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The Effect of Visual Task Difficulty on the Fixation-Related Lambda Response

by Anthony J Ries, David Slayback, and Jon Touryan

NOTICES

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Human Research and Engineering Directorate, ARL

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14. ABSTRACT

Fixation-related potentials further our understanding of overt orienting by leveraging rather than limiting eye movements in experimental paradigms. The lambda response, a prominent neural signature of the fixation-related potential, has been used to examine stimulus-driven and cognitive influences on early stages of visual processing and overt orienting behavior. Prior experiments have shown changes in lambda response amplitude due to top-down effects from auditory task difficulty; however, it is still not clear to what degree this component is sensitive to changes in visual task difficulty. Here we modulated difficulty using 2 different visual tasks. In the first, difficulty was manipulated via the working memory load of a visual N-Back task while eye movements were systematically guided across a search grid. For the second task we used a modified Tetris game where difficulty was manipulated via tetrad fall speed, without imposing eye movement constraints. Subjective reports, behavior, and other physiological measures confirmed our task manipulations increased difficulty in both paradigms. The results showed that lambda response amplitude was significantly attenuated at high with respect to low difficulty levels in the N-Back task. In contrast, the Tetris task exhibited the opposite effect showing increased lambda amplitude as a function of task difficulty. Critically, these effects were maintained when correcting for overlapping neural activity elicited from temporally adjacent stimuli and saccadic events. Together, our results suggest that task difficulty may differentially affect early visual processing depending on the requisite cognitive and perceptual processes. Understanding how the lambda response is affected by task difficulty in the visual domain may provide a more direct way to index task demands in search behavior without relying on a secondary task or probe stimulus.

15. SUBJECT TERMS
lambda potential, fixation-related potentials, working memory, eye tracking, FRP, task difficulty, cognitive load, video game

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1. Introduction

Overt visual orienting is a ubiquitous component of our everyday interactions with the environment and fundamental to how we perceive the world. Consequently, decades of research have been dedicated to investigating the constituent perceptual and neural mechanisms of eye movements in visual search (Eckstein 2011; Torralba et al. 2006; Wolfe 2007). An important component of this investigation is understanding how cognitive processes, such as working memory, influence eye movements and visual orienting. However, the majority of studies exploring the neural components of these phenomena have been conducted in highly controlled laboratory settings, requiring participants to constrain their eyes to a fixed location. Thus, much of this work has employed covert orienting tasks, which require selecting a target stimulus in a display without making directed eye movements. This approach has a clear benefit for electrophysiology in that it reduces the large and often confounding eye-movement related artifacts produced by changes in the corneo-retinal potential (Hickey et al. 2008; Kiss et al. 2008; Luck and Hillyard 1994). However, this controlled presentation of stimuli, in the absence of eye movements, provides an incomplete representation of how we process visual information in real-world settings and how cognitive factors influence information processing.

Therefore, to fully understand overt visual orienting in real-world scenarios, neurophysiological experiments must leverage rather than limit eye movements. Specifically, researchers can evaluate multiple stages of neural processing by extracting electroencephalogram (EEG) during periods prior and subsequent to an eye movement to create saccade and fixation-related potentials (S/FRPs), respectively (Dimigen et al. 2011; Kaunitz et al. 2014). The most prominent and widely studied FRP component is the lambda response, a large positive waveform that peaks around 100 ms post-fixation. Similar to the P1 event-related potential (ERP), the lambda response reflects the afferent flow of information to the visual cortex and is affected by stimulus properties such as luminance and spatial frequency (Billings 1989; Thickbroom et al. 1991; Yagi 1979). Unlike the P1 ERP, the lambda response is affected by saccade magnitude such that its amplitude increases as a function of saccade size (Dandekar et al. 2012; Dimigen et al. 2011; Kaunitz et al. 2014; Yagi 1979). Other critical differences between lambda and ERP components are seen when directly comparing their latency and amplitude under the same stimulus conditions. In this case, the lambda response generally peaks earlier and has a larger amplitude compared to the visually evoked P1 ERP (Billings 1989; Kaunitz et al. 2014; Kazai and Yagi 2003). The increased signal to noise observed in the lambda response is potentially inherited from extra retinal mechanisms not active during traditional tasks that impose eye fixation constraints (McFarland et al. 2015; Reppas et al. 2002).

Like the P1, the lambda potential is also affected by cognitive processes, such as those related to working memory. In one of the first studies to evaluate these top-down effects on the lambda response, participants searched for a target stimulus while ignoring auditory tones or performed an auditory oddball task while moving their eyes but ignoring target stimuli (Yagi 1981). The results from this study showed a decreased lambda response during the auditory relative to the visual task; however, it was not clear if this was due to an active inhibition of the passive visual task or rather a result of resource limitations in visual processing. In our previous study (Ries et al. 2016), we expanded on the findings by Yagi (1981) by incorporating a dual-task paradigm where participants responded to predefined targets during guided visual target detection while simultaneously performing an auditory N-Back task. Here, the visual demands were kept constant while auditory task difficulty varied by varying working memory load. Our results showed a significant decrease in the lambda amplitude with an increase in auditory task difficulty, providing further evidence for a link between cross-modal processing resources. Finally, Takeda et al. (2012) assessed the effect of verbal and spatial working memory on lambda amplitude. In this study, all participants performed a simulated driving task where half of the participants performed a simultaneous verbal working memory task (monitoring a stream of aurally presented digits), and the other half performed a simultaneous spatial working memory task (performing easy or difficult mental rotation based on directional auditory input). While it is not clear from this study if the working memory tasks affected driving performance, the electrophysiological results showed a similar decrease in the lambda response during the high-load spatial working memory task.

Given our increasing understanding of this neural component, the lambda response may provide a natural indicator of a more general cognitive state, such as working memory load, in the context of tasks requiring overt visual attention. Using the lambda response to track changes in visual task difficulty would provide a more direct way to index visual task demands in natural search behavior without the need of a secondary auditory task. To address this, we sought to determine if the lambda response was modulated by visual task difficulty in 2 disparate paradigms. In the first, a visual N-Back task, we controlled the nature of task difficulty (i.e., via working memory load) while maintaining a uniformity of eye movements and fixated stimulus properties (i.e., via guided search) to enable an unambiguous determination of the source of lambda response amplitude modulation. In the second, a Tetris task, eye movements were unconstrained and we quantified the effect of task difficulty on the lambda response by manipulating tetrad fall speed

(Miller et al. 2011). Importantly, we were able to control for overlapping neural activity from temporally adjacent events by implementing a multiple regression technique specifically designed for this purpose (Smith and Kutas 2015a, 2015b). Likewise, to establish the effect of our manipulations, we included several other subjective and physiological measures that are known indicators of changes in task difficulty. Based on the previous work described above, we expected to see a decrease in the amplitude of the lambda potential with increased task difficulty, specifically that induced by working memory load.

