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Auditory spatial attention gradients and cognitive control as a function of vigilance

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Abstract

Selection and effort are central to attention, yet it is unclear whether they draw on a common pool of cognitive resources, and if so, whether there are differences for early versus later stages of cognitive processing. This study assessed effort by quantifying the vigilance decrement, and spatial processing at early and later stages as a function of time-on-task. Participants performed an auditory spatial attention task, with occasional "catch" trials requiring no response. Psychophysiological measures included bilateral cerebral blood flow (transcranial Doppler), pupil dilation, and blink rate. The shape of attention gradients using reaction time indexed early processing, and did not significantly vary over time. Later stimulus-response conflict was comparable over time, except for a reduction to left hemispace stimuli. Target and catch trial accuracy decreased with time, with a more abrupt decrease for catch versus target trials. Diffusion decision modeling found progressive decreases in information accumulation rate and non-decision time, and the adoption of more liberal response criteria. Cerebral blood flow increased from baseline and then decreased over time, particularly in the left hemisphere. Blink rate steadily increased over time, while pupil dilation increased only at the beginning and then returned towards baseline. The findings suggest dissociations between resources for selectivity and effort. Measures of high subjective effort and temporal declines in catch trial accuracy and cerebral blood flow velocity suggest a standard vigilance decrement was evident in parallel with preserved selection. Different attentional systems and classes of computations that may account for dissociations between selectivity versus effort are discussed.

KEYWORDS

attention capture, DDM, diffusion decision model, eye tracking, Simon effect, sustained attention, transcranial Doppler, vigilance decrement

1 | AUDITORY SPATIAL ATTENTION AND VIGILANCE

The psychological construct of attention is broad and varied, but much of it can be condensed onto two dimensions: selectivity and effort (Broadbent, 1958; James, 1890; Kahneman, 1973). Attention selectivity refers to differential processing of a subset of information at a given time, with selection typically directed towards information related to a task goal, memory, or a physically salient stimulus

(Chun et al., 2011; Awh et al., 2012). Attention effort refers to the subjective ease, or lack thereof, in performing a given task. High amounts of effort are often interpreted as a reflection of a capacity limit for attention, with effort increasing over time in vigilance tasks. Langner and Eickhoff (2013, p. 870) made the following distinction: "This ability to keep one's mind continuously focused on a particular task is considered a fundamental dimension of attentional control, distinct from shifting or dividing the attentional focus or controlling its selectivity" (p. 870).

Prominent theories of attention take different positions on the relation between selectivity and effort. Classic work by Kahneman has a link between attention selectivity and effort due to their common influences on the allocation of resources (Kahneman, 1973). Other resource-based theories can have interactions between selectivity and effort, but it depends on the specific performance situation (Navon & Gopher, 1979; Wickens, 2008). To the extent that effort relates to working memory demands, selectivity may also be compromised by capacity limits of working memory (Caggiano & Parasuraman, 2004; Helton & Russell, 2011; Lavie, 2005) as well as the content in memory (Golob et al., 2017; Luna et al., 2020; Park et al., 2007). In contrast, Posner's theory of attention networks has a distinct alerting system for effort, and orienting and executive systems for selectivity (Petersen & Posner, 2012; Posner, 2008). Other approaches view the subjective sense of cognitive effort as a signal that indexes the costs versus benefits of the ongoing task, which is used to influence cognitive control decisions (Kurzban et al., 2013; Shenhav et al., 2017).

A fundamental property of attention is that it is limited over both space and time (James, 1890). Both attention selectivity and effort are commonly studied by experimentally varying parameters to identify when selection and effort are suboptimal or fail. In this study we use the auditory modality to examine selectivity in the realm of space. Effort can be indexed by performance reductions over time periods lasting minutes to hours (termed the "vigilance decrement"). The vigilance decrement is often characterized as a reduction in cognitive resources over time (Warm & Parasuraman, 2008). Here we tested whether the presumed resources for selectivity and effort show commonality or are distinct.

There were two main questions that motivated this study, and both examined attention selectivity as a function of effort; with effort indexed by the magnitude of vigilance decrements. The first question was whether the shape of auditory attentional bias over a wide spatial range (termed an "attention gradient") changes over the course of the vigilance decrement. If selectivity and effort reflect common attentional resources then changes in the attention gradient would covary with the vigilance decrement. This prediction would apply classic resource depletion, and potentially also withdrawal of resources from the task (Thomson et al., 2015).

Alternatively, if the shape of an attention gradient is stable during the vigilance decrement, then this would suggest different resources contribute to auditory spatial selectivity and applying effort over time. The second question was whether attention control covaries with vigilance at a later stage of response selection, where attention control or stimulus-response compatibility in response selection was indexed by "Simon effect" (described below). As in the well-studied Attention Network Test (ANT; Fan et al., 2002), the two selectivity metrics can be extracted from different comparisons within the same task dataset. Relative to Posner's attention systems described above, the attention gradient measure likely reflects the orienting system, while the Simon effect indexes the executive system.

Much of the research on both spatial attention and vigilance uses tasks in the visual modality. However, the auditory modality has an advantage over other sensory systems in the realm of spatial processing because the auditory system can detect environmental events from all directions and at a range of distances. The omnidirectional sensitivity of audition has been related to having a specialized role as a warning system that can automatically direct attention to events happening in the world (Schafer, 1977; Scharf, 1998). These and other features of the auditory system[1] highlight the possibility of finding notably different cognitive operations among sensory modalities with respect to spatial attention and vigilance. There are prior vigilance studies that presented sounds from one or two speakers (Szalma et al., 2004; Warm & Dember, 2004). However, no previous auditory vigilance studies have mapped-out auditory spatial gradients over time, which requires more than two sound locations. Similarly, we found no vigilance studies on auditory attention control of response selection that investigated the Simon effect or similar tasks.

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[1]There are other substantive reasons for why studying auditory spatial attention may advance our general understanding of spatial attention. A complicating factor in vision is that representation of space in the visual field is not uniform: there are large differences in visual acuity as a function of distance from the fovea (Rovamo & Virsu, 1979). Light information that lands within the ~2° of visual angle occupied by the fovea has an outsize representation in primary visual cortex and the ventral stream (Born et al., 2015). The limited scope of foveal vision requires specialized motor systems to move the eye around so that more of the visual field can be sampled by the high-resolution fovea. Dedicated short-term memory stores are consequently needed to retain information that was gathered from portions of the visual field that were recently sampled (Hollingworth et al., 2008). Visual attention and motor functions are likely inter-related (Rizzolatti et al., 1987), which is supported by observations of overlapping attention and eye movement circuits (Corbetta et al., 1998). In contrast, the auditory system can sample sounds in parallel from any location with smaller differences in spatial resolution, and therefore does not need a specialized motor system for spatial sampling and retention of sampled information in short-term memory.

1.1 | Spatial attention gradients in vision and audition

Spatial attention is often used to study attention selectivity. When participants respond to a simple target, performance is boosted by knowing in advance where the target is likely to occur (Anton-Erxleben & Carrasco, 2013; Downing, 1988; Einhäuser et al., 2008; Posner et al., 1978, 1980). To avoid confounding spatial attention and response mapping subjects typically either press one button to targets, or choose among two or more buttons when discriminating targets on the basis of a non-spatial feature (e.g., shape or pitch). The spatial distribution of attention (attention gradients) can be studied by occasionally presenting targets at various distances from where spatial attention is currently focused. Such attention gradients reveal how selectivity varies as a function of location within a given experimental context. Many studies have explored how experimental parameters affect visual attention gradients (reviewed in Yeshurun, 2019), and are a basic element for quantitative models of attention (Golob et al., 2017; Reynolds & Heeger, 2009).

In visual studies attention gradients are often linear, as indicated by progressive increases in reaction time with greater distance from the focus of attention (Downing & Pinker, 1985; Eriksen & St. James, 1986; LaBerge et al., 1991). In some instances gradients can adopt a quadratic shape over space, with performance benefits at the attentional focus, reduced performance to stimuli away from the focus, and then some improvement in performance to stimuli at even greater distances (Bahcall & Kowler, 1999; Caparos & Linnell, 2010). Far less is known about auditory versus visual attention gradients, but both linear (Mondor & Zatorre, 1995; Rorden & Driver, 2001) and quadratic (Golob & Mock, 2019, 2020; Golob, Winston, et al., 2017) patterns have been reported.

Gradients mapped out by occasional shifts in stimulus location likely reflect attention capture to an unexpected change in the auditory scene (Bregman, 1990; Parmentier, 2014), and is reflected by slower responses and decreased accuracy. As one example, when participants make a choice response to each stimulus in a sequence, an infrequent change between two sound locations slows reaction times, even when participants respond on the basis of a non-spatial feature such as pitch (Roeber et al., 2003; Wetzel et al., 2012). In the current study we also used occasional shifts in sound location to estimate attention capture, but included a wide range of locations to map out attention gradients. This approach is a variation on classic paradigms where attention is directed to one spatial location that usually receives a target (valid trial), but targets are sometimes presented elsewhere (invalid trials; Posner, 1978; Spence & Driver, 1994). Prior work using this paradigm found that the gradients had quadratic shapes, as indexed by reaction time x stimulus location functions, and were sensitive to variables such as where participants focused

top-down attention (left, midline, and right sides) and the type (verbal vs. spatial) of concurrent memory load (Golob & Mock, 2019, 2020; Golob, Venable, et al., 2017; Golob, Winston, et al., 2017).

Studies in the visual modality suggest left-to-right shifts in spatial attention over time in vigilance tasks. For example, when line bisection performance is assessed there is a small, rightward shift with more time on task (Benwell et al., 2013; Manly et al., 2005). A similar rightward shift over time is also evident for target detection accuracy (Matthias et al., 2009). Asymmetries between the left and right sides of egocentric auditory space are commonly seen in dichotic listening studies. In dichotic listening tasks, two sounds are presented simultaneously, one to each ear using headphones, and participants identify or remember what they heard. Under these conditions there is a prominent right ear advantage for which sound is perceived or remembered best (Hugdahl, 2003; Kimura, 1967; Morais & Bertelson, 1973, 1975; Yurgil & Golob, 2010). The right ear advantage has been observed when using speakers or spatial cues, which suggests a right side bias rather than a peculiarity limited to using headphones (Morais & Bertelson, 1973, 1975).

There are some indications that vigilance affects the right ear advantage, at least in the context of sleep deprivation in males (Johnsen et al., 2002) and split brain patients (Warm et al., 1980). One of the goals of the present study was to examine spatial attention gradients to determine if vigilance has differential effects in the left versus right side of space. If a dissociation were observed it would suggest more specific mechanisms than a general reduction in attention resources, which would be expected to have a symmetrical influence on performance.

1.2 | Stimulus-response compatibility (Simon effect) and vigilance

We next turn to the second question, that of how cognitive control and vigilance are related. It has been known for years that even when spatial information is unrelated to a task, the location of the stimulus can still affect performance (Simon & Small, 1969). Reaction times are substantially faster when stimulus and response locations are on the same side of the participant, relative to non-corresponding locations such as when the stimulus is on the right, but the left hand makes the response (now called the "Simon effect"). Slower responses on non-corresponding trials is thought to reflect conflict between stimulus-response codes, when spatial and non-spatial information are mapped onto two different responses (Lu & Proctor, 1995). The Simon effect taps into transient abstract spatial codes used for action (Buhlmann et al., 2007; Hommel, 1993; Wallace, 1971), and does not simply reflect the locations of the hands. Depending on task conditions,

there can be multiple spatial codes for both stimuli and actions (Hommel, 2011).

The Simon effect is one way to index spatial attention control, with smaller Simon effects associated with better attention control by not allowing the irrelevant spatial information to influence response selection. Cognitive control is thought to take a substantial amount of time to be engaged after a stimulus is presented (Botvinick et al., 2001; Posner & Boies, 1971). Evidence supporting this idea is provided by grouping reaction times into bins of fast, intermediate, and slow trials separately for corresponding and non-corresponding trial types. When using visual stimuli the Simon effect is consistently larger for faster trials, and diminishes with slower responses (De Jong et al., 1994; Hommel, 1993; Ivanoff, 2003). As is often the case, findings are less clear in the auditory modality. Several studies observed flat or increasing Simon effects across faster to slower reaction time bins (Proctor & Shao, 2010; Wascher et al., 2001), yet in one study when lower frequency tones were used results were comparable to visual studies (Xiong & Proctor, 2016). Differences in the efficacy of cognitive control can be manipulated using phasic arousal, operationalized by comparing trials with versus without a cue before targets. The, perhaps, counterintuitive result is that cognitive control is better on trials without cues (Fan et al., 2002), particularly for short cue-target intervals (Asanowicz & Marzecová, 2017). Better cognitive control on uncued trials is likely secondary to having slower reaction times relative to cued trials, which provides more time for cognitive control to be engaged (Nieuwenhuis & de Kleijn, 2013; Schneider, 2017).

Cognitive control is thought to decline during vigilance tasks (Warm & Dember, 2004), which may be accompanied by a larger Simon effect. However, few studies have specifically examined cognitive control in vigilance tasks, with some important exceptions (Ishigami & Klein, 2010; Luna et al., 2018; Roca et al., 2011). If reaction times decreased during the vigilance episode then the Simon effect might also increase but for a different reason; transient spatial codes may have greater influence. Previous experiments typically use tasks with infrequent responding, such as continuous performance or sustained attention to response (SART) tasks. The above paragraph shows that cognitive control in general, and the Simon effect in particular, has been extensively examined on the time scale of relatively short trial blocks, with breaks in between blocks. We are not aware of any previous studies that examined the Simon effect as a function of vigilance (i.e., over time scales of tens of minutes), although transfer effects after practice in visual Simon tasks have been examined (Proctor & Lu, 1999).

