The influence of cognitive load combined with active responses on auditory susceptibility

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Abstract

This research investigated the effect of cognitive load on auditory susceptibility and whether actively responding to auditory signals further affects this susceptibility. Previous research has shown that humans are less susceptible to auditory signals during cognitively demanding tasks (e.g. while driving). Requiring an active response to auditory stimuli can partially overcome this and increase susceptibility. However, tasks in these previous studies required visual or manual input. It is unknown whether having an active response requirement can also improve susceptibility during a cognitively demanding task without visual or manual input. Therefore, current research focusses on solely cognitive load, using an auditory verb generation task. In addition, it explores the effect of the active responses under conditions of increased cognitive load, by instructing half of the participants to give a response after hearing deviant signals. Susceptibility was measured by recording the frontal P3 response, using a three-stimulus oddball paradigm. Results show that the frontal P3 (and therefore auditory susceptibility) is reduced during cognitive load conditions. There’s insufficient evidence to conclude whether response requirement can overcome this reduction. In conclusion, these results suggest auditory susceptibility can diminish due to solely cognitive load. Further research is required to obtain sufficient evidence regarding the potential effect of active responses.

Introduction

In certain situations, for example while reading a book, the ability to ignore unexpected, distracting sounds might be useful. However, there are also situations in which it's crucial that unexpected sounds can involuntary capture one's attention. An example of the latter are systems that rely on auditory warning signals, such as an automated vehicle or a fire alarm. Humans process all incoming information automatically until one's perceptual and cognitive capacities are exhausted (S. Murphy, Spence, & Dalton, 2017), causing unexpected stimuli to involuntary capture one's attention (SanMiguel, Morgan, Klein, Linden, & Escera, 2010). However, performing highly demanding tasks can diminish the ability to perceive unexpected auditory stimuli (Scheer, Bülthoff, & Chuang, 2016, 2018).

A likely explanation arises from the perceptual load perspective. According to this perspective, the extent of processing task irrelevant stimuli decreases as the perceptual demands imposed by the primary task increases, due to limited perceptual capacities (Lavie, 1995, 2005). However, since the majority of the existing literature focused on the effect of perceptual load on auditory susceptibility, the potential effect of cognitive load is less extensively researched (G. Murphy, Groeger, & Greene, 2016). It is therefore of importance to further investigate the effect of cognitive load in absence of perceptual demands.

An explanation of how cognitive load can cause inattentional deafness, is that difficult tasks impose higher cognitive demands and therefore limit the mental resources left to process task-irrelevant stimuli (Polich, 2007; Scheer et al., 2016). Several studies investigated susceptibility to auditory signals under varieties of cognitive load. For example, research has found that humans susceptibility to unexpected, auditory signals is reduced while driving in a simulator, compared to a non-driving condition (Wester, Böcker, Volkerts, Verster, & Kenemans, 2008). A more recent study additionally found that susceptibility is also reduced, although in a lesser extent, during autonomous driving conditions, compared to being stationary (Van der Heiden et al., 2018). Auditory susceptibility seems to be affected by other cognitively demanding tasks as well. Previous studies have found a reduced auditory susceptibility during for example visual search tasks (Molloy, Griffiths, Chait, & Lavie, 2015), visuomotor control tasks (Scheer et al., 2018), and verb generation tasks (Van der Heiden, Janssen, Donker, & Kenemans, 2020).

To measure susceptibility, the aforementioned studies used electroencephalography to record the response of an event-related potential (ERP), specifically the frontal P3 (fP3), to auditory signals. An advantage of this technique is that it provides a measurement of cognitive processes without requiring behavioural responses and therefore without distorting the ongoing cognitive processes (Luck, 2014). A widely used method to elicit the frontal P3 is the auditory, novelty oddball paradigm, typically containing three types of stimuli: standard, deviant and novel (Friedman, Cycowicz, & Gaeta, 2001; Polich, 2007). In this novelty oddball paradigm, the majority of the sounds introduced to the participant are the predictable, standard tones. The occasional deviant and novel tones therefore have a low probability of appearing and are assumed to be relatively unexpected. The fP3 component is obtained by subtracting the ERP elicited by the standard tones from the ERP elicited by the novel tones (for a more detailed description of this method, see Methods). Subtracting these ERP waves eliminates concurrently active processes in the brain (Luck, 2014).