2. Materials and Methods

2.1 Stimuli and Procedure

Participants performed a dynamic visual N-Back and Tetris task from a distance of approximately 80 cm (Fig. 1) with the order of the tasks counterbalanced across the sample. These tasks were performed on a 21-inch, 1920 × 1080 pixel, 60-Hz monitor and controlled using Psychtoolbox-3 (Brainard 1997; Kleiner et al. 2007). In the N-Back task a Gabor stimulus subtending 3° visual angle (45° tilt, 2 cycles per degree, 100% Michelson contrast) containing a digit (RGB: 255,255,255) in the center randomly appeared every 1500–2000 ms in 1 of 49 locations on an invisible 7 × 7 grid.

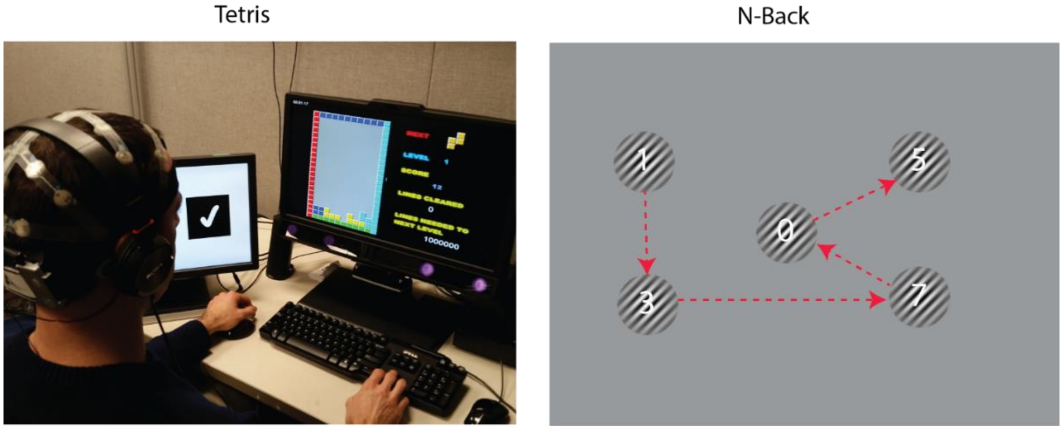

Fig. 1 Task layout. The left image shows the layout of the experimental environment while a participant performs the Tetris task. The right image shows an example of 4 successive fixations in the medium difficulty (0-Back) condition of the visual N-Back task. Note that only 1 Gabor stimulus appeared on the screen at any given time. The red arrows indicate the direction of each saccade/fixation.

Participants were instructed to saccade to and hold fixation on the digit in the center of the Gabor pattern until the next Gabor pattern appeared. In the *Ignore* condition participants fixated each stimulus disregarding the digit, while in 2 other conditions they used the digits in a 0-, 1-, or 2-Back task. In the *0-Back* condition participants made a response with their right index finger on a game pad when the number zero appeared. In the *1-Back* condition each digit was compared to the one prior requiring a response when these digits were the same (i.e., target). In the *2-Back* condition each digit was compared to the one that occurred 2 trials back. For the purposes of analysis we separate these conditions into 3 task difficulty levels: low, medium, and high. Specifically, *Ignore* = low, *0-Back* and *1-Back* = medium, and *2-Back* = high. Some participants performed the 0-Back while others performed the 1-Back; however, based on preliminary analysis we found no difference between these conditions and they are henceforth combined into the medium task difficulty condition. Each participant performed 2 consecutive 3-minute blocks of each condition, with conditions counterbalanced. Target probability was 0.15. Participants practiced the 0- and 2-Back conditions until they reached at least 50% target accuracy.

Tetrad fall speed was used to manipulate task difficulty in the modified Tetris game (Zhang 2010). Fall speed was measured as the vertical travel of the current block piece per unit of time. Fall speeds 2, 3, 4, 5, and 7 steps per second were used for this task. As with the N-Back task, these conditions were separated into 3 task difficulty levels: low, medium, and high. Specifically, fall speeds 2 and 3 = low, 4 and 5 = medium, and 7 = high. Some participants performed the 2 and 4 speed conditions while others performed the 3 and 5 speed conditions. We found no difference between speeds 2 and 3 or between speeds 4 and 5; therefore, they were combined into the low and medium task difficulty conditions respectively. All participants completed 2 consecutive 3-minute blocks at each fall speed with the order of fall speed counterbalanced. Participants were aware of the fall speed prior to the start of the game. The right hand was used to manipulate the rotation of the tetrad blocks using the up, left, and right arrows on a keyboard. The down arrow was not used in order to prevent participants from increasing the tetrad fall speed. If the tetrad block stack reached the top of the screen before the end of the block, all blocks were cleared and the game restarted with an empty tetrad field. Before the experiment participants performed a 2-minute practice block with fall speed of 5 to become familiar with the task.

Participants performed a 2-stimulus auditory oddball task simultaneously with the N-Back and Tetris task. The auditory oddball task required participants to make a speeded response by pressing a highlighted region (4 × 4 inches, ✓ in Fig. 1) with their left hand on a 19-inch Elo touch-screen monitor to an infrequent (P = 0.12, 2000 Hz) auditory stimulus presented in a series of frequent (P = 0.88, 1000 Hz) tones. Auditory tones were presented through Audio-Technica ATH-M50x headphones at a volume of 16 on Realtek HD Audio headphone device for 100 ms with a 3–4-s inter-stimulus interval using 100 ms jitter. The touch-screen monitor was located close to the visual task monitor and the highlighted response region was large enough to enable participants to make the auditory task response without an eye/head movement. Participants were instructed to rest their left hand on an adjacent mouse pad between target responses to ensure responses were initiated from the same distance. After each block of the N-Back or Tetris task, the auditory task was stopped and participants completed a modified version of the NASA Task Load Index (TLX) using a continuous visual analogue scale (1–100) to rate their perceived effort (“How hard did you have to work to accomplish your level of performance?”) and mental demand (“How mentally demanding was the task?”).

2.2 Participants

Sixteen right-handed males participated in the experiment (average age 31.1 years) each having 20/20 vision or corrected to 20/20 vision. Due to a problem with the eye tracker, we were unable to obtain enough reliable samples in the eye-tracking data for 1 participant in the Tetris task. Consequently, all eye-based measurements for this task were calculated from the remaining 15 participants. The voluntary, fully informed consent of the persons used in this research was obtained in accordance with the US Army Research Laboratory’s (ARL’s) Institutional Review Board requirements (32 CFR 219 and AR 70-25).