1.3 | Current study

In the present study participants were given an auditory spatial attention task lasting ~38 min, which was divided into 6 equal watch periods. We focused on two main questions. The first question was whether gradients reflecting attention capture change their shape as the vigilance decrement develops. One possibility is that attention gradients may become more diffuse over time due to reductions in the ability to control focused attention and resist mind wandering (McVay & Kane, 2009; Petersen & Posner, 2012). Such "diffuse" gradients would be indexed by observing flatter location x reaction time functions. The development of habituation could also lead to reduced attention capture driving the gradient shapes (Rankin et al., 2009). Adjustments in sensitivity and response bias over time may also lead to a change in attention gradient shape (Green & Swets, 1966; Thomson, Besner, Smilek, et al., 2016). Alternatively, if the shape of attention gradients does not index resources associated with effort that are presumed to lead to the vigilance decrement, then gradient shape would not change over time. The task used in this study was initially based on work showing that a change in stimulus location slows reaction time, presumably due to distracting effects of attention capture on behavior (Berti et al., 2004; Roeber et al., 2003) and neural activity (Schröger & Wolff, 1998). The effects of infrequent location changes are relative to the current focus of attention, and thus performance reflects an interplay between top-down and bottom-up processes. Accuracy was expected to decrease over time, and as described below, two measures of accuracy (targets, catch trials) provide an opportunity to test for different time courses of accuracy decreases over watch periods. Lastly, for both reaction time and accuracy any vigilance effects could differ between left versus right hemispace locations, which would rule out interpretations based on a general pool of resources.

The second main question is whether cognitive control of irrelevant spatial information, as indexed with the Simon effect, changes with time-on-task. We hypothesized that the Simon effect would increase over time, which would be consistent with performance reductions in many other tasks as a function of vigilance. The Simon effect could have decreased over time as a byproduct of slower reaction times, or increased due to faster reaction times. As a preview, the findings ruled-out both possibilities for changes in the Simon effect over time that are secondary to increases or decreases in reaction time. Behavioral measures included reaction time and accuracy in response to frequent targets as well as infrequent catch trials.

Additional methods were used to better understand any vigilance decrements in our task. Computational modeling of behavioral data was used to fractionate processing into estimates of decision variables (information accumulation rate, decision boundaries) and non-decision time ("diffusion decision model" Ratcliff et al., 2016; Wagenmakers et al., 2007). Psychophysiological methods often provide convergent evidence with behavior when studying the vigilance decrement.

Here we measured blood flow velocity in left and right middle cerebral arteries, which declines over time in vigilance tasks and is a well-validated physiological index of the vigilance decrement (Warm & Parasuraman, 2007). Eye tracking was also used to index cortical neuromodulation, as pupil dilation is positively correlated to noradrenergic activity in the locus coeruleus (Joshi et al., 2016), and blink rate is positively associated with dopamine levels (Jongkees & Colzato, 2016). Consistent with prior work using other vigilance paradigms, we hypothesized that blood flow velocity during task performance would first increase above baseline, and then progressively decrease over time. Results have been mixed when comparing blood flow in the left versus right hemisphere over time, and most work uses visual stimuli. Consequently, we did not make detailed predictions about hemispheric differences. Pupil dilation and blink rate were used as additional metrics to assess vigilance decrements in our novel task. When starting a task pupil dilation typically increases from baseline (Kahneman & Beatty, 1966), and for prolonged tasks then decreases (Abe et al., 2020). Blink rate increases with time when performing a visual task (Stern et al., 1994), and was predicted to increase over time in the current study.

2 | METHOD

2.1 | Participants

Young adult participants were recruited from the University of Texas, San Antonio, and received course credit for participation ($n = 30$, age 19.9 ± 1.7 yrs., M/F = 13/17, 27/30 right-handed). The study focused on two behavioral effects—spatial attention gradients, indexed as differences in reaction time x location, and cognitive control, indexed by the Simon effect, also by measuring reaction time. Our prior work using this paradigm had effect sizes of Cohen's $d = 0.91$ for the location effect and $d = 1.07$ for the Simon effect (Golob & Mock, 2019). Power analysis showed a minimum of 12 participants would be needed for 80% power for the smaller location effect ($p < .05$). In addition to running more than twice the needed participants ($n = 30$), the results below replicated both of these prior findings. The analysis of vigilance was powered at $d = 0.53$, which was well below effect sizes reported in a meta-analysis of the vigilance decrement (mean $d = 0.72$, median $= 0.63$; See et al., 1995). Two additional participants were not included because the transcranial Doppler sensors required the experimenter to enter the test chamber for adjustments, which likely affected vigilance performance. Potential subjects were initially screened using self-report for major psychiatric and neurological disorders, as well as substantial hearing impairments. Hearing thresholds were tested between 500–8,000 Hz using an audiometer (Maico, Eden Prairie MN) to ensure that thresholds were <25 dB and differences between ears were <10 dB. Participants also completed a handedness survey (Oldfield, 1971). Subjective effort was quantified immediately after finishing the vigilance task by using the NASA Task Load Index questionnaire (Hart & Staveland, 1988). The NASA task load index (NASA-TLX) has participants rate their performance across six dimensions (mental demand, physical demand, temporal demand, effort, performance, frustration level), which produces an overall mental workload score along with subscale scores for each dimension. Due to experimenter error, the first 7 participants did not receive the NASA-TLX questionnaire. Participants read and gave written informed consent from a protocol approved by the University of Texas, San Antonio Institutional Review Board.

2.2 | Apparatus

2.2.1 | Functional transcranial Doppler ultrasonography

After signing the consent, participants were fitted with two transcranial Doppler probes to assess left and right middle cerebral artery blood flow velocity, the arteries that supply most of the cortex with blood. Functional transcranial Doppler ultrasonography was acquired with the Doppler-Box X and QL-software (DWL, Compumedics) at a 100 Hz sampling rate. To assure each Doppler probe (2 MHz transducers) was stationary throughout the experiment, both Doppler probes were fixed to the temple of each subject using the DiaMon probe fixation headset (DWL, Compumedics). The middle cerebral artery blood flow velocity (cm/sec) was measured through a temporal window at an average depth of 50.2 ± 1.0 mm. For detailed information on functional transcranial Doppler methods see Deppe et al. (2004). Transcranial Doppler is widely used to study the vigilance decrement, and typically shows reductions in blood flow velocity with greater time on task (Tripp & Warm, 2008). Sound onset was marked in the Doppler recording using 8-bit TTL codes sent from a RX8 multi-IO processor (Tucker-Davis) that was interfaced with Matlab.

2.2.2 | Eye tracking

A video-based desktop mounted eye tracker was used to monitor gaze position, pupil diameter, and blink rate from the left eye at a sampling rate of 500 Hz (EyeLink 1000 Plus, SR Research, Ontario, Canada). Each participant completed a randomized 13-point fixed calibration and validation protocol before the experiment. After calibration, the computer monitor was pushed back and replaced with the front speaker

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that had a plus sign taped to the speaker's black mesh screen at the same x, y coordinate as the center of the monitor used for calibration and validation.

All raw eye tracking data was loaded into Matlab using a freely available function (Edf2Mat, https://github.com/uzh/edf-converter). The eye tracking data were represented as *x* and *y* gaze position (pixel coordinates; 0,0 is top left of screen), *x* and *y* velocity (arbitrary units), distance of pupil from eye tracker (millimeters), pupil size (arbitrary units), and event onset (sample point). Eye blinks produce large and consistent artifacts that need to be removed. Blink onsets and offsets are clearly visible and marked by looking for brief rapid changes in the y gaze position and y velocity data, along with pronounced dips in pupil size, loss of data between the blink onset and offset. As with previous work, blinks had durations between ~100 and 500 ms (Schiffman, 1990). To reconstruct the pupil size during these blinks, we combined two approaches. First we deleted all data from 150 ms before each blink onset and 150 ms after blink offset (Knapen et al., 2016). Next we interpolated the pupil size using a cubic-spline fit interpolation (Mathôt et al., 2018), and the x and y gaze positions using a linear interpolation. After interpolation, pupil size was filtered using a 100 ms moving average window.

To control for changes in pupil size due to pupillary light reflex the sound booth was kept at a constant ambient illuminance throughout the experiment, and participants were instructed to fixate on the plus sign on the speaker directly in front of them and to not close their eyes. Having each participant focus directly in front of them also controlled for the pupil foreshortening error, which is a distortion in the pupil image if the front of the eye is not parallel to the plane of the camera lens. Additionally, we further controlled for both pupil foreshortening error and random changes due to pupillary hippus by averaging across large time windows (each 6 min and 22 s long, totaling 38 min and 12 s), therefore only measuring gradual changes in pupil size.

2.3 | Stimuli

Participants listened to white noise stimuli (~60 dB nHL, 200 ms duration) that was amplitude modulated at either 25 or 75 Hz (90% depth). These amplitude modulation sounds were easily distinguishable, with 25 Hz sounding like a playing card "shuffle" and 75 Hz sounding like a "buzzing" sound. A third AM rate of 50 Hz was used for "catch" (no-go) trials that did not require a response. The 50 Hz stimulus was also perceived as a buzzing sound, but was distinct from 25 and 75 Hz. All sounds were presented using a 180° free field speaker array. The speaker array was built using a RX8 multi-I/O processer and two SA8 amplifiers (Tucker-Davis Technologies, Alachua, Florida) to drive five Klipsch

speakers (RP-160M, 45-25 kHz). Custom software in Matlab was created to allow for a fully customizable system where any variable (i.e., speaker, sound file, duration, amplitude) can be manipulated with millisecond precision. Each speaker was placed 45° apart in the frontal hemifield (Left → Right: −90°, −45°, 0°, +45°, +90°) at a distance of 66 cm away from the center point of each head's subject. A laser guided coordinate system was used for exact angle and distance placement. The center of each speaker was 112 cm off the ground, which was at eye level for most participants while sitting in the chair.

2.4 | Experimental procedures

Participants first listened to each of the spatialized sounds, and marked on a piece of paper the perceived location relative to the center of their head. All participants reported hearing the sounds at the approximate intended locations. Next, each subject responded by keyboard press (−90° = 1, −45° = 2, 0° = 3, +45° = 4, +90° = 5) to indicate which speaker a sound was played from (40 trials, 8 trials/location, $p = .50$/AM rate, next sound played 2.4 s after keyboard press). Participants were highly accurate at localizing sounds to each speaker location (−90° = 94.9 ± 1.9%, −45° = 98.6 ± 0.9%, 0° = 99.6 ± 0.4%, +45° = 98.2 ± 0.9%, +90° = 96.4 ± 1.9%). After quantifying that each subject could accurately localize the sounds at each speaker, they were then trained on the task. They were familiarized with the three amplitude modulation rates, and then had a short practice run before testing (10 trials that included 1 catch trial). If the subject missed more than 1 trial or responded to the catch trial, a new practice sequence was run until 90% or above accuracy was achieved.

The attention paradigm we developed to examine auditory vigilance decrements allows for separate performance measures to frequent as well as infrequent signals. Since at least the time of Mackworth (1948), responding to infrequent signals has been used to define the vigilance decrement. Yet, near continuous performance over time is also a basic consideration for understanding vigilance (Dinges & Powell, 1985). Typical test durations range from about 30–90 min, although small vigilance decrements are seen in as little as 8 or 12 min sessions (Nuechterlein et al., 1983; Temple et al., 2000). Consequently, we chose a session that lasted a little over 38 min (below).

Stimulus rate is a major contributor to the magnitude and time course of the vigilance decrement (Parasuraman, 1979). Here we used a relatively fast, 1.2 s interval between stimuli to promote a substantial vigilance decrement. This is particularly important for the auditory modality, which may have smaller vigilance decrements relative to vision (reviewed in Warm et al., 2015). Occasionally participants were cued to withhold responding, thus providing an infrequent signal that

could also be used to define vigilance decrement in terms of errors of commission.

In each "go" trial participants discriminated between the 25 and 75 Hz modulation rates ($p = .50$/AM rate) by pressing either the "V" or "M" key on a standard keyboard. The hand/AM rate mapping was approximately counterbalanced across participants. In addition, on occasional no-go "catch" trials ($p = .057$), 50 Hz modulation rate was given, and participants were asked to not respond. Thus, the impact of vigilance could be assessed both when a correct response is required (i.e., pressing the wrong button on target, "go" trials), and also when a correct "no response" is required (i.e., responding with either button on catch, "no-go" trials). This element of the task design is very similar to the Sustained Attention to Response Task (SART) task, which is a widely used task to study vigilance that also has frequent "go" targets and infrequent "no-go" trials (Robertson et al., 1997). Stimuli were presented at a fixed 1.2 s stimulus onset asynchrony (SOA), and each participant was instructed to respond rapidly but at a high level of accuracy.

The majority of stimuli were presented at the midline (0°) location ($p = .792$), but sounds were occasionally delivered to one of the other locations ($p = .038$/location). We term 0° as the "standard" location, while the four lateral locations are called "shift" locations. \Each shift trial was always followed by a standard trial with an average of 5 standard trials (range $= 1–9$) separating each shift trial. The catch trials were also infrequent ($p = .057$) at a probability that is common in the literature (e.g., Grier et al., 2003). Conversely, participants should respond by button press on 94.3% of all the trials.

Participants performed the task continuously for 38 min 12 s (total of 1,908 trials). This time period was evenly divided into 6, 6 min 22 s watch periods. Each watch period had 318 trials: 252 standards, 48 shifts (12/location), and 18 catch trials.

2.5 | Statistical analysis

Behavioral measures included reaction time on correct standard and shift trials, and accuracy for standard, shift, and catch trials. Accurate performance on catch trials was defined as not responding, and any button press before the next stimulus was considered an error. Reaction time was used to define presumed attention gradients, by indexing how the speed of stimulus processing was affected by the distance between a given stimulus and the midline focus of attention. Left- and right-hand measures to the 25/75 Hz amplitude modulation rates were averaged together for the analyses of location, including responses to standard and shift locations.

The role of stimulus-response compatibility was examined by calculating Simon effects as a function of sound and hand locations (left or right side). We first calculated the difference

between hands (left–right hand) to show any biases among response hands across all sound locations, including the midline location. The choice of subtracting left minus right hand reaction times, as opposed to right minus left, was arbitrary. The Simon effect is conventionally defined by comparing behavior when the side of the response hand and stimulus are the same ("corresponding" trials) to when they are on different sides ("non-corresponding" trials), which does not include locations at midline.

It is well-known that speed and accuracy interact, particularly when faster responses come with the performance cost of lower accuracy. Thus differences in reaction times could be attributable to differences in the rate or quality of information processing (sensitivity), as expected by attention effects, or, instead, differences in the amount of information needed before making a response (bias). Signal detection theory is often used to model sensitivity and bias, but it does not model how information accumulates over time. Serial sampling models are formally similar to signal detection theory, and include the core ideas of sensitivity and bias but also model information processing over time (Ratcliff, 1978).