The fP3, often also referred to as the ‘novelty P3’ or ‘P3a’, is a frontally oriented peak in the brain activity and is elicited by relatively unexpected events or stimuli (Friedman et al., 2001). It is thought to prepare humans to respond to sudden changes in the environment and to facilitate the processing of the information that these changes entail, by providing widespread inhibition throughout the brain (Kenemans, 2015; Polich, 2007). Relatively highly demanding tasks result in smaller fP3 components (Polich, 2007). A recent study by Molloy et al. (2015) provided behavioural evidence by revealing that smaller fP3 components are related to reductions in tone detection sensitivity, indicating that a smaller fP3 is indeed related to a reduced awareness of sounds.

The deviant tones in the oddball paradigm can be used to create an active oddball paradigm, in which participants are required to silently count the number of deviants or to press a button in response to a deviant (Friedman et al., 2001). An example of the active oddball paradigm can be found in the previously mentioned driving studies (Van der Heiden et al., 2018; Wester et al., 2008), where the fP3 component was reduced in the autonomous driving conditions and even more so in the driving conditions, compared to a stationary, non-driving control condition. An interesting finding in these studies was that actively responding to the deviant tones (i.e. using the active oddball paradigm) slightly restored the reduced fP3 peak, regardless of the driving condition. Using similar instructions, a different study also found an enhanced fP3, regardless of the induced workload (Scheer et al., 2018). This suggests that being actively engaged with auditory signals can enhance susceptibility towards other auditory signals.

A reason for this ‘boost’ in susceptibility may be that adding such instructions to the oddball paradigm directs attention towards the auditory stream (Friedman et al., 2001) and additionally makes the auditory information task relevant (Scheer et al., 2018). In addition, requiring to go back and forth between tasks that involve different modalities increases demands on cognitive control functions, which is thought to be associated with an increase in distractor processing (Lavie, 2010). Another possibility is that adding suck tasks prevents mental underload. Mental underload can occur during tasks that are not demanding enough and therefore won't require much attentional resources. This can diminish the amount of attentional resources dedicated to the task, resulting in poorer performance (Scheer et al., 2018; Young & Stanton, 2002a, 2002b).

Previous studies (e.g. Scheer et al., 2016, 2018; Van der Heiden et al., 2018; Wester et al., 2008) used tasks that were visually, and in some situations even manually, demanding. Van der Heiden et al. (2020) therefore addressed this limitation by evaluating the effect of solely cognitive load, using an auditory verb generation task to induce cognitive load. By doing this, Van der Heiden et al. (2020) aimed to investigate whether the observed reduced susceptibility to auditory signals also occurs during solely cognitive processes without visual or manual components.

In an auditory verb generation task, participants hear a noun and are instructed to verbally respond to this with a verb related to the noun. Generating verbs related to nouns is associated with increased activity in the frontal cortex, compared to control conditions where participants are instructed to read the nouns aloud (Abdullaev & Posner, 1998; Snyder, Abdullaev, Posner, & Raichle, 1995). The verb generation task is therefore assumed to impose relatively high cognitive demands (see also Kunar, Carter, Cohen, & Horowitz, 2008; Strayer & Johnston, 2001). Van der Heiden et al. (2020) found a decreased fP3 when susceptibility was probed during the verb generation task. These results suggest that cognitive load can decrease susceptibility to auditory signals in the absence of other potentially interfering factors. Further comparison of different intervals (0 ms, 200 ms, and 400 ms) between the onset of the nouns and onset of the oddballs revealed no significant differences, indicating that susceptibility was equally reduced in these three conditions.