2.3 EEG and Eye Tracking

EEG data were acquired from an Advanced Brain Monitoring (ABM) B-Alert X24 Sensor Headset (sampling rate 256 Hz; linked mastoid reference) with the single-trial ERP montage using the B-Alert software package. In addition to the scalp electrodes, 2 external input channels placed just below the right clavicle and below the left rib were used to acquire the electrocardiogram (ECG).

Ocular data were recorded from a distance of approximately 80 cm using the Tobii TX300 eye tracker. Data from each eye were sampled at 300 Hz and acquired using custom software with the Tobii SDK. Each participant performed a 9-point calibration before experimentation. Eye tracking data were used to identify saccade and fixation events, as well as provide continuous estimates of pupil diameter and gaze location. The Tobii TX300 system included continuous, online correction of gaze location and pupil diameter for changes in head position.

2.4 Data Processing

EEG and eye-tracking data synchronization was performed in MATLAB using custom software by aligning independently injected events into each data stream. EEG and subsequent FRP data were processed with EEGLAB using the ERPLAB and regression analysis (rERP) plugins (Burns et al. 2013; Delorme and Makeig 2004; Lopez-Calderon and Luck 2014). EEG data were filtered using a second-order Butterworth filter with a 0.1–40 Hz passband. Blinks were identified from stereotyped gaps in the gaze position data (Holmqvist et al. 2011) while saccades (and corresponding fixations) were detected using the velocity-based algorithm provided in the EYE-EEG plugin (http://www2.hu-berlin.de/eyetracking-eeg) for EEGLAB (Dimigen et al. 2011; Engbert and Mergenthaler 2006). Specifically, we used a velocity factor of 6, a minimum saccade duration of 30 ms, and a minimum fixation duration of 200 ms keeping only the largest saccade and subsequent fixation if 2 or more saccades were detected within the minimum fixation duration window.

FRPs were created separately for each participant in each task (N-Back, Tetris) and condition (low, medium, high) from epochs (–1000 to 2000 ms) time-locked to fixation with and without overlap correction. *Without Overlap Correction:* Fixation-locked epochs were not included if peak-to-peak activity surpassed a 120-μV threshold (–500 to 700 ms with respect to fixation onset) from all channels (excluding F1, F3, Fz, F2, and F4) using a 100-ms window size and a window step of 50 ms. Likewise, epochs were not included if they were immediately preceded or followed by an auditory target trial, blink, or boundary event. All other fixation-locked epochs were included in the final average, and are henceforth referred to as valid trials. *With Overlap Correction*: All fixation-locked epochs were included in the rERP, with a separate FRP estimated for each condition (Burns et al. 2013; Smith and Kutas 2015a). Importantly, stimulus onset (Gabor or tetrad) ERPs were simultaneously estimated to remove the overlapping effect on the subsequent FRP. In the rERP framework, an event E_1 (either stimulus or fixation) produces an ERP response β_1 spanning a range of latencies from zero (event onset) to τ. The observed signal at each electrode is then considered a linear transform of β_1 plus an independent Gaussian noise tem, $\varepsilon \sim N(0, \sigma I)$. In this way, the EEG signal at each electrode (e.g. O_z) can be represented as

$$\beta_1 = [\beta_{10}\,\beta_{11}\,\beta_{12}\,\cdots\,\beta_{1\tau}]^T \tag{1}$$

$$O_z = \mathbf{A}_1\beta_1 + \varepsilon \tag{2}$$

over the M observations (data samples). Here, $\mathbf{A_1}$ is an $M \times \tau$ matrix of event occurrences at each latency τ of the ERP. This formulation can be extended to incorporate multiple events, including potentially overlapping ERPs and FRPs. Now each event type (1…n) and corresponding ERP/FRP can be represented as

$$\boldsymbol{A} = [\boldsymbol{A_1}\ \boldsymbol{A_2}\ \boldsymbol{A_3}\ \cdots\ \boldsymbol{A_n}] \tag{3}$$

$$\beta = [(\beta_1)^T\ (\beta_2)^T\ (\beta_3)^T\ \cdots\ (\beta_n)^T]^T \tag{4}$$

In this way, the EEG signal at O_z now becomes

$$O_z = \mathbf{A}\beta + \varepsilon \tag{5}$$

The event ERPs can then be estimated through least-squares regression, with solution

$$\beta_{reg} = (\boldsymbol{A^T}\boldsymbol{A})^{-1}\boldsymbol{A^T}O_z \cong \beta \tag{6}$$

Since this parameter space is large, a regularization method is applied to the pseudoinverse (in the case of L2 nom penalized regression). More information about the rERP method and toolbox can be found at https://sccn.ucsd.edu/wiki/RERP.

Auditory evoked potentials (AEPs) were created separately for each subject by averaging epochs (–200 to 1000 ms) time-locked to auditory stimulus onset in each task and condition. Epochs were rejected if peak-to-peak activity surpassed a 120-µV threshold (–200 to 800 ms with respect to stimulus onset) from all channels (excluding F1, F3, Fz, F2, and F4) using a 100-ms window size and a window step of 50 ms or if a blink occurred –200 to 800 ms relative to stimulus onset.

3. Results

In the following sections (Behavior and Physiological Metrics) we report subjective, behavioral, and physiological results to establish the efficacy of our primary manipulation, increase in task difficulty, for both the N-Back and Tetris task. Greenhouse–Geisser statistics are reported for all ANOVA analyses (Greenhouse and Geisser 1959).

3.1 Behavior

3.1.1 Subjective Report

Subjective reports of task difficulty were analyzed using the "effort" and "mental demand" factors from the modified TLX to compare perceived difficulty both within and between tasks (N-Back/Tetris). Due to the ordinal scale of the data we used the non-parametric Wilcoxon Signed Rank Test to compare participants' median subjective ratings between tasks, which showed significantly higher ratings in Tetris relative to N-Back in both effort (Tetris = 53.08 [IQR = 42-60.79], N-Back = 43.25 [IQR = 28.04-49.63], Z = 3.16, p = .002) and mental demand factors (Tetris = 50.25 [IQR = 42.38-62.04], N-Back = 39.75 [IQR = 26.29-49.29] , Z = 2.9, p = .004). A Friedman test was used to evaluate the effect of task difficulty (low, medium, high) in each task for the effort and mental demand factors. The effect of task difficulty was significant in the N-Back condition for both effort ($\chi^2 = 21.13$, $p < .001$) and mental demand ($\chi^2 = 27.65$, $p < .001$) factors. Task difficulty was also significant in the Tetris condition for effort ($\chi^2 = 24.6$, $p < .001$) and mental demand ($\chi^2 = 24.5$, $p < .001$) factors (Fig. 2). Together the subjective reports indicate that participants perceived the Tetris task as more effortful and mentally demanding than the N-Back, and within each task perceived increases in effort and mental demand were associated with increased task difficulty.