Here we used the EZ-Diffusion model to examine the performance differences by considering the speed and accuracy tradeoff (Wagenmakers et al., 2007). The EZ-Diffusion model is derived from Ratcliff's diffusion decision model which is commonly used to model the subject's information accumulation processes in two-choice response tasks (Ratcliff et al., 2016). One limitation of the diffusion decision model is that it requires a full reaction time distribution as input (including error responses). However, in many experiments (including this one), the behavioral data contains few errors, particularly for responses at each infrequent shift location. A small error reaction time distribution can result in inaccurate parameter estimations by the diffusion decision model. EZ-Diffusion provides an alternative for sparse datasets, and only requires the mean and variance of response times and response accuracy as inputs. These inputs are translated into diffusion decision model parameters that represent information accumulation over time (drift rate), the conservativeness of the response selection (boundary separation), and a catch-all parameter (non-decision time). Non-decision time reflects early perceptual encoding before the decision processes, and action implementation that occurs once the response decision has been made.[2]

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[2]As suggested by Wagenmakers (2007), checks were made to verify that the reaction time distribution had a right skew, and that the assumption of an unbiased starting point for information accumulation was also plausible. The speed of correct and error trials, however, did differ with faster responses on error (482 ± 89 ms) relative to correct (513 ± 76 ms) trials. The effect of not having equivalent reaction times is that the parameters were likely underestimated. However, since we were interested in relative comparisons of parameters among the five locations, the main conclusions of the analysis do not depend on whether the assumption of equal response times for correct and error trials is plausible.

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Functional transcranial Doppler methods were used to simultaneously measure blood flow velocity in the left and right middle cerebral arteries 1 min before, during, and 1 min after performing the vigilance task. The main measure was middle cerebral artery blood flow velocity (cm/sec). Due to unknowns such as the middle cerebral artery diameter and the measurement angle (angle between Doppler probe and the section of middle cerebral artery being measured), it is recommend to use some form of normalization that expresses blood flow velocity relative to a prestimulus baseline period (Deppe et al., 2004). In this study we quantified transcranial Doppler measures during the task as a percentage of the 1 min baseline.

Factors in behavioral analyses included watch period, stimulus type (standard, shift), and stimulus location. The levels were usually either 3 or 6 for watch period and 4 or 5 for location, depending on the particular analysis (described below). For detailed analysis of only the lateral locations two factors were used: side (left, right) and eccentricity ($\pm 45°$, $\pm 90°$). Factors for transcranial Doppler measures included watch period, with levels either 3 or 6 and hemisphere (left, right). Factors for pupil size included watch period, with 7 levels (pre, watch periods 1–6). Blink rate included factors of watch period, with 6 levels (watch period 1–6). Significance was defined as $p < .05$, and Greenhouse-Geisser correction was used to control for violations of sphericity. For clarity, the original degrees of freedom are reported below, and the epsilon value (ε) to correct for the degree of sphericity violation is also included. Post hoc testing used either t-tests with Bonferroni correction or ANOVA.

3 | RESULTS

3.1 | Behavior

3.1.1 | NASA task load index

To quantify the subjective effort of our vigilance task, the paper and pencil version of the NASA task load index (Hart, 2006) was administered after completing the vigilance task to the last consecutive 23 study participants. The median weighted overall workload score was 66.0 ± 14.6 (*SD*). The magnitude scores for each subscale suggests the vigilance task took little physical demand (27.4 ± 5.3), had equal levels of demand on performance (52.0 ± 16.1) and frustration (54.4 ± 16.9), with temporal (65.9 ± 24.3) and mental demand (66.5 ± 20.1) showing the highest demand. For perspective, a meta-analysis of the NASA-TLX in a range of tasks shows that median overall scores with no task were <15, sorting playing cards by suit was 25.6, driving a car was 41.2, and visual search was 57.9 (Grier, 2015). The NASA-TLX data show that our participants thought that the vigilance task was highly demanding.

3.1.2 | Reaction time and accuracy

Behavioral findings for reaction time and accuracy collapsed across hands are shown in Figure 1. The following analyses used ANOVA tests with factors of watch and sound location. For simplicity, when examining all 5 sound locations, the watch factor was analyzed using three combined periods (1–2, 3–4, 5–6, each pair lasted 12 min 44 s), which did not differ substantially from analyses that used all 6 watch periods. For some analyses data from the four shift locations were collapsed, in which case the watch factor had 6 levels (one for each 6 min 22 s watch period).

The reaction time results are shown in Figure 1a,b. A 3 (watch) $\times$ 5 (location) ANOVA test had main effects of watch ($F_{(2,58)} = 18.3$, $p < .001$, $\varepsilon = 0.77$, $\eta_p^2 = 0.39$) and location ($F_{(4,116)} = 13.5$, $p < .001$, $\varepsilon = 0.74$, $\eta_p^2 = 0.32$); the interaction was not significant ($p > .15$). The watch effect was due to progressively faster reaction times over watch periods. Note the hemispace asymmetry, with progressively increasing reaction times with distance from the standard on the left side ($t_{(29)} = 2.9$, $p < .01$) but a plateau on the right side ($t_{(29)} = 0.3$, $p > .75$). Mean reaction times showing the generally progressive decreases for standard and shift trials over the 6 watch periods are shown in Figure 1b. The decrease in reaction time was greatest between watches 1 and 2, but analysis of watches 2–6 showed that reaction time continued to decrease (linear contrast $F_{(1,29)} = 7.9$, $p < .01$, $\eta_p^2 = 0.21$). The reaction time x watch curves for standard and shift trials were both well-fit by a power law function (standard $r^2 = .0.97$, shift $r^2 = .89$).

The accuracy results for targets (25 or 75 Hz sounds) at all five locations are shown in Figure 1c. The 3 (watch) $\times$ 5 (location) ANOVA test had a main effect of watch ($F_{(2,58)} = 10.7$, $p < .001$, $\varepsilon = 0.68$, $\eta_p^2 = 0.27$), due to progressive reductions in accuracy over watch periods. The main effect of location and the watch x location interaction were not significant. Trials without a response were uncommon ($2.1 \pm 0.4\%$ of trials), and did not differ over watch periods ($p > .50$, $\eta_p^2 = 0.03$), which suggests that catch trial "false alarms" did not decrease over time perhaps due to a floor effect, as suggested by Thomson et al. (2016).

We next examine accuracy over all six watch periods for targets and infrequent catch trials, where the correct outcome was to not respond (Figure 1d). Trials were averaged over all five locations in each watch period, as there were not enough catch trials to analyze separate locations, and the main effect of location was not significant for targets. For comparison, Figure 1d separately presents standard and shift targets, but they were collapsed in the main analysis to focus on target versus catch trial effects. A 2 (go/no-go: target, catch) $\times$ 6 (watch) ANOVA had main effects of go/no-go ($F_{(1,29)} = 26.7$, $p < .001$, $\eta_p^2 = 0.48$), watch ($F_{(5,145)} = 7.9$, $p < .001$, $\varepsilon = 0.51$, $\eta_p^2 = 0.21$), and a go/no-go x watch interaction ($F_{(5,145)} = 4.0$,

$p < .01$, $\varepsilon = 0.77$, $\eta_p^2 = 0.12$). Curve fitting showed that target accuracy over watches was fit well by a linear contrast ($F_{(1,29)} = 11.2$, $p = .002$, $\eta_p^2 = 0.28$), while catch trials were well-fit by a quadratic function ($F_{(1,29)} = 22.4$, $p < .001$, $\eta_p^2 = 0.41$).

3.2 | Diffusion decision modeling

The parameters of drift rate, decision boundaries, and non-decision time are plotted in Figure 2a–c as a function of watch period (1&2, 3&4, 5&6). In order to have enough trials to
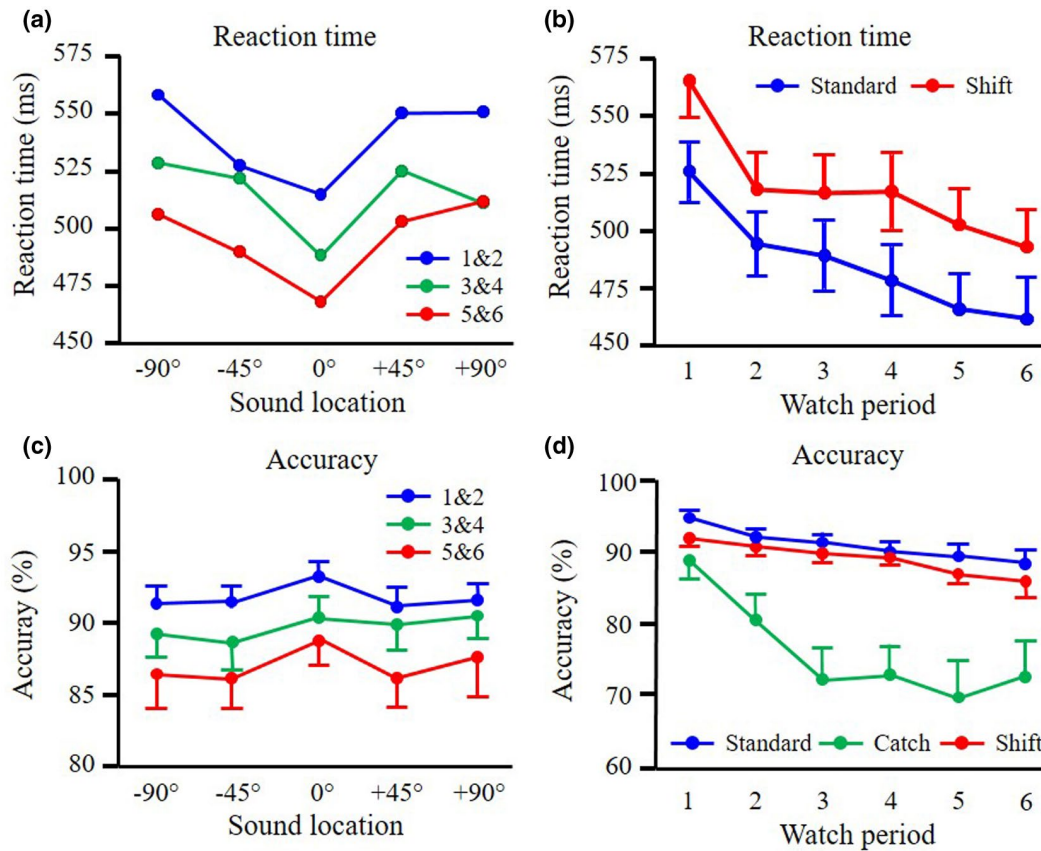
FIGURE 1 Behavioral measures as a function of stimulus location. (a) Reaction time as a function of watch period (1&2, 3&4, 5&6) and sound location. (b) Mean reaction time across all 6 watch periods. Data for shift trials are collapsed over the four lateral shift locations. (c) Accuracy as a function of watch period and sound location. (d) Accuracy to targets at the standard location, shift trials collapsed across the four shift locations, and no-go catch trials, also collapsed across locations. Error bars = *SE*
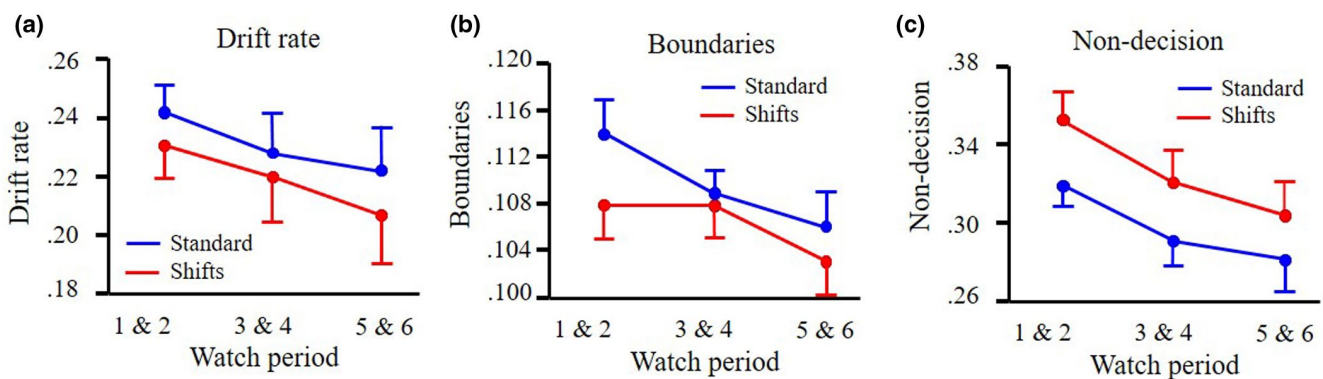
FIGURE 2 Results from diffusion modeling analysis. Parameters of drift rate (a), boundaries (b), and non-decision time (c) are plotted against watch period. Results show that drift rate, boundaries, and non-decision time all progressively declined over watch periods. Data were collapsed across shift locations for each adjacent pair of watch periods. Error bars = *SE*

determine if the diffusion model parameters differed with vigilance we had to collapse across the four shift locations and use pairs of watch periods. One participant could not be included because they had perfect accuracy. The analysis used separate 2 (trial type: standard, shift) × 3 (watch) ANOVA tests. For drift rate, there were significant in effects of location type ($F_{(1,28)} = 10.9$, $p < .01$, $\eta_p^2 = 0.28$) and watch ($F_{(2,56)} = 3.8$, $p < .04$, $\varepsilon = 0.86$, $\eta_p^2 = 0.12$), indicating a faster drift rate for standard versus shift trials and an overall reduction in drift rate across watch periods. Analysis of decision boundaries also had significant main effects of trial type ($F_{(1,28)} = 8.2$, $p < .01$, $\eta_p^2 = 0.23$) and watch ($F_{(2,56)} = 8.6$, $p < .01$, $\varepsilon = 0.71$, $\eta_p^2 = 0.24$). The trial type effect was due to more conservative boundaries for standards, and the watch effect had progressively more liberal decision boundaries over time. For non-decision time there were significant main effects of trial type ($F_{(1,28)} = 71.2$, $p < .001$, $\eta_p^2 = 0.72$) and watch ($F_{(2,56)} = 12.0$, $p < .001$, $\varepsilon = 0.63$, $\eta_p^2 = 0.30$). The trial type effect indicated longer non-decision times for shift trials, and the watch effect was due to progressive reductions in non-decision time across watch periods. Overall, the diffusion decision modeling results show that over time the rate of information accumulation slowed down (drift rate), less information was needed before selecting a response (i.e., more liberal boundaries), and non-decision time decreased. The observation that reaction times sped-up over watch periods was likely due to a combination of more liberal boundaries and faster non-decision times, which outweighed the slowing of drift rate.