However, Van der Heiden et al. (2020) only investigated the effect of cognitive load on auditory susceptibility and not yet the effect of adding a response requirement to the oddball paradigm (as in Scheer et al., 2018; Van der Heiden et al., 2018). Therefore, current research first aims to investigate whether cognitive load induced by a verb generation task reduces auditory susceptibility (as in Van der Heiden et al., 2020). Secondly, it aims to investigate whether this potentially reduced auditory susceptibility can be enhanced when an occasional response to deviant sounds is needed (as in Scheer et al., 2018; Van der Heiden et al., 2018; Wester et al., 2008). Or perhaps whether these auditory tasks will counter-act each other, in case of interference between auditory stimuli. To this end, participants are required to perform the auditory verb generation task, while also being probed with oddball stimuli using an auditory, three-stimulus novelty oddball paradigm. To test the effect of response requirements, half of the participants will be instructed to actively respond to a deviant tone by pressing a button.

The following outcomes are expected. First, a decreased fP3 (i.e. auditory susceptibility) in the verb generation conditions, due to relatively high cognitive load (cf. Van der Heiden et al., 2018, 2020; Wester et al., 2008). Secondly, an enhanced fP3 in the active response requirement conditions (cf. Scheer et al., 2018; Van der Heiden et al., 2018; Wester et al., 2008). Furthermore, the existing literature suggest there may be an interaction between cognitive load and response requirement, which can have two possible outcomes. In case the response requirement diminishes underload (Young & Stanton, 2002a, 2002b), this may result in a slightly restored fP3 in the response requirement conditions during cognitive load. However, in case the response requirement increases fP3 by directing attention towards auditory information that has become task-relevant (Friedman et al., 2001; Scheer et al., 2018), there will presumably be no difference between the active and passive response conditions during cognitive load.

Methods

Participants

To determine the number of participants needed in this study, a power analysis was conducted using G*Power 3.1.9.5 (Faul, Erdfelder, Lang, & Buchner, 2007) for a repeated measures ANOVA with a within-between interaction. The effect size ($\eta^2_p = 0.28$) from a previous study on the effect cognitive load on auditory susceptibility (Van der Heiden et al., 2020) was used. Power was set to 0.8 and the alpha level to 0.05. This returned a required sample of 8 participants. In order to counterbalance the design, 18 participants were aimed for during recruitment (see Design). Due to safety regulations in response to the Covid-19 pandemic, data collection was terminated earlier than anticipated. Therefore, Bayesian analysis was used to determine whether the evidence is sufficient or whether more observations are needed to distinguish possible effects.

In the end, 10 participants (9 F; 1 M) were recruited via social media, posters, and flyers. Participants were on average 21.2 years old (*SD* = 1.93 years; range = 18 to 23 years old). All participants spoke fluently Dutch and all participants reported to have normal hearing. Participants were rewarded with either student credits or a monetary reward of €6 per hour. The experiment was approved by the ethics committee of the Faculty of Social and

Behavioural Sciences of Utrecht University (approval number FETC16-042). All participants provided written informed consent prior to participating.

Materials

Apparatus

All tasks used only auditory stimuli. All auditory stimuli were binaurally presented via Earlink earphones at 70 dB using Presentation (Neurobehavioural Systems). Tasks instructions were presented on a computer screen. Electroencephalography (EEG) data were recorded using a BioSemi ActiveTwo system at 2048 Hz, with 64 active Ag-AgCl electrodes placed at the international 10/10 system (Chatrian, Lettich, & Nelson, 1985). Four electro-oculography (EOG) electrodes were used to be able to compensate for noise due to eyeblinks or eye movements. In addition, an electrode was placed on each mastoid for offline re-referencing.

Auditory oddball paradigm

In the three-stimulus auditory oddball paradigm, participants were frequently presented with auditory stimuli. In each experimental block, 80% of these stimuli were ‘standard’, 10% ‘deviant’, and 10% ‘novel’ stimuli. The standard stimuli were 1000 Hz tones and the deviant stimuli 1100 Hz tones. Both the standards and the deviants were presented for 340 ms. The novel stimuli were obtained from a database by Fabiani and Friedman (1995), consisting of 100 unique environmental sounds, such as a barking dog, a cough, or a sneeze. The duration of the novel stimuli varied from 159 ms to 399 ms.