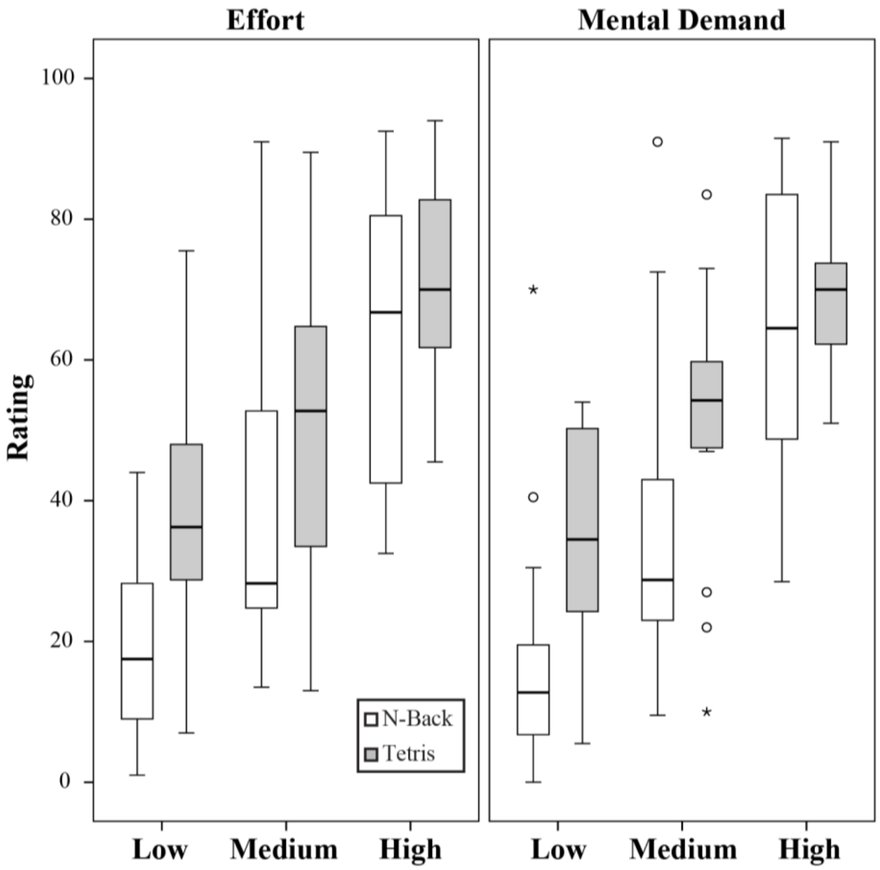

Fig. 2 **Box and whisker plots of participants' TLX ratings of perceived effort and mental demand in the N-Back (white boxes) and Tetris (shaded boxes) tasks as a function of task difficulty (low, medium, high)**

3.1.2 Accuracy and Reaction Time

Target-detection accuracy and reaction time were analyzed in the visual N-Back task. However, the low-difficulty condition did not require responses from the participant (see Stimuli and Procedure); therefore, only the medium and high conditions are reported. Here the effect of task difficulty was significant, F(1,15) = 11.6, p = .004, η^2 = .44, with higher accuracy in the medium (98.4%, stdv 3.8%) relative to high (85.5 %, stdv 15.3%) condition. Reaction time also showed a significant effect of task difficulty, F(1,15) = 83.08, p < .001, η^2 = .85, with medium (744.4 ms, stdv 84.1 ms) having faster RTs than high (933.9 ms, stdv 104.1 ms). Similarly, Tetris scores showed a significant relationship with task difficulty F(1.38,20.74) = 209.52, p < .001, η^2 = .93 with the most points obtained in the high (292.81, stdv 32.87), followed by medium (241.59, stdv 33.46) and low (104, stdv 23.01) conditions. Points were awarded based on the number of lines cleared in the game and since more tetrads were presented with increased difficulty it is not surprising that more points were given in the high-difficulty condition. An additional performance metric for the Tetris task was the frequency at which the game board was cleared and game restarted due to the tetrad stack reaching the top of the game board. This metric also showed a significant effect of task difficulty, F(1.57,23.59) = 30.33, $p < .001$, $\eta^2 = .67$, with low (0.0, stdv 0), medium (1.0, stdv 0.97), and high (2.38, stdv 1.5) conditions all different from each other, $p < .05$. In sum, our manipulation of task difficulty induced changes in both perceived mental effort and behavioral performance.

Accuracy and reaction time were also calculated for the targets presented in the auditory oddball task as a function of (visual) task difficulty in each condition. Interestingly, task difficulty did not significantly affect auditory target accuracy F(1.25,18.84) = 1.49, p = .244, $\eta^2 = .09$, or reaction time F(1.87,28.06) = 1.65, p = .211, $\eta^2 = .099$ in the N-Back task. In the Tetris task there was a main effect of task difficulty, though just short of statistical significance, on auditory target accuracy F(1.97,27.54) = 3.35, p = .051, $\eta^2 = .193$ with highest accuracy in the low load condition (Table 1). Likewise, reaction time was not significantly modulated by task difficulty F(1.36,18.99) = 1.89, p = .185, $\eta^2 = .119$. These results suggest that increased visual task difficulty generally had a negligible effect on the auditory oddball detection performance.

Table 1 Behavioral performance for auditory targets in the N-Back and Tetris tasks as a function of task difficulty

Task	Difficulty	% Correct	Reaction Time (ms)
N-Back	Low	98.5 (3.1)	970.9(141.0)
	Med	99.5(2.1)	950.8(109.5)
	High	96.3(8.0)	1001.1(85.5)
Tetris	Low	99.2(2.4)	966.1(142.8)
	Med	95.5(8.6)	1018.0(169.2)
	High	93.4(9.3)	1066.7(309.0)

3.2 Physiological Metrics

3.2.1 Saccade Magnitude

A number of studies have shown that saccade magnitude affects the amplitude of the lambda response. Specifically, lambda amplitude has been shown to increase with saccade magnitude (Dandekar et al. 2012; Dimigen et al. 2011; Kaunitz et al. 2014; Yagi 1979). Therefore, we compared saccade magnitude in each condition (high, medium, low) in both tasks (N-Back and Tetris) to determine if changes in lambda amplitude could be attributed to this feature. As expected, we found no significant effect of condition on saccade magnitude in the N-Back task, F(1.82,27.29) = 2.04, p = .15; however, there was a significant effect of condition on saccade magnitude in the Tetris task, F(1.71, 23.88) = 6.11, p = .01, η^2 = .30, with increased task difficulty associated with decreased saccade magnitude (Tables 2 and 3). This suggests that the lambda amplitude should be smaller in the high with respect to low load condition if saccade magnitude is the primary influence on this response.

Table 2 Saccade magnitude, pupil diameter, and heart rate variability (HRV) in the N-Back and Tetris tasks as a function of task difficulty. Note: Numbers represent the mean with standard deviation in parentheses for each measure.