3.3 | Simon effect analyses

For the initial analysis of the Simon effect, the dependent variable for reaction time and accuracy was a simple subtraction of left hand–right hand. Thus, negative values indicate the left hand showed faster reaction times or less accurate responses. The reason for this approach was to first map-out compatibility effects over the five locations, including the midline, which cannot be classified as a corresponding/non-corresponding location because it is not lateralized. The main analysis compared the four locations in the left and right hemispaces, and calculated reaction times at each location when the responding hand is at the corresponding (hand and sound on same side) versus non-corresponding (hand and sound on different sides) location.

The Simon effect results for reaction time are shown in Figure 3. A 3 (watch) × 5 (location) ANOVA for left–right reaction times had a main effect of location ($F_{(4,116)} = 29.0$, $p < .000$, $\varepsilon = 0.72$, $\eta_p^2 = 0.50$), reflecting the roughly S-shaped change in reaction times from the left to right side, and watch ($F_{(2,58)} = 4.5$, $p < .02$, $\varepsilon = 0.99$, $\eta_p^2 = 0.13$; Figure 3a). The watch effect is shown more clearly in the next analysis, where the four lateral sound locations are analyzed as a function of corresponding (ipsilateral: stimulus and hand on same side) and non-corresponding (contralateral: stimulus and hand on different sides) trials. The existence of Simon effects was tested using one sample t-tests at each of the four lateral locations, and all p values were significant at $p < .01$ (Bonferonni correction $p = .0125$). A t test at midline showed no significant differences between hands ($p = .16$).

For the main analysis shift trials were collapsed across the 45° and 90° locations on the left or right sides, for a maximum of 24 corresponding (ipsilateral sound and hand location) and 24 non-corresponding (contralateral sound × hand) trials for each of the three watch levels. A 3 (watch) × 2 (side) ANOVA test had a significant interaction of watch × side ($F_{(2,58)} = 4.8$, $p < .02$, $\varepsilon = 0.99$, $\eta_p^2 = 0.14$), due to reductions in the Simon effect over watch periods 5–6 for stimuli on the
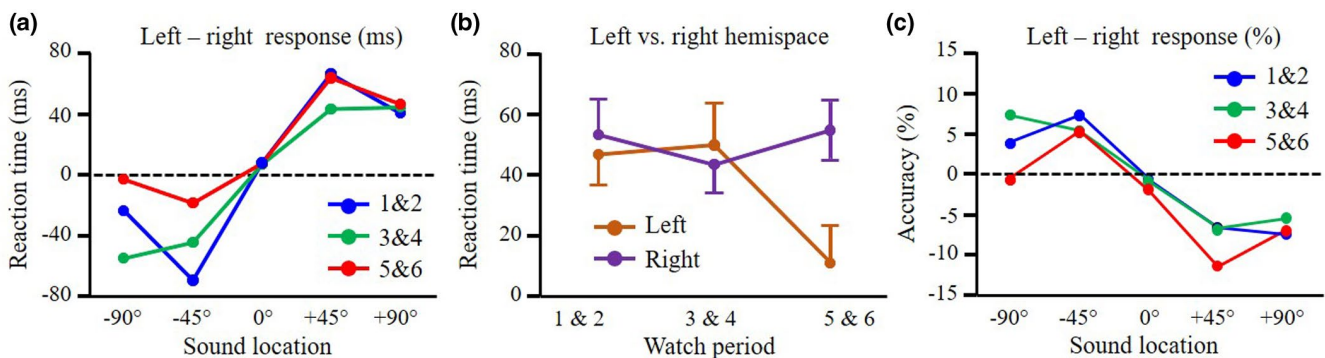
FIGURE 3 Simon effect results. Difference in left-right (a) reaction time and (c) accuracy as a function of stimulus location. The Simon effect is indicated by faster reaction times and accuracy by the left hand to sounds on the left side of space, and vice versa for right hand responses to sounds on the right. Reaction times and accuracy were comparable for both hands to sounds at the midline. (b) The Simon effect (non-corresponding minus corresponding) over watch periods, collapsed across lateral locations on the left (−45°, −90°) and right (+45°, +90°). There was a significant watch x hemispace interaction ($p < .02$), due to a reduction in the Simon effect on the left side in watch periods 5&6 ($p < .005$). Error bars = SE

left, but not right in the last pair of blocks (watch 5–6: left vs. right side, $p < .005$; Figure 3b). The reduction in the Simon effect was significant but marginal, and to better appreciate the evidence for the results Bayes factors were calculated. The watch × side interaction was in the conventional range of anecdotal level of evidence ($BF_{10} = 1.5$), while the left-right difference in watches 5–6 had a moderate-strong level of evidence ($BF_{10} = 9.4$). Analysis of the difference between non-corresponding and corresponding reaction times as a percentage of corresponding trials ([non-corresponding − corresponding]/corresponding) had the same significant watch × side interaction ($F_{(2,58)} = 4.3$, $p < .02$, $\varepsilon = 0.93$, $\eta_p^2 = 0.13$).

Analysis of accuracy differences between hands (left–right) used a 3 (watch) × 5 (location) ANOVA, and also had a significant location effect due to an S-shaped curve with greater accuracy for ipsilateral sounds ($F_{(4, 116)} = 38.0$, $p < .001$, $\varepsilon = 0.82$, $\eta_p^2 = 0.57$, Figure 3c).
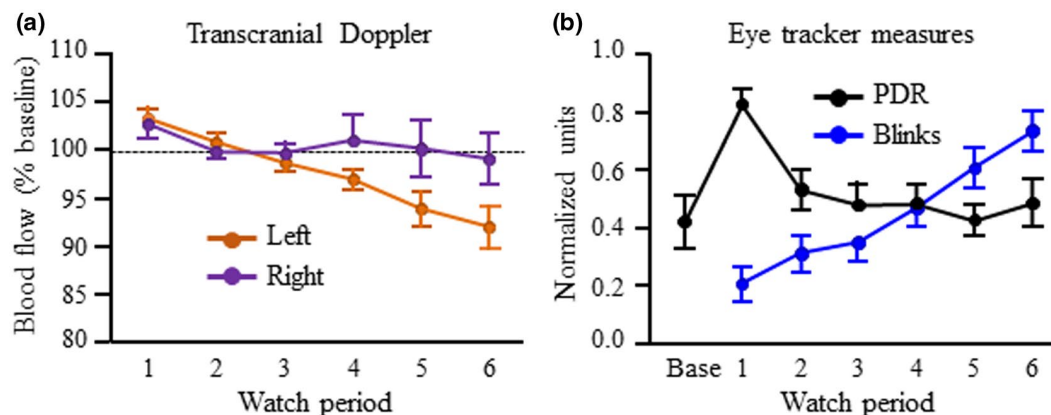
3.4 | Transcranial Doppler measures

A subset of 23 participants had quality transcranial Doppler measures in both hemispheres at baseline and all 6 watch periods. Blood flow velocity relative to a 1 min baseline as a function of hemisphere and time period is shown in Figure 4a. Blood flow increased from baseline to the first watch period in left and right hemisphere middle cerebral artery measures, and then declined over watch periods.

Blood flow velocity during task performance, relative to baseline, was tested using a 6 (watch) × 2 (hemisphere) ANOVA. There was a main effect of watch ($F_{(5,110)} = 5.9$, $p < .02$, $\varepsilon = 0.29$, $\eta_p^2 = 0.21$) due to an increase in the first watch period and then progressive reductions over watch periods. Blood flow velocity increased in the first watch period relative to baseline for 20/23 participants ($t_{(22)} = 3.0$, $p < .01$), and a Helmert contrast showed that the first watch was also greater than watch periods 2–6 ($F_{(1,22)} = 10.3$, $p < .01$, $\eta_p^2 = 0.32$). There was also a main effect of hemisphere, with slower blood flow velocity in the left versus right hemisphere ($F_{(1,22)} = 4.8$, $p < .04$, $\eta_p^2 = 0.21$). There was a trend towards a watch x hemisphere interaction, which did not attain significance ($p < .06$). The trend suggests a progressive reduction over watches in the left hemisphere, while the right hemisphere essentially returned to baseline after the first watch period.

3.5 | Eye tracking measures

A subset of 23 participants had adequate pupillometry measures at baseline and all 6 watch periods. Eighteen of these 23 participants also contributed to the transcranial Doppler analysis. Normalized measures of pupil dilation and blink rate are shown in Figure 4b. Normalization was used instead of percept of baseline, as with transcranial Doppler measures, because, unlike the >6 min watch periods, the 1 min baseline was not long enough to reliably measure blink rate. Pupil dilation was tested using a one-way ANOVA with the factor of watch period (baseline, watch periods 1–6). There was a main effect of watch period ($F_{(6,132)} = 4.0$, $p < .01$, $\varepsilon = 0.53$, $\eta_p^2 = 0.16$). A follow-up Helmert contrast showed that pupil dilation was significantly larger for the first relative to the remaining watch periods (watch 2–6; $F_{(1,22)} = 18.3$, $p < .001$, $\eta_p^2 = 0.45$), with no significant differences among remaining watch periods. Pupil dilation also increased from baseline to the first watch period 1 ($t_{(22)} = 3.4$, $p < .01$), with 18/23 participants showing increases in pupil size.

FIGURE 4 Psychophysiological measures across watch periods. (a) Transcranial Doppler measures of blood flow velocity (% of 1 min baseline). Blood flow significantly increased from baseline to watch period 1 in both hemispheres, and then returned to baseline (right hemisphere) or continued to decrease over the remaining watch periods (left hemisphere). (b) Eye tracking measures as a function of watch period. Pupil dilation response (PDR) increased for the first watch relative to baseline, and then decreased towards baseline. Blink rate progressively increased over watch periods

Blink rate was tested with a one-way ANOVA using the factor of watch period with 6 levels (watch periods 1–6). A one-way ANOVA had a significant effect of watch period ($F_{(5,110)} = 8.2$, $p < .001$, $\varepsilon = 0.60$, $\eta_p^2 = 0.27$). Blink rate progressively increased over the watch periods, and was well-fit by a linear contrast ($F_{(1,22)} = 20.1$, $p < .001$, $\eta_p^2 = 0.48$).

3.6 | Correlations among slopes over watch periods

Lastly, we performed an exploratory analysis of watch period effects by calculating the linear slopes of select dependent variables as a function of watch period (6 values) for individual participants. The slopes for reaction time and accuracy in standard and shift trials, blood flow velocity in the left and right hemisphere, and blink rate were calculated. Note that the blood flow velocity and blink rate measures had <30 participants. Measures with non-linear profiles over watch periods (catch trial accuracy, Simon effect, pupil dilation) were not included.

As expected, correlations between standard and shift trials were large for both reaction time and accuracy measures (p's > .85, p values < .001). Correlations among reaction time and accuracy slopes were not significant for either standard ($r = .27$, $p = .15$) or shift ($r = .19$, p value = .32) trials, suggesting that speed and accuracy changes over watch periods were not strongly related. Blood flow velocity measures had no significant correlations to behavioral measures (all p values > .21). Most correlations to blink rate were not significant (p values > .37), with the exception of standard reaction time ($r = .47$, $p = .019$), which we cautiously interpret given the sample size and non-significant correlation to shift reaction time ($r = .34$, $p = .09$). To the extent that this is a trend, as increases in the positive blink rate slope were associated with smaller, negative reaction time slopes.

4 | DISCUSSION

This study used a novel auditory spatial attention task to examine attention capture and response selection as a function of vigilance. The shape of the reaction time curve indexing attention gradients did not significantly change shape across watch periods. Instead, there was an overall speeding-up of reaction times across watch periods. In contrast, for multiple accuracy measures there was a vigilance decrement. Accuracy reductions over time were precipitous for catch trials and gradual for target trials. Diffusion decision modeling showed that vigilance was accompanied by reductions in the rate of information accumulation, more liberal response selection boundaries, and reduced non-decision time. Simon effects were observed to stimuli on the left and right sides, but only the left side had a significant reduction over the watch

periods (watches 5–6). Blood flow velocity effects were bilateral, with increases at the beginning of the task and then progressive decreases, particularly in the left hemisphere. Pupil size, presumably reflecting noradrenergic activity, and blink rates, associated with dopaminergic activity, responded to the vigilance decrement in different ways. Pupil size increased from baseline at the beginning of the task but quickly returned to baseline levels after watch period 1, and held stable over subsequent watch periods. In contrast, blink rate had a linear increase across the watch periods.

Taken together, the above findings support attention theories with largely independent systems for selectivity and effort, such as Posner's distinction between alerting and orienting attention networks (Petersen & Posner, 2012), or newer ideas on effort as a motivational signal to guide and optimize behavior (Kurzban et al., 2013; Shenhav et al., 2017). The results do not support theories positing general attention resources (Kahneman, 1973). Models of more complex resource allocation (Wickens, 2008) or links between effort and working memory demands would require further testing (Lavie, 2005; Warm & Parasuraman, 2008).

4.1 | Dissociation between attention control (gradient shape) and effort (vigilance)

The shape of a presumed attention gradient, indexed by reaction time, was consistent over watch periods even though a vigilance decrement was evident by decreased accuracy to targets and catch trials, a slowing of the diffusion model drift rate, and reductions in blood flow velocity. The dissociation between attention gradient shape and the vigilance decrement indicates some independence between resources for spatial attention selectivity and those needed to maintain vigilance but are depleted (Warm & Parasuraman, 2008), at least in the task that was used in the current study. In contrast, there is evidence from visual studies that reductions in alertness have a disproportionate cost for processing information in the left hemifield, relative to the right side (Benwell et al., 2013; Chandrakumar et al., 2019, 2020). Future work would be needed to more specifically test relations between effort and alertness, which take into account task and modality differences (Arrabito et al., 2015; Hatfield & Loeb, 1968).

The interpretation of a stable reaction time profile over time with respect to theories that propose resource reallocation and strategic control is less clear. If mind wandering is presumed to re-allocate resources essential for maintaining spatial attention gradients, then our results would challenge that position (Smallwood & Schooler, 2006). Alternatively, the reaction time profile results are compatible with more complex theories involving changes in executive control of resources or strategic control with time-on-task, which are considered in the last section of the Discussion.