Verb generation task

In the verb generation task, participants heard a noun and were instructed to verbally respond with a verb related to this noun (e.g. after hearing “apple”, participants can reply with “eating”). The verb generation task consisted of a list of 120 Dutch words, developed by Van der Heiden et al. (2020), based on an English database for this task (Abdullaev & Posner, 1998; Snyder et al., 1995). The duration of the words was set at 400 ms. As a total of 360 verb generation trials were used in the experiment (see Verb generation task with the oddball paradigm), each word was presented three times across the experiment.

Each word had a so-called ‘imaginability score’ (Van Loon-Vervoorn, 1985), which indicates the difficulty to imagine the word and to generate an associated verb. To balance the imaginability across different blocks, the words were carefully divided into separate folders for each block. Based on their imaginability scores, the words were divided into three equally sized (each 40 words) categories: easy, medium, and hard. The words were randomized within each category. Subsequently, the first 36 words from each category were divided into three folders. The remaining 12 words (four from each category) were put in a separate folder. The process of randomizing and dividing the words within the categories was repeated twice, resulting in nine folders and a separate, tenth folder, consisting the remaining words. As a result, each folder eventually contained 12 words from each category (easy, medium, hard), resulting in a total of 36 words per folder.

To further minimize the chance of presenting a stimulus two times in a row, each participant was randomly assigned a predetermined order of the presentation of the folders. The order of the folders was determined per set of three (i.e. folder 1-2-3, folder 2-3-1, or folder 3-1-2). For the subsequent two sets of three folders, the order of the first set was repeated. Folder 10 was presented as last to each participant.

All participants were tested for their intelligibility of the words, by instructing the participants to repeat each word. During this task, all 120 words were presented at an interval of 1600 ms. The responses were recorded and the experimenter additionally took notes of the responses. Since no particularities were noticed during the tasks, the results were not further analysed. During the experimental trials, the reaction times of the verbal responses were recorded in the EEG data using a microphone. The reaction times were not analysed and the responses were not assessed on correctness, as this was not the purpose of the study.

Verb generation task with the oddball paradigm

Trials containing stimuli from the verb generation task were compared with trials containing stimuli from solely the oddball paradigm. In each experimental block, 80 oddball stimuli (i.e. trials) were presented (64 standards, 8 deviants, and 8 novels). Blocks containing solely oddball probes (and no nouns) are referred to as the “control blocks”. In the “cognitive load blocks”, 36 of these oddball probes (32 standards and 4 novels) were directly preceded by a noun. After a verb generation trial, the subsequent trial was presented 4000 ms after onset of the noun, to allow for a verbal response. Between two subsequent oddball trials was an interval of 2000 ms.

As large components such as the P3 are typically measured using a minimum of 30-40 trials (see for example Luck, 2014), the current experiment was set up to reach a minimum of 40 measurements per oddball stimulus per condition. The experiment therefore consisted of ten cognitive load blocks and five control blocks, in order to reach the minimum of 40 measurements, creating a total of 15 blocks.

Design

A 3 (cognitive load) x 2 (response requirement) mixed design was used for this experiment. Cognitive load was manipulated within-subjects, using oddball probes from the control block (control condition), oddball probes from the cognitive load blocks on occasions where the oddball probe was not preceded by a noun (control under load condition), and oddball probes presented directly following presentation of a noun (cognitive load condition). The response requirement was manipulated between-subjects, by instructing half of the participants to press the spacebar after hearing a deviant stimulus (active condition) and the other half to ignore the oddball stimuli (passive condition).

The experiment consisted of ten cognitive load blocks and five control blocks. The order of the blocks (and thus conditions) was semi-randomized. Per set of three blocks, participants performed two cognitive load blocks and one control block. Each participant was randomly assigned a specific order of these blocks (i.e. control-load-load, load-control-load, or load-load-control). The order of the first set was repeated in the subsequent four sets of three blocks for each participant. For each block order, all orders of the folders containing the nouns for the verb generation task were used, resulting in nine unique orders. To ensure that each order is experienced in both groups of participants (active and passive condition), 18 participants were aimed for during recruitment. In the end, after ending the data collection earlier than anticipated, the active condition and the passive both included five participants.

