsequent changes in brainwave frequencies. Without neurological feedback, it’s difficult to determine the mechanism(s) through which binaural beats might improve performance. The current study showed that significant differences did exist between audio conditions on *c* and primary appraisals, perhaps these are some of the mechanisms through which binaural beats operate. Without future research, however, the interpretation of these effects is still unclear.

Future Research.

Future research should replicate this study with neuroimaging technology to verify that brainwave entrainment is actually occurring. The data obtained from neuroimaging may also be able to help identify which specific brain areas are affected by the binaural beats and whether activation of these areas is the mechanism through which binaural beats impact vigilance performance. For example, Langner and Eickhoff (2012) found that the vigilance decrement was connected to decreases in activity associated with the ventro- and dorsolateral prefrontal cortex and parietal and temporal cortex. While most research on binaural beats have examined EEG patterns, little is known about how, or if, beta binaural beats would impact activity in these regions. In addition, future research should investigate whether other binaural beat frequencies can have positive effects on vigilance task performance. For example, alpha frequencies reflect a calm and peaceful but alert state (Haung & Charyton, 2008). Perhaps these frequencies can also impact vigilance performance.

Finally, future research should explore a within-subjects design to maximize results and power, and identify how different binaural beat frequencies operate on the individual. Although the current study sought to minimize exposure to both audio conditions, within-subjects designs can provide a better estimate of how binaural beats could improve individual behavior and potentially highlight individual differences in binaural beat effectiveness. Additionally, important research questions remain concerning how frequently and how long binaural beats should be applied to maximize efficacy. Identifying the precise regimen of binaural beats and more carefully exploring their effects on vigilance is the only way that this technology can be truly utilized in applied industrial settings.

Conclusion

Vigilance will continue to be an important human engineering problem as long as jobs continue to become more automated. Binaural beats are a promising technology for vigilance research and for practical applications of vigilance. However, this area is in its infancy and will only become useful with more research. This study demonstrated that a simple 30-minute binaural beat intervention is capable of improving performance on an *n*-back vigilance task at slow event rates. Furthermore, these differences were produced with binaural beats that were made with readily available software and not proprietarily by a company. Whether this technology can be applied to different types of tasks in different environments is still unknown. With further research and continued innovation, binaural beats may eventually help improve the vigilance decrement.

VI. APPENDICES

ANOVA Summary Tables

Table 8.
ANOVA Summary Table for Performance

	SS	*df*	MS	*F*	Partial η^2
			Hits		
Randomized Groups					
Audio (A)	1.81	1.00	1.81	1.10	.03
Event Rate (ER)	0.69	1.00	0.69	2.76	.01
A x ER	1.46	1.00	1.46	2.22	.03
S/A	51.21	78.00	0.66		
Repeated Measures					
Trial	13.80	3.71	3.72	52.84**	.40
A x Trial	0.80	3.71	0.22	3.05*	.04
ER x Trial	0.77	3.71	0.21	2.95*	.04
A x ER x Trial	0.68	3.71	0.18	2.60*	.03
B x S/A	20.37	289.15	0.07		
			False Alarms		
Randomized Groups					
Audio (A)	0.03	1.00	0.03	0.92	0.01
Event Rate (ER)	0.02	1.00	0.02	0.63	0.01
A x ER	0.02	1.00	0.02	0.67	0.01
S/A	2.70	78.00	0.04		
Repeated Measures					
Trial	0.05	3.11	0.02	2.11	0.03
A x Trial	0.05	3.11	0.02	2.18	0.03
ER x Trial	0.03	3.11	0.01	1.29	0.02
A x ER x Trial	0.04	3.11	0.01	1.68	0.02
B x S/A	1.83	242.47	0.01		

Note. **p*<.05; ***p*<.01. Box's Epsilon correction factor for hits was .74, for false alarms .62, for *d'* .81, and for *c* .75.