N-Back Measure	Low	Medium	High
Sac Mag (deg)	11.97(2.08)	12.63(1.76)	12.06(1.61)
Pupil Dia (%change)	-2.18(1.66)	-1.34(2.05)	4.88(2.1)
HRV (ms)	79.58(41.18)	67.78(37.28)	59.5(29.68)

Tetris Measure	Low	Medium	High
Sac Mag (deg)	13.6(2.2)	13.27(2.2)	12.4(2.3)
Pupil Dia (%change)	-4.09(2.5)	0.36(1.33)	4.08(1.95)
HRV (ms)	68.88(37.3)	58.98(30.7)	58.03(27.8)

Table 3 Paired t-tests for significant main effects of task difficulty

N-Back Measure	Low/Med t(df)	p	Low/High t(df)	p	Med/High t(df)	p
Sac Mag (deg)	NA	NA	NA	NA	NA	NA
Pupil Dia (%change)	-1.24(15)	0.233	-8.16(15)	<.001	-7.05(15)	<.001
HRV (ms)	3.82(15)	0.002	4.78(15)	<.001	2.06(15)	0.058

Tetris Measure	Low/Med t(df)	p	Low/High t(df)	p	Med/High t(df)	p
Sac Mag (deg)	1.12(14)	0.281	2.87(14)	0.012	2.55(14)	0.023
Pupil Dia (%change)	-5.57(14)	<.001	-8.73(14)	<.001	-4.88(14)	<.001
HRV (ms)	3.78(14)	0.002	2.68(14)	0.018	0.32(14)	0.751

3.2.2 Pupil Diameter and HRV

The main effect of task difficulty on pupil diameter was analyzed for both the N-Back and Tetris tasks using a repeated measures ANOVA. This effect was highly significant in both the N-Back [F(1.82, 27.28) = 45.1, p < .001, η^2 = .75] and Tetris [F(1.99, 27.82) = 55.95, p < .001, η^2 = .8] tasks showing increased pupil diameter as a function of task difficulty (Fig. 3). A similar analysis was performed on measures of HRV, calculated by taking the standard deviation of the beat-to-beat interval. Here, we found decreased HRV as a function of task difficulty in both the N-Back [F(1.79, 26.83) = 14.07, $p < .001$, $\eta^2 = .48$] and Tetris [F(1.53, 21.45) = 6.8, $p = .009$, $\eta^2 = .33$] tasks (Fig. 3).

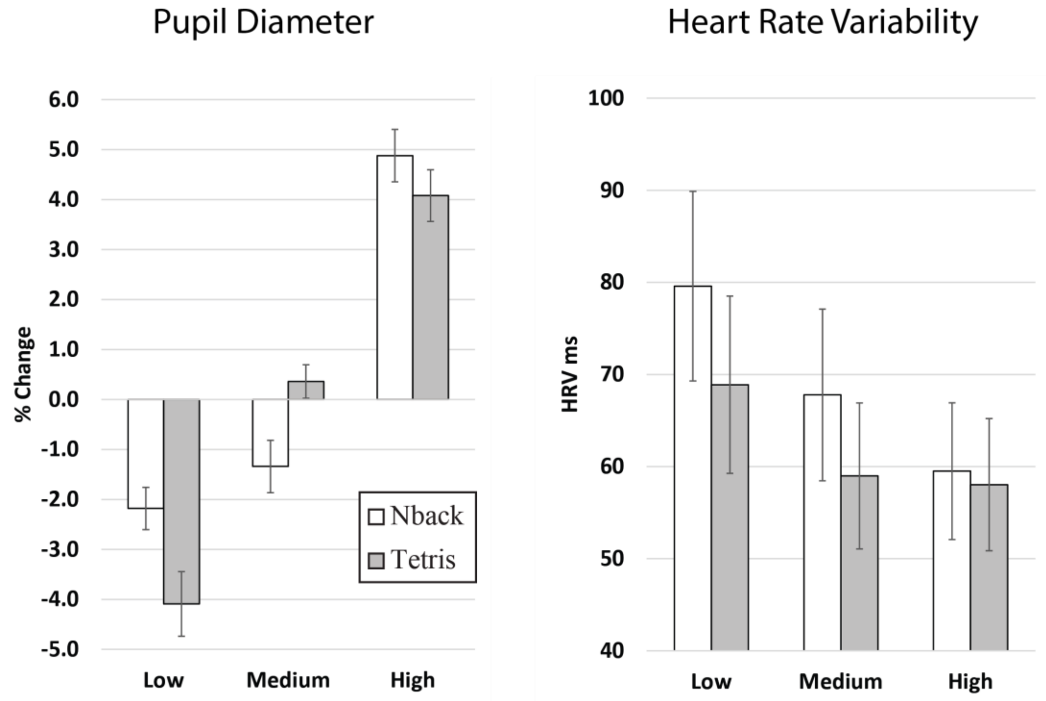

Fig. 3 The effect of task difficulty on pupil diameter and HRV in the N-Back (white) and Tetris (shaded) tasks. Error bars represent the standard error.

3.3 FRPs: Lambda Potential

The lambda potential was measured at electrode O_z both with and without correcting for overlapping neural activity due to temporally adjacent stimuli and short inter-saccadic intervals. Lambda peak latency and amplitude was evaluated separately for each task (N-Back and Tetris) with task difficulty (low, medium, high) as the main factor. Amplitude was measured as the mean voltage over 20 ms (± 10 ms) around the peak latency value for each participant and condition. FRP calculations were performed separately for data with and without overlap correction for temporally adjacent stimuli. For data not corrected for temporally adjacent overlap, we focused only on valid nontarget trials that met the criteria for inclusion (see Data Processing), while all nontarget trials were analyzed in the overlap corrected data. The nontarget trials were chosen due to their relative frequency (compared with target trials) and hence better signal-to-noise ratio. FRP measurements were all relative to a –300 to –100 ms pre-fixation baseline. For data without overlap correction, the average number of trials, with standard deviation, for each participant in the N-Back task was 90.8(31.4) for low, 94.3(29.9) for medium, and 106.6(33.6) for high conditions. Likewise, for the Tetris tasks the average number of trials, with standard deviation, was 219.1(73.8) for low, 262.5(70.1) for medium, and 275.8(80.5) for high conditions. For data with overlap correction, the average number of trials, with standard deviation, for each participant in the N-Back task was 131.4(30.7) for low, 138.8(31.4) for medium, and 141.9(27.1) for high conditions, and 294(76.2) for low, 331.8(80.4) for medium, and 339.1(88.8) for high conditions in the Tetris task.