Procedure

Upon arrival, participants received an overview of the experiment and general instructions regarding the task (including the instruction to turn off all electronical devices). After this, the participants read and signed the consent form. Subsequently, the participants were instructed to put in the earphones and then they performed the intelligibility task. After this, four ocular electrodes were applied on the face (above and below the right eye and on both outer canthi of the eyes) and two electrodes were placed on the left and right mastoid. An EEG cap with 64 electrodes was placed on the participant’s head. The signal of all electrodes was inspected and where necessary small adjustments were made (e.g. adding gel) to improve the signal. During this preparation, participants were allowed to temporarily remove the earphones.

After the EEG preparation, participants received more detailed task instructions and started with a small practice round to familiarize them with the verb generation task and the oddball stimuli. After this, the main experiment started. The experiment consisted of 15 blocks, with a break (ca. 2-3 minutes) after every three blocks and a slightly larger break (ca.

5 minutes) after the ninth block. At the end of the experiment, the EEG cap and all electrodes were removed. Participants were instructed to fill in a questionnaire regarding demographic information, task experience, and general feedback. The questionnaire in the active condition contained two additional questions regarding the response requirement. All participants received compensation for their participation. The total length of the experiment was 2.5 hours, including the EEG preparation.

Analysis

Signal analysis

BrainVision Analyzer 2.1 (Brain Products GmbH, München, Germany) was used for the EEG signal analysis. First, the sampling rate was down sampled to 250 Hz. Secondly, data were re-referenced to the average signal of the left and right mastoid electrodes. Subsequently, three filters were applied: a 50 Hz notch filter to compensate for noise from the mains, a 0.16 Hz high-pass filter (with a slope of 24 dB/oct), and a 30 Hz low-pass filter (with a slope of 24 dB/oct).

After applying the filters, ERP segments of 1100 ms were created, starting 100 ms before the onset of the oddball stimuli and ending 1000 ms after onset. An artefact rejection was applied on all segments from the FCz channel and the ocular channels, to correct for extreme artefacts. In this artefact rejection, the maximal allowed difference of values in the intervals was set to 1500 µV and the interval length to 1700 ms[1]. Then, an ocular correction was applied on each segment using the Gratton, Coles and Donchin method (Gratton, Coles, & Donchin, 1983), to correct for eye movements and eyeblinks. After this, all segments were baseline corrected over the interval of 100 ms preceding the oddball stimulus. Another artefact rejection was applied, using the standard settings in BrainVision Analyzer 2.1.

Lastly, averages were calculated per oddball stimulus type (standard, deviant, and novel) per within-subjects condition (control, control under load, and cognitive load). The difference waves were calculated for each within-subjects condition by subtracting the average ERP for the standard oddball stimuli from the average ERPs for the novel oddball stimuli.

Statistical analysis

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[1] This is an error in the analysis and should have been 1100 ms, as this was the length of the segments made in the previous step. However, this did not pose any problems for the statistical analysis, as in the end there was still a minimum of 30 measurements per condition for each participant.

A 3x2 Bayesian Repeated Measures ANOVA was conducted using JASP (Version 0.11.1; JASP Team, 2019). Cognitive load (control, control under load, and cognitive load) was set as the within-subjects factor and Response requirement (active and passive) as the between-subjects factor. This analysis produced a model comparison table (see Table 1 in Results), containing the comparisons of each possible model to the null-model. The models were sorted from best to worst fit, based on their BF_{10} value (the likelihood of the alternative hypothesis over the null hypothesis). To gain further insight into the potential effects, a post hoc comparison analysis (see Table 2 in Results) and an analysis of effects (see Table 3 in Results) was conducted.

