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The efficacy of auditory probes in indexing cognitive workload is dependent on stimulus complexity

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ABSTRACT

We examined whether the utility of a recently developed auditory probe technique for indexing cognitive workload was dependent on the stimulus properties of the probes. EEG was recorded while participants played a videogame under various levels of cognitive workload. At each level of workload, participants were probed with one of four different types of auditory stimuli: novel complex, repeated complex, novel simple, or repeated simple sounds. Probe efficacy at indexing cognitive workload was assessed by determining which probes elicited ERP components that decreased monotonically as a function of workload. Results suggest that complex auditory stimuli were significantly more effective in indexing cognitive workload than simple stimuli. The efficacy of complex stimuli was due to their ability to elicit a robust orienting response, indexed by the early P3a component of the ERP, which decreased monotonically as a function of cognitive workload.

1. Introduction

The measurement of cognitive workload is useful in many ways (Rietschel and Miller, 2013). For example, such measurement can be employed to assess how various task conditions affect cognitive workload, gauge the automaticity with which an individual performs a task, and enhance user-task interaction by altering task demands to match a user's cognitive state. The measurement of cognitive workload with event-related potentials (ERPs) is of interest because such a method enables the objective (physiological) measurement of workload. Indeed, over the past 5 decades a number of studies have employed ERPs in attempt to measure cognitive workload (for discussion of these studies, see Allison and Polich, 2008; Miller et al., 2011).

Contemporary efforts to measure cognitive workload with ERPs have focused on the task-irrelevant auditory probe technique (Allison and Polich, 2008; Miller et al., 2011; Ullsperger et al., 2001). This technique involves intermittently presenting task-irrelevant auditory stimuli to an individual engaged in a task varied with respect to cognitive workload, extracting ERPs time-locked to the stimuli, and then analyzing amplitudes of ERP components to infer workload. If successful, the auditory probe technique reveals monotonic reductions in amplitude of one or more ERP components as a function of cognitive workload. This is because processing of task-irrelevant stimuli is constrained by the availability of neural resources, which are progressively consumed as cognitive workload increases. The auditory probe technique has been emphasized because it avoids interfering with task performance and hence confounding assessment of cognitive workload (for discussion of this issue, see Allison and Polich, 2008; Miller et al., 2011; Papanicolaou and Johnstone, 1984; Ullsperger et al., 2001).

Miller et al. (2011) were successful in measuring cognitive workload with the auditory probe technique. Specifically, the authors observed monotonic reductions in amplitudes of ERP components (e.g., P3 component) as a function of cognitive workload. Miller et al. suggested their study's success resulted from combining the strengths of two earlier studies. Like Ullsperger et al. (2001), Miller et al. employed novel, complex sounds (e.g., human cough, cat purr, glass clink) for auditory probes as opposed to repeated simple sounds (e.g., 1000 Hz pure tones). Ullsperger et al. employed novel complex sounds because they likely elicit higher-order processing which would be expected to consume spare neurocognitive resources due to their relatively high salience (Friedman et al., 2001). Specifically, such sounds elicit attentional orienting, as reflected by the early and late P3a components (eP3a and lP3a, respectively; Alho et al., 1998; Escera et al., 1998; McDonald et al., 2010; Yago et al., 2003). The eP3a has been proposed to reflect the call for the orienting response to a novel stimulus, whereas the lP3a is believed to reflect the orienting response itself (Čeponiene et al., 2004). Presumably, when eP3a amplitude crosses a threshold

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level, it triggers the deployment of attention towards the stimulus, which is indexed by the lP3a. Despite employing novel complex sounds, Ullsperger et al. did not observe significant monotonic reductions in ERP component amplitudes (N1, eP3a, or lP3a) as a function of cognitive workload. This may be because participants did not perform a task that was incrementally varied with respect to cognitive workload, which could have precluded detection of monotonic decreases in ERP component amplitude as a function of workload (Miller et al.). Thus, Miller et al. incrementally varied cognitive workload, incorporating a strength of the approach taken by Allison and Polich (2008). However, Allison and Polich did not observe significant monotonic reductions in ERP component amplitude as a function of cognitive workload, possibly because they employed repeated simple sound probes that failed to elicit higher-order processing of the stimuli (Miller et al.).

It is important to note that Allison and Polich (2008) and Miller et al. (2011) employed different tasks: a first-person shooter and tile-matching puzzle videogame, respectively. Thus, it is not clear whether the authors' differing levels of success in measuring cognitive workload was due to the nature of the auditory probes they employed or the task they employed. For example, it could be argued the tile-matching puzzle videogame simply better lent itself to cognitive workload measurement. Additionally, Miller et al.'s auditory probes differed from Allison & Polich's in two ways: novelty and complexity. The purpose of the present study was to tease apart these issues. Accordingly, participants' electroencephalographic (EEG) signals were recorded while performing a tile-matching puzzle videogame under incrementally-varied levels of cognitive workload. During each level of cognitive workload, participants were probed with one of four different types of task-irrelevant auditory stimuli: novel complex sounds, repeated complex sounds, novel simple sounds, or repeated simple sounds. ERPs time-locked to the stimuli were extracted, and ERP component amplitudes were calculated. The efficacy of the stimuli in measuring cognitive workload was assessed by determining which stimuli elicited ERP components that decreased monotonically as a function of workload.