3.3.1 Without Overlap Correction

The main effect of task difficulty on the peak latency of the lambda component was not significant in either the N-Back [F(1.23,18.37) = 0.07, p = 0.845] or Tetris [F(1.96,27.42) = 0.58, p = 0.563] tasks. However, as predicted there was a significant effect of difficulty on lambda amplitude in the N-Back [F(1.71,25.64) = 4.28, p = 0.03, η^2 = .22] task and approached significance in the Tetris [F(1.99,27.85) = 2.98, p = 0.07, η^2 = .18] task (Fig. 4). Interestingly, the direction of this effect was different between tasks as lambda amplitude decreased as a function of difficulty in the N-Back task but increased with task difficulty in the Tetris task (Fig. 5).

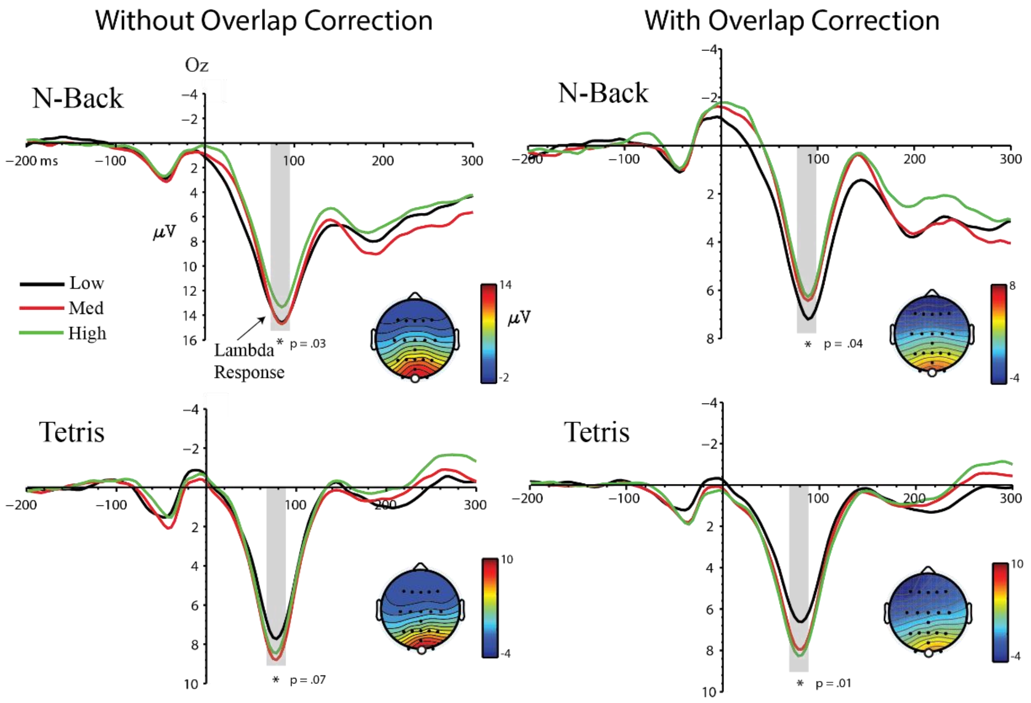

Fig. 4 FRPs obtained from electrode O_z as a function of task difficulty in the N-Back (top row) and Tetris (bottom row) tasks. The right and left columns show FRPs with and without stimulus/saccade overlap correction, respectively. Scalp voltage (microvolts) maps highlight the spatial distribution of the lambda response 70–90 ms post-fixation. Electrode O_z is depicted as the white circle on the scalp maps. FRPs and scalp maps are plotted using a –300 to –100 ms pre-fixation baseline.

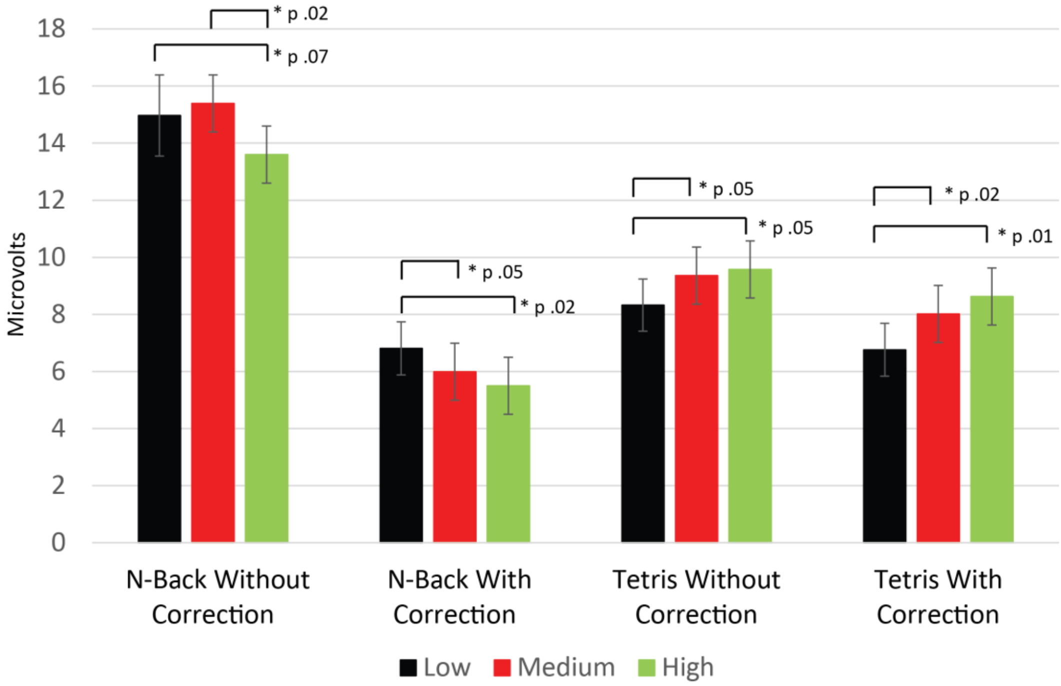

Fig. 5 Comparison of lambda amplitudes as a function of task, condition, and overlap correction. P values were obtained from planned paired comparisons between levels of task difficulty. Error bars represent the standard error of the mean.

3.3.2 With Overlap Correction

To rule out the possibility that our effects were caused by overlapping neural activity from temporally adjacent events, we employed a multiple regression technique recently developed for this purpose (Smith and Kutas 2015a, 2015b). Briefly, this technique uses a general linear modeling framework to simultaneously estimate the response of each event of interest, in this case stimulus and fixation onset. By calculating a simultaneous estimate of each process, this approach can robustly attribute overlapping activity to the eliciting event as well as minimize the contribution of independent signals (e.g., artifacts). After application of this technique, the effect of difficulty on the lambda latency remained nonsignificant for both the N-Back [F(1.47,22) = 0.484, p = 0.565] and Tetris [F(1.99,27.96) = 0.343, p = 0.712] tasks. Lambda amplitude, however, was significantly affected by difficulty in both the N-Back [F(1.69,25.40) = 3.8, p = 0.04, η^2 = .202] and Tetris [F(1.9,26.73) = 5.58, p = 0.01, η^2 = .285] tasks. Figure 4 indicates that Gabor-evoked activity significantly overlapped the lambda response in the N-Back task as the overall lambda amplitude decreased after this activity was removed. While the overall amplitude changed, the main effect of task difficulty on the lambda response did not. In contrast, there was little effect of stimulus and saccade overlap on the lambda response in the Tetris task. However, in contrast to the

N-Back task the lambda amplitude significantly increased with difficulty in the Tetris task.