The interpretation of the Bayes Factors was based on the interpretation by Jeffreys (1961; see also chapter 7 in Lee and Wagenmakers, 2013). For example, a Bayes Factor between 3 and 10 is considered as moderate evidence for the alternative hypothesis and a Bayes Factor between 10 and 30 as strong evidence. A Bayes Factor above 30 is considered as very strong or extreme evidence. Bayes Factors below 1/3 are considered as evidence for the null hypothesis. Bayes Factors between 1/3 and 3 are considered as anecdotal evidence for either the alternative or the null hypothesis and therefore require more data in order to draw conclusions.

For the active group of participants, the reaction times to the deviant oddball stimuli were measured. The means and the standard deviations of the reaction times were analysed in JASP (Version 0.11.1; JASP Team, 2019) using Bayesian paired t-tests. In this analysis, the performance in the control blocks was compared with the performance in the cognitive load blocks. There was no distinction made between “control under load” and “cognitive load”, as none of the deviant tones were preceded by a noun from the verb generation task. Therefore, the measurements in the cognitive load blocks can all be considered “control under load”.

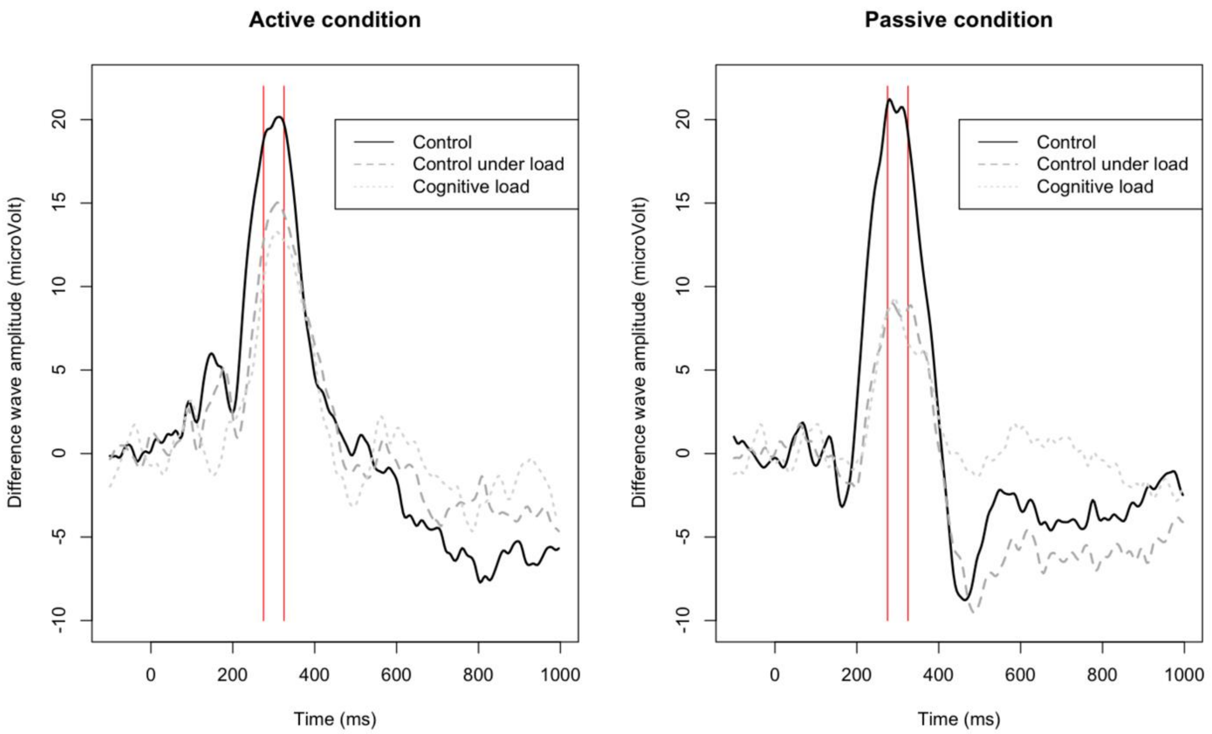
Results

Auditory susceptibility (fP3)

The difference waves (novel minus standard) for all conditions at electrode FCz are provided in Figure 1. In both graphs, the peak is highest in the control conditions. For further analyses, the average amplitude around the peak (275-325 ms) was calculated.