It is possible to vary the shapes of attention spatial gradients, as shown by visual studies that manipulated variables such as perceptual load (Caparos & Linnell, 2010; Lavie et al., 2004), spatial cueing (Greenwood & Parasuraman, 1999), the positioning of objects (Hollingworth et al., 2012), motion (Cavanagh & Alvarez, 2005), and sometimes non-adjacent locations (Cave & Bichot, 1999). In the current task, spatial short-term memory load and the range of sound locations can also influence the shape of auditory attention gradients (Golob & Mock, 2020; Golob, Winston, et al., 2017). As an empirical question, the consistent shape of the attention gradient across watch periods suggests that the gradient shape is not driven by classic attentional orienting responses to unexpected stimuli (Sokolov, 1963), or processes associated with the orienting response that habituate over time (Barry, 2009). However, bottom-up effects from shifts, such as interfering with task set or arousal (Horváth, 2014; SanMiguel et al., 2010), are likely present but may not be affected in the present task over the tested watch periods. Convergent evidence from prior work in this task shows that manipulating stimulus rate, which should influence habituation if it was present, also did not significantly alter the shape of attention gradients (Golob & Mock, 2020). It is currently unclear whether the distracting effects of location shift in this task can be voluntarily suppressed (see Horváth, 2013; Sussman et al., 2003), but prior work shows that top-down influences such as spatial memory load do influence the reaction time profile (Golob, Winston, et al., 2017).

The shape of the reaction time × location curves in this study replicated findings from other reports when the same task was tested over shorter time periods (Golob & Mock, 2019, 2020; Golob, Venable, et al., 2017; Golob, Winston, et al., 2017). Reaction time often slows in vigilance tasks (Warm & Parasuraman, 2008), yet in the present study reaction time sped-up over time. A key distinction is that in the current study reaction time decreases occurred to frequent targets that were presented every 1.2 s. In contrast, typical vigilance tasks measure reaction time to infrequent targets separated by 10's of seconds. The profile of reaction time versus watch conformed to a power law function, which is commonly observed in a wide range of tasks (Newell & Rosenbloom, 1981). We could not assess reaction time to infrequent targets here because the correct outcome to the infrequent catch trials was to not respond. Recent work using visual tasks shows that depending on the type of vigilance task, reaction time can either progressively increase or decrease (reviewed in Rubinstein, 2020). Similarly, in a task that measured reaction times to frequent targets and infrequent deviant stimuli, reaction time decreased to targets and increased to deviants with time-on-task (Luna et al., 2020). Having to make choice responses on 94.3% of the trials, as opposed to the typical vigilance task were participants respond to infrequent targets was a key variable that led to reaction times speeding up as time on task increased.

In this study only one location, the midline, was the focus of attention. Based only on the present observations, we can't be sure that the attention gradient-like patterns are solely due to the fact that the midline location was attended. However, previous studies that used the same task already found that the shape of reaction time and accuracy gradients are strongly affected by where attention is directed in space (Golob & Mock, 2019; Golob, Venable, et al., 2017; Golob, Winston, et al., 2017). Moreover, when subjects divide attention among all five locations that are made to be equally probable, there is a relatively flat reaction time curve across locations (Golob & Mock, 2020; Scheuerman et al., 2017). Spatial short-term memory load also contracts the gradient shape relative to a no load condition (Golob, Winston, et al., 2017). These observations suggest that midline per se was not a major factor driving the profile of reaction times over the five spatial locations.

The diffusion decision model results provide more insight into how the rate of information accumulation (drift rate) relates to the placement of the decision boundaries, which are assumed to reflect later stages of decision making prior to response execution (Smith & Ratcliff, 2009). The decision boundaries are the main mechanism for modeling speed accuracy trade-offs in diffusion models; liberal thresholds confer faster speed and lower accuracy, while conservative boundaries slow responding but improve accuracy (Ratcliff, 1978). The results showed, as expected, that the drift rate was faster at the attended standard location relative to the four shift locations. In addition, the decision boundaries when processing stimuli at the standard location were more conservative than at the shift locations. Having more conservative decision boundaries at the attended standard may have been a mechanism to protect against compromising accuracy for faster responses. Note that the profiles of the three diffusion model parameters in Figure 2 are calculated from both correct and error trials, so the pattern of parameters as a function of location does not have to precisely match either the reaction time or accuracy results.

Diffusion decision modeling across watch periods showed that drift rate progressively decreased, boundaries became more liberal, and non-decision time decreased. The findings contribute to the longstanding question of whether attention affects early sensory processing versus later response selection criteria (Kahneman, 1973; Posner, 1978; Thomson, Besner, & Smilek, 2016), and the current results suggest that both mechanisms were affected during the vigilance episode. The progressive reductions in drift rate and sensitivity are often seen in vigilance tasks with infrequent target responses (Mueller et al., 2020; Nelson et al., 2014), while increasingly liberal decision boundaries are known to regulate the speed-accuracy balance in choice-reaction time tasks (Donkin & Brown, 2018). The finding that reaction times got faster over time was not due to faster accumulation of stimulus information, indeed the

diffusion modeling suggested that information accumulation (drift rate) slowed over time. Drift did show differences as a function of spatial attention, as the drift rate was much faster at the attended standard versus shift locations.

The progressive decrease in reaction time over watch periods seems to relate to the other two diffusion model mechanisms. Having a more liberal response criteria with time on task sacrifices some accuracy for greater speed, and is consistent with work on the importance of response criteria in the vigilance decrement (Donkin & Brown, 2018; Thomson, Besner, & Smilek, 2016). The non-decision time parameter also got smaller across watch periods, indicating less time was needed for early perceptual and/or late motor processing. Further experiments are needed to test for hemispace asymmetries in diffusion parameters, as well as to explore non-decision mechanisms. Similarly, other work would be needed for a detailed comparison of reaction time and accuracy curves to diffusion model results, especially with respect to power law versus linear changes over time.

4.2 | Catch trial accuracy over watch periods

In the majority of vigilance tasks participants occasionally respond to a pre-specified target (Funke et al., 2017; Mackworth, 1948). The present experiment examined performance to infrequent stimuli, but participants withheld a response to the occasional catch trial. Note that the types of errors in the two approaches are distinct, with errors of omission in typical vigilance tasks and errors of commission to catch trials in the present study. The two error classes reflect substantially different cognitive and neurobiological processes, with errors of commission often being studied in tasks that examine inhibitory function such as stop-signal, continuous performance, and sustained attention to response (SART) tasks (Robertson et al., 1997; Rosvold et al., 1956; Verbruggen & Logan, 2008).

The profile of errors to targets and catch trials differed, with a much steeper and earlier drop over watch periods for catch relative to target trials. Catch trials were far less probable than standard trials, but were comparable to the probability of shifting to a given location (shift location $p = .038$ vs. catch $p = .057$). However, the probability of standards was much greater than shifts ($p = .79$ vs. .152), yet the slopes of accuracy over watch periods were comparable (see Figure 1d). Thus, the low probability of no-go catch trials does not appear to account for the more rapid decrease in accuracy over watch periods relative to target go-trials (standard and shift trials). Researchers have considered different patterns of vigilance decrements over time, and the time course of no-go accuracy more closely fits the classic exponential decline, while accuracy to targets is more consistent with a linear decline (Hancock, 2017).

4.3 | Cognitive control and vigilance

In contrast to the preserved attention gradient shape over time, the Simon effect did show a modest change over time, with a decrease in the left hemispace towards the end of testing (watch periods 5–6). Reductions in the Simon effect were present in the left but not right hemispace. This places constraints on the interpretation, because prior work on cognitive control points to nonspecific factors such as time of day (Lara et al., 2014) and phasic alertness (Asanowicz & Panek, 2020; Schneider, 2017). Similarly, practice effects would not be expected to differ among hemispaces. Finding a smaller Simon effect towards the end of the watch for sounds on the left, but not right, side of space is unlikely due to such nonspecific factors. Future work is needed to replicate and more precisely understand any left versus right side differences in cognitive control as a function of vigilance.

The initial hypothesis that the Simon effect would increase over time was not supported. Prior studies that did find reductions in cognitive control over vigilance watch periods most often used visual search tasks (e.g., Craig & Klein, 2019) or dual-task paradigms (e.g., Helton & Russell, 2011, 2013, 2017). The flanker effect in the ANT also decreases over the initial 15–20 min of testing (Zholdassova et al., 2019). Increasing working memory load, either spatial or verbal, enhances the vigilance decrement, which suggests that common executive resources were being utilized (Helton & Russell, 2011). The results also bear on observations that trials with the fastest reaction times have the worst cognitive control in the visual flanker task (Nieuwenhuis & de Kleijn, 2013; Schneider, 2017). Since we found that reaction times sped-up over watch periods, a consideration of faster overall reaction times would also predict increases in the Simon effect over watch periods, which was not found. Given the need for replication, mixed results within auditory Simon tasks, and potential differences between modalities, it is premature to pinpoint reasons for why the Simon effect to left hemispace sounds decreased in this study. However, analysis of factors that influence the magnitude of the Simon effect, such as sequence effects across trials ("congruency sequence effects") or the base rate of corresponding versus non-corresponding trials have an extant theory base that may be useful to probe the mechanisms of any vigilance effects (Chinn et al., 2018; Egner, 2017).

4.4 | Psychophysiological results

Bilateral measures of blood flow velocity had robust increases during the first watch period, and then decreased in the other five watch periods. Previous studies have shown that reductions in blood flow velocity reliably accompany the vigilance decrement, and do not decline over time when

participants are not performing a task (Funke et al., 2017; Warm & Parasuraman, 2007). The current experiment had declines in left and right middle cerebral artery blood flow velocity over time, with a transient increase in the right hemisphere and a prolonged increase and then decrease in the left hemisphere. Results have been mixed in previous vigilance studies, with some finding greater declines in the right hemisphere (Shaw et al., 2009) while others found similar results in both hemispheres (Helton et al., 2010). Some variables that may relate to symmetrical versus asymmetrical results among hemispheres are task difficulty and task duration, with right hemisphere reductions for easier, and/or shorter tasks and bilateral reductions for more difficult tasks and longer durations (Helton et al., 2010). Greater bilateral engagement is broadly consistent with neuroimaging studies showing bilateral recruitment with increased difficulty within tasks as well as across adult age groups (Cabeza, 2002; Cabeza & Nyberg, 2000).

Modality differences in transcranial Doppler results have received little attention, but may also be relevant because the vigilance decrement can be less pronounced in audition versus vision (Arrabito et al., 2015; Szalma et al., 2004). More research is needed to reach firm conclusions on the role of modality, but one study that directly compared vision and audition with careful controls found no significant difference in the reduction of blood flow over time among modalities (Shaw et al., 2009). This same group used a spatialized auditory vigilance task (40 min duration), and found strikingly similar results to the present study. Blood flow increased bilaterally at early time periods, decreased to baseline levels, and then continued to decrease in the left hemisphere (Shaw et al., 2013, Figure 3a).

Work using humans as well as animal models have defined a strong association between eye tracking measures and neuromodulation. Phasic pupil dilation can index norepinephrine levels and activity in the locus coeruleus, while rate of spontaneous eye blinking reflects neuromodulation by dopamine (Jongkees & Colzato, 2016; Joshi et al., 2016). Direct measures of locus coeruleus activity show a strong correlation to pupil dilation (Joshi et al., 2016; Murphy et al., 2014). The evidence is not as strong for an association of eye blink rate and dopamine tone, but consists of push-pull effects from dopamine agonists/antagonists that increase/decrease blink rate, and patient studies with presumed higher (e.g., schizophrenia) or lower (e.g., Parkinson's disease) than normal levels of dopamine showing the same pattern (Deuschl & Goddemeier, 1998; Jongkees & Colzato, 2016). The current finding of increased blinking rate in an auditory task supports prior work showing similar increases during visual tasks (Stern et al., 1994).

Comparison of the time course of behavioral indications of vigilance decrement and the eye tracking measures suggest that pupil dilation has a similar profile over time to performance on the catch trials, while linear increases in blink rate are similar to linear decreases in target accuracy (cf. Figures 1d and 4b). A more rigorous comparison would be needed in a future study designed to assess individual differences, but we speculate that that the different time courses of behavioral vigilance decrements for targets and catch-trials may be due, in part, by different influences of noradrenergic and dopaminergic neuromodulation.

Taking a broader perspective, prior work suggests that the concept of vigilance should be multi-faceted. For example, classic work showed that factors such as memory load, presentation rate of stimuli, and modality had systematic effects on performance (Parasuraman, 1979; Warm & Dember, 2004). Another more recent distinction is between executive-vigilance and arousal-vigilance (Fernando Gabriel Luna et al., 2018). It may be worthwhile to loosely group the results into a set of temporal profiles as a function of watch period. One set of results occurred transiently over one or two watch periods, primarily at the beginning of the task (decrease in catch trial accuracy, increase in pupil dilation, increase in right hemisphere blood flow) which then returned to baseline or leveled-off. The decrease in the Simon effect for left hemispace sounds may also fit this grouping, although more watch periods would be needed to see if it continued. The other grouping had a more progressive pattern over all watch periods, albeit with greater changes early in the session, and included decreases in reaction time and accuracy to standard and shift stimuli (especially in the left hemispace), blood flow in the left hemisphere, and blink rate. These results suggest that the impact of vigilance on certain cognitive processes can be expressed through different temporal profiles.

4.5 | Attention control and effort over space and time

We suggested above that the single dissociation between preserving spatial selectivity over the course of the vigilance decrement implies that these phenomena do not reflect a general pool of resources. Here we speculate that the dissociation is the result of deeper reasons having to do with solving different engineering problems of attention. Previous efforts have considered the vigilance decrement as an active attentional response to the test situation (Hancock, 2013; Hockey, 2011). Attention gradients reflect the classic problem of selectivity, either because too much information is present at one time (Posner, 1978) and/or too few actions can be done at one time (Allport, 1989). The computations for attention selectivity have long been a main focus in the visual attention literature (Bundesen, 1990; Reynolds & Heeger, 2009; Wolfe, 2007).