3.4 AEPs

Only nontarget AEPs were analyzed due to their relative frequency and therefore better signal-to-noise ratio. Here, we focused on the N1 (140–160 ms) and P2 (220–280 ms) components of the AEP from electrode Cz. AEP measurements were relative to a –200 to 0 ms pre-stimulus baseline. We found no significant effect of difficulty in the N-Back task for the N1 [F(1.98,29.63) = 0.84, p = .442] or P2 [F(1.49,22.28) = 2.41, p = .125]. Likewise, we found no significant effect of difficulty for the N1 [F(1.74,26.09) = 0.302, p = .712] and P2 [F(1.52,22.73) = 1.24, p = .298] components in the Tetris task. Importantly, this result corresponds to the behavioral findings and together these suggest that the auditory oddball task required too little effort (accuracy near ceiling) to be significantly affected by increased visual task demands, or participants allocated the same amount of cognitive resources to the oddball task irrespective of the modulations in task difficulty.

4. Discussion

4.1 Task Difficulty

In this study we investigated the effect of visual task difficulty on the amplitude of the fixation-related lambda potential in 2 disparate tasks, an N-Back task that controlled for stimulus and saccade properties and a Tetris task that used a dynamic, unconstrained paradigm while still preserving parametric control of difficulty (Lindstedt and Gray 2015). Perceived subjective ratings of effort and mental demand, behavioral performance, HRV, and pupil diameter were all significantly affected by changes in difficulty for both tasks. Critically, it was shown that the amplitude of the lambda response was significantly reduced under high with respect to low *visual* task difficulty when controlling for saccadic magnitude and stimulus properties in the N-Back task. This extends upon prior research that showed high compared to low *auditory* task difficulty, manipulated through working memory load, significantly attenuated the amplitude of the lambda response (Ries et al. 2016; Takeda et al. 2012). Together these findings suggest the lambda response is directly affected by capacity-limited processing resources involved in working memory.

Contrary to our prediction, the lambda response in the Tetris task was significantly larger in high with respect to low task difficulty. This finding could not be attributed to differences in saccade magnitude as saccades in the high task difficulty condition were significantly smaller than those in the low difficulty condition. If saccade magnitude was the primary contributor to lambda response amplitude, this observation would have led to smaller lambda amplitudes in the high with respect to low conditions. Similarly, the change in lambda amplitude between conditions could be due to luminance differences at each fixation location. It is well-known that lambda amplitude increases as a function of luminance (Gaarder et al. 1964). The high task difficulty condition could have resulted in more high-luminance fixations since, on average, more tetrads were present on the game board relative to the other conditions. However, it is unlikely that luminance was the main contributor to the lambda amplitude in the Tetris task as pupil size *increased* with task difficulty (e.g., Beatty 1982). Since luminance likely increased as a function of difficulty, we would have expected a smaller, not larger, pupil diameter in the high difficulty condition.

A tenable hypothesis concerning the differential effect of task difficulty on the lambda response in our 2 tasks is that the N-Back and Tetris tasks relied on different processing mechanisms. The N-Back task primarily recruited cognitive processes related to working memory while those in the Tetris task required more perceptual and motor processes. Indeed it has been shown that cognitive and perceptual load produce differential effects on behavior such that when perceptual load is high, peripheral distractors are *less* likely to be processed; however, when cognitive demands are high due to working memory load, irrelevant peripheral distractors are *more* likely to be processed (Lavie et al. 2004). This supports the possibility that processing resources may have been allocated differently in our experiment based on the load requirements of the task consistent with predictions from perceptual load theory (Lavie 1995, 2005). Participants required more cognitive processing resources for internal maintenance of information in the N-Back task as difficulty increased; therefore, fewer cognitive resources were available for visual stimulus processing at fixation. This is consistent with smaller lambda amplitudes in the high compared to low difficulty condition. In the Tetris task fewer perceptual processing resources were needed to successfully perform the task in the low compared to high load as the slow fall speed allowed ample time to align the tetrad. Once aligned, participants could disengage from the task and wait for the tetrad to fall into place since they could not control its downward trajectory. Alternatively, in the high difficulty condition, tetrads were moving quickly and there was little time to disengage from the task, thus demanding more perceptual processing resources to complete the task. This is consistent with larger lambda amplitudes in the high compared to the low difficulty condition. Future research must control for stimulus features between levels of cognitive and perceptual load to adequately address the possibility that the lambda amplitude, like behavior, is differentially influenced by these constructs. Together the results demonstrate that the lambda response is affected by capacity-limited processing resources related to task difficulty, specifically those involved in working memory.

4.2 Stimulus and Ocular Overlap Correction

An additional goal of our FRP analysis was to evaluate the potential confounding influence of both preceding stimuli (which were subsequently fixated) and temporally adjacent saccades on the lambda potential. It is not clear from prior research whether the effects of task difficulty on the lambda response could be attributed to differential overlapping neural activity between conditions. It is possible that inter-saccadic intervals were different between difficulty levels, which would result in different degrees of overlap. For example, neural activity from one FRP overlaps with the subsequent FRP at short inter-fixation intervals (less than 500 ms), such that the response elicited from one fixation will extend into subsequent fixation intervals (Nikolaev et al. 2016). Furthermore, when participants must saccade/fixate an abruptly appearing visual stimulus in the periphery, the stimulus-evoked neural activity will overlap with the fixation-evoked response. The separation or deconvolution of overlapping stimulus-evoked or saccade-related potentials on the lambda response is an open methodological inquiry. In this study, we applied a regression-based technique that has been shown to accurately separate temporally overlapping ERPs (Burns et al. 2013; Smith and Kutas 2015a, 2015b). This overlap correction procedure demonstrated that stimulus-evoked activity produced in the N-Back task had a substantial impact on the subsequent lambda response, as the amplitude of the response was significantly smaller after correction (see Fig. 5). Importantly, while the stimulus-evoked activity did have an impact on the fixation-locked neural response, it did not change the overall pattern of results, with the exception of the medium difficulty condition. As there were significantly more trials included in the overlap correction analysis, this difference could have been the result of additional noise contained within these trials. Using a heuristic approach to excluding trials, as is common in ERP analysis, can result in reduced noise in the ERP. However, this can come at the cost of a large number of trials and is potentially susceptible to subjective criteria for exclusions. By using both a standard exclusion and overlap correction approach we provide a more confident assertion that the observed modulation in the lambda amplitude was not a conflation of the stimulus response nor a consequence of artifact contamination.