2. Methods

2.1. Participants

After the study received institutional approval, 80 young adults (44 females, *M* age = 22.5, SD = 3.7 years) provided informed written consent and completed the study. Participants' experience playing the tile-matching puzzle videogame ranged from never having previously played to having played more than 50 h. The study was completed in four groups such that the first group of 20 participants was probed with novel complex sounds, the next group with repeated complex sounds, the subsequent group with novel simple sounds, and the final group with repeated simple sounds. A one-way (Group) analysis of variance (ANOVA) revealed no significant differences with respect to age, gender, or videogame experience ($ps > .08$; alpha levels for this analysis and all others were set to .05).

2.2. Task

Participants performed the tile-matching puzzle videogame Tetris while the song "Korobeiniki"("Music A" in the standard Tetris® game) was played (72–76 dB SPL) from a speaker built into the computer on which Tetris® was being played. Tetris® asks individuals to manipulate different-shaped game pieces presented on a video monitor (in the present case, a computer screen) in order to place them in their optimal location on the game board (computer screen). The experiment involved three cognitive workload conditions, which were counterbalanced across participants. During the view cognitive workload condition, participants fixated on a paused game while the music continued to play. During the easy condition, participants began to play at level 1, in which the game pieces move down the game board at a velocity of 1.67 cm/s. During the hard condition, participants began to play at level 8, in which the game pieces move down the game board at a velocity of 3.56 cm/s. Although participants could manually increase the velocity at which game pieces fell, they were restricted from doing so (i.e., the velocity of the pieces was solely determined by game level). When participants completed 10 horizontal lines of game pieces that contained no gaps between the pieces, they advanced to the next level (i.e., the velocity at which game pieces moved down the game board increased, thus increasing cognitive workload). When participants failed at the task (i.e., the game pieces accumulated to the top of the game board), they resumed to play at the highest level they were halfway through (e.g., if they were halfway through level 9, they resumed to play at level 9). Game difficulty adapted to participants' skill levels. For example, a poor Tetris player and a good Tetris player would both start the easy condition at level 1, but the good Tetris player may have advanced to level 4 during this condition, whereas the poor player may have stayed at level 1. Similarly, a poor player and a good player would both start the hard condition at level 8, but the good player may have advanced to level 12 during this condition, whereas the poor player may have stayed at level 8. In this way, it is likely the easy and hard conditions were indeed easy and hard, respectively, for all participants. No participant advanced beyond level 4 in the easy condition, thus ensuring this condition was sufficiently different from the hard condition. Each condition lasted approximately 9 min.

2.3. Auditory probes

During each condition, participants in the novel complex sound group were probed with a set of 30 novel complex sounds (e.g., a door knock, a dog bark, a whistle) randomly selected from a larger collection obtained from the New York State Psychiatric Institute (Fabiani et al., 1996). Each participant in the repeated complex sound group was probed 30 times during each condition with a single randomly selected sound from the set presented to the novel complex sound group (e.g., a door knock *or* a dog bark *or* a whistle). Participants in the novel simple sound group were probed with a set of 30 novel simple sounds during each condition. These sounds were pure tones of the following frequencies: 500, 550, 600, 650, 700, 750, 800, 850, 900, 950, 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1800, 2000, 2500, 3000, 3500, 4000, 4500, 5000, 6000, 7000, 8000, 9000, and 10,000 Hz. This range of tones and the differences between them was employed after pilot testing wherein the tones were presented in the order of frequency (i.e., 500, 550, 600 Hz) revealed participants could hear every tone and distinguish each one from the one preceding it. Durations of the pure tones were matched to those of the complex sounds, which ranged from 159 to 399 ms. Each participant in the repeated simple sound group was probed 30 times during each condition with a single randomly selected sound from the set presented to the novel simple sound group. Each participant was probed with the same 30 sounds in each cognitive workload condition. All sounds were presented at 87–96 dB SPL from 2 speakers positioned 70 cm behind participants; interstimulus intervals (ISIs) varied randomly between 6 and 30 s. Participants in the novel complex and novel simple sound groups were presented sounds in random order.

2.4. EEG recording and signal processing

Scalp EEG was collected from 32 channels of an EEG cap housing a 64 channel BrainVision actiCAP system (Brain Products GmbH, Munich, Germany) labeled in accord with an extended international 10–20 system (Oostenveld and Praamstra, 2001). EEG data were online referenced to the left earlobe, and a common ground was employed at the FPz electrode site. Electrode impedances were maintained below 10 kΩ throughout the study and a high-pass filter was set at 0.016 Hz with a sampling rate of 1000 Hz. The EEG signal was amplified and