In contrast, the concepts of resources or arousal are often invoked when theorizing about the vigilance

decrement, and the subjective sense of employing attentional effort (Kahneman, 1973). Most recognize that "resources" or "arousal" are not completely satisfying explanations, and will eventually be replaced by more precise concepts (Navon, 1984). Clues for attaining greater precision can be found in other topics of seemingly general psychological phenomena that have been usefully modeled as the outcome of specific computations. Progress has been made in understanding computations that may underpin emotions, such as the "affect as information" hypothesis (Clore & Huntsinger, 2007), and more broadly the framework of understanding cognitive adaptations shaped by evolution (Cosmides & Tooby, 2013; Tooby & Cosmides, 2010). Loneliness, for example, may be an indication of estrangement, which had great importance in hunter-gatherer times because survival depended on being a part of the group (Hawkley & Cacioppo, 2010). Similar evolutionary considerations have been applied to emotions such as happiness (Buss, 2000) and pain (Craig, 2003).

We speculate that the subjective reduction in attention effort that occurs during the vigilance decrement may also indicate the output of an evolutionary important computation. One possibility is that the subjective and objective decline with time-on-task may be the outcome of computing the costs versus benefits of continuing the current task relative to other things that could be done instead. Multiple groups have recently developed ideas on how the sense of mental effort may index opportunity costs (Kurzban et al., 2013) or comparisons of payoffs for exploration versus exploitation (Shenhav et al., 2017), which was inspired by work on animal behavior (Charnov, 1974; Schoener, 1971). The subjective state of boredom, and related performance declines seen in the vigilance decrement, may reflect the outcome of such computations (Geana et al., 2016). From this perspective, dissociations among variables such as attention selectivity and cognitive control may provide additional clues about the information processing mechanisms that give rise to the vigilance decrement.

AUTHOR CONTRIBUTIONS

Edward J. Golob: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Supervision; Validation; Visualization; Writing-original draft; Writing-review & editing. **Jeremy Nelson:** Conceptualization; Methodology; Writing-review & editing. **Jaelle Scheuerman:** Data curation; Formal analysis; Writing-review & editing. **Kristen Brent Venable:** Conceptualization; Formal analysis; Writing-review & editing. **Jeffrey Mock:** Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Resources; Software; Validation; Visualization; Writing-original draft; Writing-review & editing.

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REFERENCES

Abe, T., Mishima, K., Kitamura, S., Hida, A., Inoue, Y., Mizuno, K., Kaida, K., Nakazaki, K., Motomura, Y., Maruo, K., Ohta, T., Furukawa, S., Dinges, D. F., & Ogata, K. (2020). Tracking intermediate performance of vigilant attention using multiple eye metrics. *Sleep*, *43*(3), 1–17. https://doi.org/10.1093/sleep/zsz219

Allport, A. (1989). Visual attention. In M. I. Posner (Ed.), *Foundations of cognitive science* (pp. 631–682). MIT Press.

Anton-Erxleben, K., & Carrasco, M. (2013). Attentional enhancement of spatial resolution: Linking behavioural and neurophysiological evidence. *Nature Reviews Neuroscience*, *14*(3), 188–200. https://doi.org/10.1038/nrn3443

Arrabito, G. R., Ho, G., Aghaei, B., Burns, C., & Hou, M. (2015). Sustained attention in auditory and visual monitoring tasks: Evaluation of the administration of a rest break or exogenous vibrotactile signals. *Human Factors*, *57*(8), 1403–1416. https://doi.org/10.1177/0018720815598433

Asanowicz, D., & Marzecová, A. (2017). Differential effects of phasic and tonic alerting on the efficiency of executive attention. *Acta Psychologica*, *176*(September 2016), 58–70. https://doi.org/10.1016/j.actpsy.2017.03.004

Asanowicz, D., & Panek, B. (2020). Phasic alerting facilitates endogenous orienting of spatial attention: Evidence from event-related lateralizations of the EEG. *Attention, Perception, and Psychophysics*, *82*, 1644–1653. https://doi.org/10.3758/s13414-019-01958-3

Awh, E., Belopolsky, A. V., & Theeuwes, J. (2012). Top-down versus bottom-up attentional control: A failed theoretical dichotomy. *Trends in Cognitive Sciences*, *16*(8), 437–443. https://doi.org/10.1016/j.tics.2012.06.010

Bahcall, D. O., & Kowler, E. (1999). Attentional interference at small spatial separations. *Vision Research*, *39*(1), 71–86. https://doi.org/10.1016/S0042-6989(98)00090-X

Barry, R. J. (2009). Habituation of the orienting reflex and the development of preliminary process theory. *Neurobiology of Learning and Memory*, *92*(2), 235–242. https://doi.org/10.1016/j.nlm.2008.07.007

Benwell, C. S. Y., Thut, G., Learmonth, G., & Harvey, M. (2013). Spatial attention: Differential shifts in pseudoneglect direction with time-on-task and initial bias support the idea of observer subtypes. *Neuropsychologia*, *51*(13), 2747–2756. https://doi.org/10.1016/j.neuropsychologia.2013.09.030

Berti, S., Roeber, U., & Schroger, E. (2004). Bottom-up influences on working memory: Behavioral and electrophysiological distraction varies with distractor strength. *Experimental Psychology*, *51*(4), 249–257. https://doi.org/10.1027/1618-3169.51.4.249

Born, R. T., Trott, A. R., & Hartmann, T. S. (2015). Cortical magnification plus cortical plasticity equals vision? *Vision Research*, *111*, 161–169. https://doi.org/10.1016/j.visres.2014.10.002

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*(3), 624–652. https://doi.org/10.1037/0033-295X.108.3.624

Bregman, A. S. (1990). *Auditory scene analysis: The perceptual organization of sound*. MIT Press.

Broadbent, D. E. (1958). *Perception and communication*. Pergamon Press.

Buhlmann, I., Umilta, C., & Wascher, E. (2007). Response coding and visuomotor transformation in the Simon task: The role of action goals. *Journal of Experimental Psychology: Human Perception and Performance*, *33*(6), 1269–1282. https://doi.org/10.1037/0096-1523.33.6.1269

Bundesen, C. (1990). A theory of visual attention. *Psychological Review*, *97*(4), 523–547. https://doi.org/10.1037/0033-295X.97.4.523

Buss, D. M. (2000). The evolution of happiness. *American Psychologist*, *55*(1), 15–23. https://doi.org/10.1016/j.bbrc.2016.03.040

Cabeza, R. (2002). Hemispheric asymmetry reduction in older adults: The HAROLD model. *Psychology and Aging*, *17*(1), 85–100. https://doi.org/10.1037/0882-7974.17.1.85

Cabeza, R., & Nyberg, L. (2000). Imaging cognition II: An empirical review of 275 PET and fMRI studies. *Journal of Cognitive Neuroscience*, *12*(1), 1–47. https://doi.org/10.1162/08989290051137585

Caggiano, D. M., & Parasuraman, R. (2004). The role of memory representation in the vigilance decrement. *Psychonomic Bulletin & Review*, *11*(5), 932–937. https://doi.org/10.3758/bf03196724

Caparos, S., & Linnell, K. J. (2010). The spatial focus of attention is controlled at perceptual and cognitive levels. *Journal of Experimental Psychology. Human Perception and Performance*, *36*(5), 1080–1107. https://doi.org/10.1037/a0020367

Cavanagh, P., & Alvarez, G. A. (2005). Tracking multiple targets with multifocal attention. *Trends in Cognitive Sciences*, *9*(7), 349–354. https://doi.org/10.1016/j.tics.2005.05.009

Cave, K. R., & Bichot, N. P. (1999). Visuospatial attention: Beyond a spotlight model. *Psychonomic Bulletin & Review*, *6*(2), 204–223. https://doi.org/10.3758/bf03212327

Chandrakumar, D., Dorrian, J., Banks, S., Keage, H. A. D., Coussens, S., Gupta, C., Centofanti, S. A., Stepien, J. M., & Loetscher, T. (2020). The relationship between alertness and spatial attention under simulated shiftwork. *Scientific Reports*, *10*(1), 1–12. https://doi.org/10.1038/s41598-020-71800-6

Chandrakumar, D., Keage, H. A. D., Gutteridge, D., Dorrian, J., Banks, S., & Loetscher, T. (2019). Interactions between spatial attention and alertness in healthy adults: A meta-analysis. *Cortex*, *119*, 61–73. https://doi.org/10.1016/j.cortex.2019.03.016

Charnov, E. L. (1974). Optimal foraging, the marginal value theorem. *Theoretical Population Biology*, *9*, 129–136. https://doi.org/10.1016/0040-5809(76)90040-X

Chinn, L. K. K., Pauker, C. S. P., & Golob, E. J. (2018). Cognitive control and midline theta adjust across multiple timescales. *Neuropsychologia*, *111*, 216–228. https://doi.org/10.1016/j.neuropsychologia.2018.01.031

Chun, M, Golomb, J.D., & Turk-Browne, N.B. (2011). A Taxonomy of external and internal attention. *Annual Review of Psychology*, *62*(1), 73–101. https://www.annualreviews.org/doi/abs/10.1146/annurev.psych.093008.100427?casa_token=G4E0lqinY74AAAAA%3A5Qkesue1_ZhPV_mITvr3TEKOpGoG4V0NaWcLLuOjd6j0j1msutiMTKDZY5iojW-zNsd62lZR050s

Clore, G. L., & Huntsinger, J. R. (2007). How emotions inform judgment and regulate thought. *Trends in Cognitive Sciences*, *11*(9), 393–399. https://doi.org/10.1016/j.tics.2007.08.005

Corbetta, M., Akbudak, E., Conturo, T. E., Snyder, A. Z., Ollinger, J. M., Drury, H. A., Linenweber, M. R., Petersen, S. E., Raichle, M. E., Van Essen, D. C., & Shulman, G. L. (1998). A common network of functional areas for attention and eye movements. *Neuron*, *21*(4), 761–773. https://doi.org/10.1016/S0896-6273(00)80593-0

Cosmides, L., & Tooby, J. (2013). Evolutionary psychology: New perspectives on cognition and motivation. *Annual Review of Psychology*, *64*, 201–229. https://doi.org/10.1146/annurev.psych.121208.131628

Craig, A. D. (2003). A new view of pain as a homeostatic emotion. *Trends in Neurosciences*, *26*(6), 303–307. https://doi.org/10.1016/S0166-2236(03)00123-1

Craig, C. M., & Klein, M. I. (2019). The abbreviated vigilance task and its attentional contributors. *Human Factors*, *61*(3), 426–439. https://doi.org/10.1177/0018720818822350

De Jong, R., Liang, C. C., & Lauber, E. (1994). Conditional and unconditional automaticity: A dual-process model of effects of spatial stimulus-response correspondence. *Journal of Experimental Psychology: Human Perception and Performance*, *20*(4), 731–750. https://doi.org/10.1037/0096-1523.20.4.731

Deppe, M., Ringelstein, E. B., & Knecht, S. (2004). The investigation of functional brain lateralization by transcranial Doppler sonography. *NeuroImage*, *21*(3), 1124–1146. https://doi.org/10.1016/J.NEUROIMAGE.2003.10.016

Deuschl, G., & Goddemeier, C. (1998). Spontaneous and reflex activity of facial muscles in dystonia, Parkinson's disease, and in normal subjects. *Journal of Neurology, Neurosurgery and Psychiatry*, *64*, 320–324. https://doi.org/10.1136/jnnp.64.3.320

Dinges, D. F., & Powell, J. W. (1985). Microcomputer analyses of performance on a portable, simple visual RT task during sustained operations. *Behavior Research Methods, Instruments, & Computers*, *17*(6), 652–655. https://doi.org/10.1080/19475683.2010.513153

Donkin, C., & Brown, S. D. (2018). Response times and decision-making. In J.T. Wixted & E.J. Wagenmakers (Eds.), *Stevens' handbook of experimental psychology and cognitive neuroscience* (4 ed., Vol. *5*, pp. 349–381). West Sussex, UK: John Wiley & Sons. https://doi.org/10.1002/9781119170174.epcn509

Downing, C. J. (1988). Expectancy and visual-spatial attention: Effects on perceptual quality. *Journal of Experimental Psychology. Human Perception and Performance*, *14*(2), 188–202. https://doi.org/10.1037/0096-1523.14.2.188

Downing, C. J., & Pinker, S. (1985). The spatial structure of visual attention. In M. I. Posner & O. S. M. Marin (Eds.), *Attention and performance: XI* (pp. 171–187). Lawrence Erlbaum Assoc.

Egner, T. (2017). Conflict adaptation: Past, present, and future of the congruency sequence effect as an index of cognitive control. In *The Wiley handbook of cognitive control* (pp. 64–78). West Sussex, UK: John Wiley & Sons.

Einhäuser, W., Rutishauser, U., & Koch, C. (2008). Task-demands can immediately reverse the effects of sensory-driven saliency in complex visual stimuli. *Journal of Vision*, *8*(2008), 1–19. https://doi.org/10.1167/8.2.2.Introduction

Eriksen, C. W., & St. James, J. D. (1986). Visual attention within and around the field of focal attention: A zoom lens model. *Perception & Psychophysics*, *40*, 225–240. https://doi.org/10.3758/BF03211502

Fan, J., McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience*, *14*(3), 340–347. https://doi.org/10.1162/089892902317361886

Funke, M. E., Warm, J. S., Matthews, G., Funke, G. J., Chiu, P. Y., Shaw, T. H., & Greenlee, E. T. (2017). The neuroergonomics of vigilance. *Human Factors*, *59*(1), 62–75. https://doi.org/10.1177/0018720816683121

Geana, A., Wilson, R. C., Daw, N., & Cohen, J. D. (2016). Boredom, information-seeking and exploration. In A. Papafragou, D. Grodner, D. Mirman, & J. Trueswell (Eds.), *Proceedings of the 38th Annual Conference of the Cognitive Science Society* (pp. 38, 1751–1756).

Golob, E. J., & Mock, J. R. (2019). Auditory spatial attention capture, disengagement, and response selection in normal aging. *Attention, Perception, & Psychophysics*, *81*(1), 270–280. https://doi.org/10.3758/s13414-018-1611-y

Golob, E. J., & Mock, J. R. (2020). Dynamics of auditory spatial attention gradients. *Cognition*, *194*, 1–9. https://doi.org/10.1016/j.cognition.2019.104058

Golob, E. J., Venable, K. B., Scheuerman, J., & Anderson, M. T. (2017). Computational modeling of auditory spatial attention. *Annual Conference of the Cognitive Science Society*, *39*, 1–7.

Golob, E. J., Winston, J., & Mock, J. R. (2017). Impact of spatial and verbal short-term memory load on auditory spatial attention gradients. *Frontiers in Neuroscience*, *8*(Nov), 1–11. https://doi.org/10.3389/fpsyg.2017.02028

Green, D. M., & Swets, J. A. (1966). *Signal detection theory and psychophysics*. John Wiley and Sons Inc.