Interestingly, temporal overlap from eye movements had a minimal effect in the Tetris task where eye movements were unconstrained. Upon further inspection, this result was not surprising given the average inter-saccadic interval in this tasks (i.e., fixation duration) was 667 ms. Given this interval, the fixation-locked neural response was returning to baseline well before the next saccade occurred. Although inter-saccadic overlap was not a factor in this study, due to the relatively long fixation durations, other tasks such as free-view visual search tend to produce even shorter fixation durations and thus may have a more confounding impact on the lambda response. While this study was focused on the lambda response, which has a relatively short onset latency, later components such as the P300 are more likely to be impacted by temporal overlap (e.g., Devillez et al. 2015), which will benefit from the removal from adjacent neural responses.

4.3 Subjective and Physiological Measures of Task Difficulty

To establish the effect of our manipulations, we included several other subjective and physiological measures that are known indicators of changes in task difficulty. Specifically, we compared the modulation of the lambda response with another ERP component, the AEP, which has been shown to index visual task difficulty (Allison and Polich 2008; Miller et al. 2011). As such, participants performed an auditory oddball task in conjunction with both visual tasks (N-Back and Tetris). Other reliable measures of task difficulty were also included: the TLX subjective rating scale (Hart and Staveland 1988), HRV (Backs et al. 1994; Prinzel et al. 2003), main sequence (Di Stasi et al. 2011), and tonic pupil dilation (Beatty 1982; Kahneman and Beatty 1966; Van Orden et al. 2000). Subjective ratings of perceived mental demand and effort significantly increased with task difficulty. Additionally, HRV significantly decreased while pupil diameter significantly increased as a function of task difficulty.

Based on previous studies (Allison and Polich 2008; Miller et al. 2011), we expected to find a significant influence of visual task difficulty on both behavior and AEP amplitude. While there was a small reduction in accuracy for auditory targets in the high difficulty condition for Tetris, overall the effect of visual task difficulty on auditory oddball detection was negligible. One potential explanation for this concerns the way in which participants responded to the auditory targets. Participants were instructed to keep their hand in a fixed position some distance from the touch screen throughout the experiment; however, it is likely resting hand position varied somewhat throughout the experiment thus introducing large fluctuations in measured reaction time. While we did not see an effect of visual task difficulty on the AEP components, a critical difference between the current and past studies is that Allison and Polich (2008) and Miller et al. (2011) incorporated primarily passive, task-irrelevant auditory probes. Using irrelevant auditory stimuli allowed participants to allocate their attentional resources contingent on visual task difficulty only. Participants in the current study had to allocate resources to the auditory task to identify and respond to oddball targets. Additionally, the oddball targets used in the current study were simple pure tones and easy to discriminate from the standard tones. Recent research has shown that auditory evoked responses are more sensitive to modulations in visual task difficulty when more complex auditory probes are used (Dyke et al. 2015). The implementation of the oddball task in the current experiment also varied slightly from those used in prior studies. For example, in Miller et al. (2011) a single auditory tone was presented every 6–30 s; however, in the current study 1 of 2 auditory tones was presented more frequently (approximately 3.5 s). This required participants to attend to the auditory stream to make frequent target/non-target discrimination decisions. As such, participants may have favored the auditory over the visual task by allocating the necessary processing resources to auditory processing to ensure optimal performance. Moreover, the increased frequency of auditory tones may have led to habituation of the auditory evoked response (e.g., Pan et al. 2000). A design limitation of this task was not having a true baseline auditory response. It would have been beneficial to have measured the auditory evoked response either before any visual task was presented or included a passive viewing condition in the Tetris task. Nevertheless, there is convincing corroborating evidence from multiple measures (e.g., subjective ratings, pupil diameter, HRV, and behavior) that our task difficulty manipulations were effective despite the lack of modulation in the auditory data.

5. Applications and Conclusion

Lambda amplitude has been used in a variety of applied contexts. For example, Yagi et al. (1998) found a positive correlation between lambda amplitude and mental concentration under various lighting conditions. Other research has found increased lambda amplitude over time during enjoyable tasks while lambda amplitude decreased when tasks were perceived as boring or fatiguing (Daimoto et al. 1998; Takeda et al. 2001). Daimoto et al. (2007) assessed the effect of perceptual, motor, and cognitive workload on the lambda response by crossing a high/low difficulty manual tracking task with a high/low difficulty numerical problem. While the results of this study showed that the lambda amplitude was smaller under the high difficulty condition relative to the others, the potentially confounding effects of changes in the distribution of eye movements and stimulus properties were not reported. It is possible that the observed dynamics of the lambda response were due to differences in saccade magnitude or luminance contrast of the fixated locations, both of which have direct effects on the amplitude of the lambda response (Kazai and Yagi 2005; Yagi 1979). Moreover, it was not clear if overlapping activity from temporally adjacent saccades impacted the results. It is well known that both stimulus and ocular events occurring in rapid succession produce overlapping neural activity (Devillez et al. 2015; Woldorff 1993).

The current study demonstrates that the lambda response of the fixation-related potential is affected by changes in task difficulty, specifically those that affect working memory when controlling for saccade size, stimulus properties, and temporal overlap from adjacent neural responses. The lambda response amplitude may therefore be a useful metric to obtain task demand information. Acquiring task demand information in this way would allow individuals to interact with their environment and augment current measures of cognitive state. Traditional subjective measures of task difficulty often break task flow by interrupting the user at various times throughout the task, leading to disruptions in mental concentration. Additionally, subjective self-assessments are not sensitive to fluctuations of cognitive state within a task; instead they provide an average estimate over an interval of time, often on the order of several minutes, which can introduce unintended effects due to memory lapses (Moroney et al. 1995). Likewise, introducing a secondary task or probe stimuli may disrupt performance in the primary task of interest. However, caution must be used when leveraging FRPs in general, and the lambda potential in particular, as an indicator of task difficulty since FRP component amplitudes are affected by stimulus characteristics and saccade distance.

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List of Symbols, Abbreviations, and Acronyms

ABM	Advanced Brain Monitoring
AEP	auditory evoked potential
ARL	US Army Research Laboratory
ECG	electrocardiogram
EEG	electroencephalogram
ERP	event-related potential
FRP	fixation-related potential
HRV	heart rate variability
NASA	National Aeronautics and Space Administration
rERP	regression analysis
S/FRPs	saccade and fixation-related potentials
TLX	Task Load Index

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