Table 8 (Cont).
ANOVA Summary Table for Performance

	SS	*df*	MS	*F*	Partial η^2
		d'			
Randomized Groups					
Audio (A)	49.64	1.00	49.64	3.44	0.04
Event Rate (ER)	0.55	1.00	0.55	0.04	0.00
A x ER	20.45	1.00	20.45	1.42	0.02
S/A	1,126.73	78.00	14.45		
Repeated Measures					
Trial	155.68	4.03	38.63	28.14**	0.27
A x Trial	9.66	4.03	2.40	1.75	0.02
ER x Trial	22.02	4.03	5.46	3.98**	0.05
A x ER x Trial	5.44	4.03	1.40	0.98	0.01
B x S/A	431.52	314.38	1.37		
		c			
Randomized Groups					
Audio (A)	6.60	1.00	6.60	2.88	0.04
Event Rate (ER)	9.20	1.00	9.20	4.02*	0.05
A x ER	4.23	1.00	4.23	1.85	0.02
S/A	178.39	78.00	2.29		
Repeated Measures					
Trial	51.09	3.74	13.65	36.03**	0.32
A x Trial	6.23	3.74	1.66	4.40**	0.05
ER x Trial	7.65	3.74	2.05	5.40**	0.07
A x ER x Trial	4.63	3.74	1.24	3.27*	0.04
B x S/A	110.60	291.95	0.38		

Note. *p<.05; **p<.01. Box's Epsilon correction factor for hits was .74, for false alarms .62, for *d'* .81, and for *c* .75.

Table 9.
ANOVA Summary Table for Pre-Post SSSQ Subscale Difference Scores

	SS	*df*	MS	*F*	Partial η^2
			SSSQ Worry		
Audio (A)	1.01	1	1.01	2.98	0.04
Event Rate (ER)	0.74	1	0.74	2.18	0.03
A x ER	0.75	1	0.75	2.21	0.03
S/A	26.45	78	0.34		
			SSSQ Distress		
Audio (A)	0.91	1	0.91	2.65	0.03
Event Rate (ER)	0.38	1	0.38	1.11	0.01
A x ER	0.56	1	0.56	1.62	0.02
S/A	26.83	78	0.34		
			SSSQ Engagement		
Audio (A)	0.12	1	0.12	0.60	0.01
Event Rate (ER)	2.09	1	2.09	10.17**	0.12
A x ER	0.01	1	0.01	0.05	0.00
S/A	16.01	78	0.21		

Note. *p<.05; **p<.01.

Table 10.
ANOVA Summary Table for Pre-Post SAS Subscale Difference Scores

	SS	*df*	MS	*F*	Partial η^2
			SAS Primary Appraisal		
Audio (A)	6.15	1	6.15	5.22*	0.06
Event Rate (ER)	5.05	1	5.05	4.28*	0.05
A x ER	2.05	1	2.05	1.74	0.02
S/A	91.93	78	1.18		
			SAS Secondary Appraisal		
Audio (A)	0.00	1	0.00	0.00	0.00
Event Rate (ER)	0.96	1	0.96	0.36	0.01
A x ER	0.72	1	0.72	0.27	0.00
S/A	208.17	78	2.67		

Note. **p*<.05; ***p*<.01.

Table 11.
ANOVA Summary Table for NASA-TLX

	SS	*df*	MS	*F*	Partial η^2
Randomized Groups					
Audio (A)	1,112.64	1.00	1,112.64	0.77	0.01
Event Rate (ER)	5,357.59	1.00	5,357.59	3.72	0.05
A x ER	4,956.41	1.00	4,956.41	3.44	0.04
S/A	112,484.77	78.00	1,442.11		
Repeated Measures					
Subscales	72,531.83	4.07	1,4506.27	20.95**	0.21
A x Subscales	1,228.89	4.07	301.82	0.36	0.00
ER x Subscales	8,340.20	4.07	2,048.40	2.41*	0.03
A x ER x Subscales	1,983.03	4.07	487.04	0.57	0.01
B x S/A	270,048.20	317.58	850.32		

Note. **p*<.05; ***p*<.01. Box’s Epsilon correction factor was .81.

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