Greenwood, P. M., & Parasuraman, R. (1999). Scale of attentional focus in visual search. *Perception & Psychophysics*, *61*(5), 837–859. https://doi.org/10.3758/BF03206901

Grier, R. A. (2015, January). How high is high? A meta-analysis of NASA-TLX global workload scores. *Proceedings of the Human Factors and Ergonomics Society*, *59*, 1727–1731. https://doi.org/10.1177/1541931215591373

Grier, R. A., Warm, J. S., Dember, W. N., Matthews, G., Galinsky, T. L., Szalma, J. L., & Parasuraman, R. (2003). The vigilance decrement reflects limitations in effortful attention, not mindlessness. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *45*(3), 349–359. https://doi.org/10.1518/hfes.45.3.349.27253

Hancock, P. A. (2013). In search of vigilance: The problem of iatrogenically created psychological phenomena. *The American Psychologist*, *68*(2), 97–109. https://doi.org/10.1037/a0030214

Hancock, P. A. (2017). On the nature of vigilance. *Human Factors*, *59*(1), 35–43. https://doi.org/10.1177/0018720816655240

Hart, S. G. (2006). Nasa-task load index (NASA-TLX); 20 years later. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *50*(9), 904–908. https://doi.org/10.1177/154193120605000909

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (task load index): Results of empirical and theoretical research. *Advances in Psychology*, *52*(C), 139–183. https://doi.org/10.1016/S0166-4115(08)62386-9

Hatfield, J. L., & Loeb, M. (1968). Sense mode and coupling in a vigilance task. *Perception & Psychophysics*, *4*(1), 29–36. https://doi.org/10.3758/BF03210443

Hawkley, L. C., & Cacioppo, J. T. (2010). Loneliness matters: A theoretical and empirical review of consequences and mechanisms. *Annals of Behavioral Medicine*, *40*(2), 218–227. https://doi.org/10.1007/s12160-010-9210-8

Helton, W. S., & Russell, P. N. (2011). Working memory load and the vigilance decrement. *Experimental Brain Research*, *212*(3), 429–437. https://doi.org/10.1007/s00221-011-2749-1

Helton, W. S., & Russell, P. N. (2013). Visuospatial and verbal working memory load: Effects on visuospatial vigilance. *Experimental Brain Research*, *224*(3), 429–436. https://doi.org/10.1007/s00221-012-3322-2

Helton, W. S., & Russell, P. N. (2017). Rest is still best. *Human Factors*, *59*(1), 91–100. https://doi.org/10.1177/0018720816683509

Helton, W. S., Warm, J. S., Tripp, L. D., Matthews, G., Parasuraman, R., & Hancock, P. A. (2010). Cerebral lateralization of vigilance: A function of task difficulty. *Neuropsychologia*, *48*(6), 1683–1688. https://doi.org/10.1016/j.neuropsychologia.2010.02.014

Hockey, G. R. J. (2011). A motivational control theory of cognitive fatigue. In P. Ackerman (Ed.), *Cognitive fatigue: Multidisciplinary perspectives on current research and future applications* (pp. 167–187). American Psychological Association. https://doi.org/10.1037/12343-008

Hollingworth, A., Maxcey-Richard, A. M., & Vecera, S. P. (2012). The spatial distribution of attention within and across objects. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(1), 135–151. https://doi.org/10.1037/a0024463

Hollingworth, A., Richard, A. M., & Luck, S. J. (2008). Understanding the function of visual short-term memory: Transsaccadic memory, object correspondence, and gaze correction. *Journal of Experimental Psychology: General*, *137*(1), 163–181. https://doi.org/10.1037/0096-3445.137.1.163

Hommel, B. (1993). Inverting the Simon effect by intention - Determinants of direction and extent of effects of irrelevant spatial information. *Psychological Research Psychologische Forschung*, *55*(4), 270–279. https://doi.org/10.1007/BF00419687

Hommel, B. (2011). The Simon effect as tool and heuristic. *Acta Psychologica*, *136*(2), 189–202. https://doi.org/10.1016/j.actpsy.2010.04.011

Horváth, J. (2013). Preparation interval and cue utilization in the prevention of distraction. *Experimental Brain Research*, *231*(2), 179–190. https://doi.org/10.1007/s00221-013-3681-3

Horváth, J. (2014). Sensory ERP effects in auditory distraction: Did we miss the main event? *Psychological Research*, *78*(3), 339–348. https://doi.org/10.1007/s00426-013-0507-7

Hugdahl, K. (2003). Dichotic listening in the study of auditory laterality. In K. Hugdahl & R. J. Davidson (Eds.), *The asymmetrical brain* (pp. 441–475). MIT Press.

Ishigami, Y., & Klein, R. (2010). Repeated measurement of the components of attention using two versions of the Attention Network Test (ANT): Stability, isolability, robustness, and reliability. *Journal of Neuroscience Methods*, *190*(1), 117–128. https://doi.org/10.1016/j.jneumeth.2010.04.019

Ivanoff, J. (2003). On spatial response code activation in a Simon task. *Acta Psychologica*, *112*(2), 157–179. https://doi.org/10.1016/S0001-6918(02)00081-1

James, W. (1890). *The principles of psychology*. Henry Holt.

Johnsen, B., Laberg, J., Eid, J., & Hugdahl, K. (2002). Dichotic listening and sleep deprivation: Vigilance effects. *Scandinavian Journal of Psychology*, *43*(5), 413–417. https://doi.org/10.1111/1467-9450.00309

Jongkees, B. J., & Colzato, L. S. (2016). Spontaneous eye blink rate as predictor of dopamine-related cognitive function—A review. *Neuroscience and Biobehavioral Reviews*, *71*, 58–82. https://doi.org/10.1016/j.neubiorev.2016.08.020

Joshi, S., Li, Y., Kalwani, R. M., & Gold, J. I. (2016). Relationships between pupil diameter and neuronal activity in the locus coeruleus, colliculi, and cingulate cortex. *Neuron*, *89*(1), 221–234. https://doi.org/10.1016/j.neuron.2015.11.028

Kahneman, D. (1973). *Attention and effort*. Lawrence Erlbaum Assoc.

Kahneman, D., & Beatty, J. (1966). Pupil diameter and load on memory. *Science*, *154*(3756), 1583–1585. https://doi.org/10.1126/science.154.3756.1583

Kimura, D. (1967). Functional asymmetry of the brain in dichotic listening. *Cortex*, *3*, 163–178. https://doi.org/10.1016/S0010-9452(67)80010-8

Knapen, T., de Gee, J. W., Brascamp, J., Nuiten, S., Hoppenbrouwers, S., & Theeuwes, J. (2016). Cognitive and ocular factors jointly determine pupil responses under equiluminance. *PLoS ONE*, *11*(5), e0155574. https://doi.org/10.1371/journal.pone.0155574

Kurzban, R., Duckworth, A., Kable, J. W., & Myers, J. (2013). An opportunity cost model of subjective effort and task performance. *Behavioral and Brain Sciences*, *36*(6), 661–679. https://doi.org/10.1017/S0140525X12003196

LaBerge, D., Brown, V., Carter, M., Bash, D., & Hartley, A. (1991). Reducing the effects of adjacent distractors by narrowing attention. *Journal of Experimental Psychology. Human Perception and Performance*, *17*(1), 65–76. https://doi.org/10.1037/0096-1523.17.1.65

Langner, R., & Eickhoff, S. B. (2013). Sustaining attention to simple tasks: A meta-analytic review of the neural mechanisms of vigilant attention. *Psychological Bulletin*, *139*(4), 870–900. https://doi.org/10.1037/a0030694

Lara, T., Madrid, J. A., & Correa, Á. (2014). The vigilance decrement in executive function is attenuated when individual chronotypes perform at their optimal time of day. *PLoS ONE*, *9*(2), 1–9. https://doi.org/10.1371/journal.pone.0088820

Lavie, N. (2005). Distracted and confused?: Selective attention under load. *Trends in Cognitive Sciences*, *9*(2), 75–82. https://doi.org/10.1016/j.tics.2004.12.004

Lavie, N., Hirst, A., de Fockert, J. W., & Viding, E. (2004). Load theory of selective attention and cognitive control. *Journal of Experimental Psychology: General*, *133*(3), 339–354. https://doi.org/10.1037/0096-3445.133.3.339

Lu, C. H., & Proctor, R. W. (1995). The influence of irrelevant location information on performance: A review of the Simon and spatial Stroop effects. *Psychonomic Bulletin & Review*, *2*(2), 174–207. https://doi.org/10.3758/BF03210959

Luna, F. G., Marino, J., Roca, J., & Lupiáñez, J. (2018). Executive and arousal vigilance decrement in the context of the attentional networks: The ANTI-Vea task. *Journal of Neuroscience Methods*, *306*(May), 77–87. https://doi.org/10.1016/j.jneumeth.2018.05.011

Luna, F. G., Roca, J., Martín-Arévalo, E., & Lupiáñez, J. (2020). Measuring attention and vigilance in the laboratory vs. online: The split-half reliability of the ANTI-Vea. *Behavior Research Methods*, *53*, 1124–1147. https://doi.org/10.3758/s13428-020-01483-4

Luna, F. G., Telga, M., Vadillo, M. A., & Lupiáñez, J. (2020). Concurrent working memory load may increase or reduce cognitive interference depending on the attentional set. *Journal of Experimental Psychology: Human Perception and Performance*, *46*, 667–680. https://doi.org/10.1037/xhp0000740

Mackworth, N. H. (1948). The breakdown of vigilance during prolonged visual search. *Quarterly Journal of Experimental Psychology*, *1*(1), 6–21. https://doi.org/10.1080/17470214808416738

Manly, T., Dobler, V. B., Dodds, C. M., George, M. A. (2005). Rightward shift in spatial awareness with declining alertness. *Neuropsychologia*, *43*(12), 1721–1728. https://doi.org/10.1016/j.neuropsychologia.2005.02.009

Mathôt, S., Fabius, J., Van Heusden, E., & Van der Stigchel, S. (2018). Safe and sensible preprocessing and baseline correction of pupil-size data. *Behavior Research Methods*, *50*(1), 94–106. https://doi.org/10.3758/s13428-017-1007-2

Matthias, E., Bublak, P., Costa, A., Müller, H. J., Schneider, W. X., & Finke, K. (2009). Attentional and sensory effects of lowered levels of intrinsic alertness. *Neuropsychologia*, *47*(14), 3255–3264. https://doi.org/10.1016/j.neuropsychologia.2009.08.004

McVay, J. C., & Kane, M. J. (2009). Conducting the train of thought: Working memory capacity, goal neglect, and mind wandering in an executive-control task. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *35*(1), 196–204. https://doi.org/10.1037/a0014104

Mondor, T. A., & Zatorre, R. J. (1995). Shifting and focusing auditory spatial attention. *Journal of Experimental Psychology: Human Perception and Performance*, *21*(2), 387–409. https://doi.org/10.1037/0096-1523.21.2.387

Morais, J., & Bertelson, P. (1973). Laterality effects of diotic listening. *Perception*, *2*(1), 107–111. https://doi.org/10.1068/p020107

Morais, J., & Bertelson, P. (1975). Spatial position versus ear of entry as determinant of the auditory laterality effects: A stereophonic test. *Journal of Experimental Psychology: Human Perception and Performance*, *1*(3), 253–262. https://doi.org/10.1037/0096-1523.1.3.253

Mueller, S. T., Alam, L., Funke, G. J., Linja, A., Ibne Mamun, T., & Smith, S. L. (2020). Examining methods for combining speed and accuracy in a Go/No-Go vigilance task. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *64*(1), 1202–1206. https://doi.org/10.1177/1071181320641286

Murphy, P. R., O'Connell, R. G., O'Sullivan, M., Robertson, I. H., & Balsters, J. H. (2014). Pupil diameter covaries with BOLD activity in human locus coeruleus. *Human Brain Mapping*, *35*(8), 4140–4154. https://doi.org/10.1002/hbm.22466

Navon, D. (1984). Resources—A theoretical soup stone? *Psychological Review*, *91*(2), 216–234. https://doi.org/10.1037/0033-295X.91.2.216

Navon, D., & Gopher, D. (1979). On the economy of the human-processing system. *Psychological Review*, *86*(3), 214–255. https://doi.org/10.1037/0033-295X.86.3.214

Nelson, J. T. J. T., McKinley, R. A. A., Golob, E. J., Warm, J. S., & Parasuraman, R. (2014). Enhancing vigilance in operators with prefrontal cortex transcranial direct current stimulation (tDCS). *NeuroImage*, *85*(3), 909–917. https://doi.org/10.1016/j.neuroimage.2012.11.061

Newell, A., & Rosenbloom, P. S. (1981). Mechanisms of skill acquisition and the law of practice. In J. Anderson (Ed.), *Cognitive skills and their acquisition* (pp. 1–55). Lawrence Erlbaum Assoc.

Nieuwenhuis, S., & de Kleijn, R. (2013). The impact of alertness on cognitive control. *Journal of Experimental Psychology. Human Perception and Performance*, *39*(6), 1797–1801. https://doi.org/10.1037/a0033980

Nuechterlein, K. H., Parasuraman, R., & Jiang, Q. (1983). Visual sustained attention: Image degradation produces. *Science*, *220*(4594), 327–329. https://doi.org/10.1126/science.6836276

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, *9*(1), 97–113. https://doi.org/10.1016/0028-3932(71)90067-4

Parasuraman, R. (1979). Memory load and event rate control sensitivity decrements in sustained attention. *Science*, *205*, 924–927. https://doi.org/10.1126/science.472714

Park, S., Kim, M.-S., & Chun, M. M. (2007). Concurrent working memory load can facilitate selective attention: Evidence for specialized load. *Journal of Experimental Psychology. Human Perception and Performance*, *33*(5), 1062–1075. https://doi.org/10.1037/0096-1523.33.5.1062

Parmentier, F. B. R. (2014). The cognitive determinants of behavioral distraction by deviant auditory stimuli: A review. *Psychological Research Psychologische Forschung*, *78*(3), 321–338. https://doi.org/10.1007/s00426-013-0534-4

Petersen, S. E., & Posner, M. I. (2012). The attention system of the human brain: 20 years after. *Annual Review of Neuroscience*, *35*, 73–89. https://doi.org/10.1146/annurev-neuro-062111-150525

Posner, M. I. (1978). *Chronometric explorations of mind*. Halsted Press.

Posner, M. I. (2008). Measuring alertness. *Annals of the New York Academy of Sciences*, *1129*, 193–199. https://doi.org/10.1196/annals.1417.011

Posner, M. I., & Boies, S. J. (1971). Components of attention. *Psychological Review*, *78*(5), 391–408. https://doi.org/10.1037/h0031333

Posner, M. I., Nissen, M. J., & Ogden, W. C. (1978, November). Attended and unattended processing modes: The role of set for spatial location. In H. L. Pick & I. J. Saltzman (Eds.), *Modes of perceiving and processing information* (pp. 137–157). Erlbaum. https://doi.org/10.1080/00335558008248231

Posner, M. I., Snyder, C. R., & Davidson, B. J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology: General*, *109*(2), 160–174. https://doi.org/10.1037/0096-3445.109.2.160

Proctor, R. W., & Lu, C. H. (1999). Processing irrelevant location information: Practice and transfer effects in choice-reaction tasks. *Memory & Cognition*, *27*(1), 63–77. https://doi.org/10.3758/BF03201214

Proctor, R. W., & Shao, C. (2010). Does the contribution of stimulus-hand correspondence to the auditory Simon eVect increase with practice? *Experimental Brain Research*, *204*(1), 131–137. https://doi.org/10.1007/s00221-010-2284-5

Rankin, C. H., Abrams, T., Barry, R. J., Bhatnagar, S., Clayton, D. F., Colombo, J., Coppola, G., Geyer, M. A., Glanzman, D. L., Marsland, S., McSweeney, F. K., Wilson, D. A., Wu, C.-F.-F., & Thompson, R. F. (2009). Habituation revisited: An updated and revised description of the behavioral characteristics of habituation. *Neurobiology of Learning and Memory*, *92*(2), 135–138. https://doi.org/10.1016/j.nlm.2008.09.012

Ratcliff, R. (1978). A theory of memory retrieval. *Psychological Review*, *85*(2), 59–108. https://doi.org/10.1037/0033-295X.85.2.59

Ratcliff, R., Smith, P. L., Brown, S. D., & McKoon, G. (2016). Diffusion decision model: Current issues and history. *Trends in Cognitive Sciences*, *20*(4), 260–281. https://doi.org/10.1016/j.tics.2016.01.007

Reynolds, J. H., & Heeger, D. J. (2009). The normalization model of attention. *Neuron*, *61*(2), 168–185. https://doi.org/10.1016/j.neuron.2009.01.002

Rizzolatti, G., Riggio, L., Dascola, I., & Umiltá, C. (1987). Reorienting attention across the horizontal and vertical meridians: Evidence in favor of a premotor theory of attention. *Neuropsychologia*, *25*(1A), 31–40. https://doi.org/10.1016/0028-3932(87)90041-8

Robertson, I. H., Manly, T., Andrade, J., Baddeley, B. T., & Yiend, J. (1997). "Oops!": Performance correlates of everyday attentional failures in traumatic brain injured and normal subjects. *Neuropsychologia*, *35*(6), 747–758. https://doi.org/10.1016/S0028-3932(97)00015-8

Roca, J., Castro, C., López-Ramón, M. F., & Lupiáñez, J. (2011). Measuring vigilance while assessing the functioning of the three attentional networks: The ANTI-Vigilance task. *Journal of Neuroscience Methods*, *198*(2), 312–324. https://doi.org/10.1016/j.jneumeth.2011.04.014

Roeber, U., Widmann, A., & Schröger, E. (2003). Auditory distraction by duration and location deviants: A behavioral and event-related potential study. *Brain Research. Cognitive Brain Research*, *17*(2), 347–357. https://doi.org/10.1016/S0926-6410(03)00136-8

Rorden, C., & Driver, J. (2001). Spatial deployment of attention within and across hemifields in an auditory task. *Experimental Brain Research*, *137*(3–4), 487–496. https://doi.org/10.1007/s002210100679

Rosvold, H. E., Mirsky, A. F., Sarason, I., Bransome, E. D., & Beck, L. H. (1956). A continuous performance test of brain damage. *Journal of Consulting Psychology*, *20*(5), 343–350. https://doi.org/10.1037/h0043220

Rovamo, J., & Virsu, V. (1979). An estimation and application of the human cortical magnification factor. *Experimental Brain Research*, *37*(3), 495–510. https://doi.org/10.1007/BF00236819

Rubinstein, J. S. (2020). Divergent response-time patterns in vigilance decrement tasks. *Journal of Experimental Psychology: Human Perception and Performance*, *46*(10), 1058–1076. https://doi.org/10.1037/xhp0000813

SanMiguel, I., Linden, D., & Escera, C. (2010). Attention capture by novel sounds: Distraction versus facilitation. *European Journal of Cognitive Psychology*, *22*(4), 481–515. https://doi.org/10.1080/09541440902930994

Schafer, R. M. (1977). *The tuning of the world: Toward a theory of soundscape design* (1st ed.). Random House.

Scharf, B. (1998). Auditory attention: The psychoacoustical approach. In H. Pashler (Ed.), *Attention* (pp. 75–117). Psychology Press.

Scheuerman, J., Venable, K. B., Anderson, M. T., & Golob, E. J. (2017). Modeling spatial auditory attention: handling equiprobable attended locations. *Cognition and Artificial Intelligence for Human-Centred Design Conference*, *2099*, 1–7.

Schiffman, H. R. (1990). *Sensation and perception: An integrated approach* (3rd ed.). John Wiley & Sons.

Schneider, D. W. (2017). Alertness and cognitive control: testing the early onset hypothesis. *Journal of Experimental Psychology: Human Perception and Performance*, *44*(5), 756–766. https://doi.org/10.1037/xhp0000497

Schoener, T. W. (1971). Theory of feeding strategies. *Annual Review of Ecology and Systematics*, *2*(1), 369–404. https://doi.org/10.1146/annurev.es.02.110171.002101

Schröger, E., & Wolff, C. (1998). Attentional orienting and reorienting is indicated by human event-related brain potentials. *NeuroReport*, *9*(15), 3355–3358. https://doi.org/10.1097/00001756-199810260-00003

See, J. E., Howe, S. R., Warm, J. S., & Dember, W. N. (1995). Meta-analysis of the sensitivity decrement in vigilance. *Psychological Bulletin*, *117*(2), 230–249. https://doi.org/10.1037/0033-2909.117.2.230

Shaw, T. H., Satterfield, K., Ramirez, R., & Finomore, V. (2013). Using cerebral hemovelocity to measure workload during a spatialised auditory vigilance task in novice and experienced observers. *Ergonomics*, *56*(8), 1251–1263. https://doi.org/10.1080/00140139.2013.809154

Shaw, T. H., Warm, J. S., Finomore, V., Tripp, L., Matthews, G., Weiler, E., & Parasuraman, R. (2009). Effects of sensory modality on cerebral blood flow velocity during vigilance. *Neuroscience Letters*, *461*(3), 207–211. https://doi.org/10.1016/j.neulet.2009.06.008

Shenhav, A., Musslick, S., Lieder, F., Kool, W., Griffiths, T. L., Cohen, J. D., & Botvinick, M. M. (2017). Toward a rational and mechanistic account of mental effort. *Annual Review of Neuroscience*, *40*(1), 99–124. https://doi.org/10.1146/annurev-neuro-072116-031526

Simon, J. R., & Small, A. M. (1969). Processing auditory information: Interference from an irrelevant cue. *Journal of Applied Psychology*, *53*, 433–435. https://doi.org/10.1037/h0028034

Smallwood, J., & Schooler, J. W. (2006). The restless mind. *Psychological Bulletin*, *132*(6), 946–958. https://doi.org/10.1037/0033-2909.132.6.946

Smith, P. L., & Ratcliff, R. (2009). An integrated theory of attention and decision making in visual signal detection. *Psychological Review*, *116*(2), 283–317. https://doi.org/10.1037/a0015156

Smith-Lovin, L., Lewis, M., & Haviland, J. M. (2010). The evolutionary psychology of the emotions and their relationship to internal regulatory variables. *Handbook of Emotions*, *24*, 114–137. https://doi.org/10.2307/2076468

Sokolov, E. N. (1963). Higher nervous functions; the orienting reflex. *Annual Review of Physiology*, *25*, 545–580. https://doi.org/10.1146/annurev.ph.25.030163.002553

Spence, C., & Driver, J. (1994). Covert spatial orienting in audition: Exogenous and endogenous mechanisms. *Journal of Experimental Psychology: Human Perception and Performance*, *20*(3), 555–574. https://doi.org/10.1037/0096-1523.20.3.555

Stern, J. A., Boyer, D., & Schroeder, D. (1994). Blink rate: A measure of fatigue. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *36*(2), 285–297. https://doi.org/10.1177/001872089403600209

Sussman, E., Winkler, I., & Schröger, E. (2003). Top-down control over involuntary attention switching in the auditory modality. *Psychonomic Bulletin & Review*, *10*(3), 630–637. https://doi.org/10.3758/BF03196525

Szalma, J. L., Warm, J. S., Matthews, G., Dember, W. N. N., Weiler, E. M. M., Meier, A., Eggemeier, F. T. T., Szalma, J. L., Warm, J. S., Matthews, G., Dember, W. N. N., Weiler, E. M. M., Meier, A., & Eggemeier, F. T. T. (2004). Effects of sensory modality and task duration on performance, workload, and stress in sustained attention. *Human Factors*, *46*(2), 219–233. https://doi.org/10.1518/hfes.46.2.219.37334

Temple, J. G., Warm, J. S., Dember, W. N., Jones, K. S., LaGrange, C. M., & Matthews, G. (2000). The effects of signal salience and caffeine on performance, workload, and stress in an abbreviated vigilance task. *Human Factors*, *42*(2), 183–194. https://doi.org/10.1518/001872000779656480

Thomson, D. R., Besner, D., & Smilek, D. (2015). A resource-control account of sustained attention: Evidence from mind-wandering and vigilance paradigms. *Perspectives on Psychological Science*, *10*(1), 82–96. https://doi.org/10.1177/1745691614556681

Thomson, D. R., Besner, D., & Smilek, D. (2016). A critical examination of the evidence for sensitivity loss in modern vigilance tasks. *Psychological Review*, *123*(1), 70–83. https://doi.org/10.1037/rev0000021

Tripp, L. D., & Warm, J. S. (2008). Transcranial doppler sonography. In R. Parasuraman & M. Rizzo (Eds.), *Neuroergonomics: The brain at work* (pp. 82–94). Oxford University Press.

Verbruggen, F., & Logan, G. D. (2008). Response inhibition in the stop-signal paradigm. *Trends in Cognitive Sciences*, *12*(11), 418–424. https://doi.org/10.1016/j.tics.2008.07.005

Wagenmakers, E. J., van der Maas, H. L. J., & Grasman, R. P. P. (2007). An ez-diffusion model for response time and accuracy. *Psychonomic Bulletin & Review*, *14*(1), 3–22. https://doi.org/10.3758/BF03194023

Wallace, R. J. (1971). S-R compatibility and the idea of a response code. *Journal of Experimental Psychology*, *88*, 354–360. https://doi.org/10.1037/h0030892

Warm, J. S., & Dember, W. N. (2004). Tests of vigilance taxonomy. In R. R. Hoffman, M. F. Sherrick, & J. S. Warm (Eds.), *Viewing psychology as a whole: The integrative science of William N. Dember* (pp. 87–112). Washington, D.C.: American Psychological Association. https://doi.org/10.1037/10290-004

Warm, J. S., Finomore, V. S., Vidulich, M. A., & Funke, M. E. (2015). Vigilance: A perceptual challenge. In R. Hoffman, P. A. Hancock, M. W. Scerbo, R. Parasuraman, & J. L. Szalma (Eds.), *The Cambridge handbook of applied perception research* (pp. 241–283). Cambridge University Press.

Warm, J. S., & Parasuraman, R. (2007). Cerebral hemodynamics and vigilance. In R. Parasuraman & M. Rizzo (Eds.), *Neuroergonomics: The brain at work* (pp. 146–158). Oxford University Press.

Warm, J. S., Parasuraman, R., & Matthews, G. (2008). Vigilance requires hard mental work and is stressful. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *50*(3), 433–441. https://doi.org/10.1518/001872008X312152

Warm, J. S., Richter, D. O., Sprague, R. L., Porter, P. K., & Schuky, D. A. (1980). Listening with a dual brain: Hemispheric asymmetry in sustained attention. *Bulletin of the Psychonomic Society*, *15*(4), 229–232. https://doi.org/10.3758/BF03334516

Wascher, E., Schatz, U., Kuder, T., & Verleger, R. (2001). Validity and boundary conditions of automatic response activation in the Simon task. *Journal of Experimental Psychology: Human Perception and Performance*, *27*(3), 731–751. https://doi.org/10.1037/0096-1523.27.3.731

Wetzel, N., Widmann, A., & Schröger, E. (2012). Distraction and facilitation-two faces of the same coin? *Journal of Experimental Psychology: Human Perception and Performance*, *38*(3), 664–674. https://doi.org/10.1037/a0025856

Wickens, C. D. (2008). Multiple resources and mental workload. *Human Factors*, *50*(3), 449–455. https://doi.org/10.1518/001872008X288394

Wolfe, J. M. (2007). Guided search 4.0: Current progress with a model of visual search. In W. Gray (Ed.), *Integrated models of cognitive systems* (pp. 99–119). Oxford University Press. https://doi.org/10.1093/acprof:oso/9780195189193.003.0008

Xiong, A., & Proctor, R. W. (2016). Decreasing auditory Simon effects across reaction time distributions. *Journal of Experimental Psychology: Human Perception and Performance*, *42*(1), 23–38. https://doi.org/10.1037/xhp0000117

Yeshurun, Y. (2019). The spatial distribution of attention. *Current Opinion in Psychology*, *29*, 76–81. https://doi.org/10.1016/j.copsyc.2018.12.008

Yurgil, K. A., & Golob, E. J. (2010). Neural activity before and after conscious perception in dichotic listening. *Neuropsychologia*, *48*(10), 2952–2958. https://doi.org/10.1016/j.neuropsychologia.2010.06.004

Zholdassova, M., Kustubayeva, A., & Matthews, G. (2019). The ANT executive control index: No evidence for temporal decrement. *Human Factors*, *63*, 254–273. https://doi.org/10.1177/0018720819880058