Figure 1

Grand-average fP3 at electrode FCz



Note. Grand-average difference waves (novel minus standard) in microvolts for the three different cognitive load conditions (represented by the three separate lines) in the active condition (left) and the passive condition (right). The red lines indicate the interval of the fP3 peak.

Table 1 provides an overview of the model comparison results, sorted on the BF_{10} values (i.e. the likelihood of the alternative hypothesis compared to the null hypothesis). The model comparison analysis found decisive evidence (BF_{10} = 245.8) for the model including solely a main effect of cognitive load on auditory susceptibility. Therefore, Table 2 shows a post hoc comparison of the cognitive load conditions. The fP3 peak amplitude is higher in the control condition (*M* = 20.15 µV, *SD* = 4.98 µV), compared to the control under load condition (*M* = 11.49 µV, *SD* = 5.87 µV, $BF_{10,\,U}$ = 28.9, strong evidence), and compared to the cognitive load condition (*M* = 10.41 µV, *SD* = 6.87 µV, $BF_{10,\,U}$ = 46.6, very strong evidence). There is anecdotal evidence that there is no difference between the control under load and the cognitive load condition ($BF_{10,\,U}$ = 0.34, i.e. “null effect”).

Table 1

Model comparison results

Models	P(M)	P(M|data)	BF $_{\mathrm{M}}$	BF $_{10}$	error %
Null model (incl. subject)	0.200	0.002	0.008	1.000	
Load	0.200	0.464	3.468	245.827	0.857
Load + Response	0.200	0.304	1.750	161.087	0.870
Load + Response + Load ✻ Response	0.200	0.228	1.183	120.853	3.623
Response	0.200	0.001	0.004	0.567	0.802

Note. Load = cognitive load, Response = response requirement. All models include subject.

Table 2

Post hoc comparisons for cognitive load

		Prior Odds	Posterior Odds	BF $_{10,\mathrm{U}}$	error %
Ctrl	Load_Ctrl	0.587	16.978	28.904	1.657e -4
	Load	0.587	27.343	46.550	3.263e -6
Load_Ctrl	Load	0.587	0.203	0.345	0.006

Note. Ctrl = control condition, Load_Ctrl = control under load condition, Load = cognitive load condition. The posterior odds have been corrected for multiple testing by fixing the prior probability that the null hypothesis holds across all comparisons to 0.5 (Westfall, Johnson, & Utts, 1997). Individual comparisons are based on the default t-test with a Cauchy (0, r =1/sqrt(2)) prior. The "U" in the Bayes factor denotes that it is uncorrected.

Effects were further analysed by comparing models containing the effect to equivalent models without the effect. Table 3 provides a summary of the results. There is decisive evidence for a main effect of cognitive load ($\mathrm{BF}_{\mathrm{incl}} = 259.7$). The analysis further revealed anecdotal evidence in favour of the null-hypothesis for the effect of response requirement on auditory susceptibility ($\mathrm{BF}_{\mathrm{incl}} = 0.7$) and anecdotal evidence in favour of the null-hypothesis for the interaction between response requirement and cognitive load ($\mathrm{BF}_{\mathrm{incl}} = 0.8$).

Table 3

Analysis of effects

Effects	P(incl)	P(incl|data)	BF $_{\text{incl}}$
Load	0.400	0.769	259.676
Response	0.400	0.305	0.655
Response ✻ Load	0.200	0.228	0.750

Note. Compares models that contain the effect to equivalent models stripped of the effect. Higher-order interactions are excluded.

Oddball response times

A Bayesian Paired Samples T-test analysis on the mean reaction times in response to the deviant tones in the active condition revealed a Bayes Factor of 2.2. Thus, there is anecdotal evidence that reaction time is higher in the cognitive load condition (*M* = 611.23 ms, *SD* = 112.54 ms), compared to the control condition (*M* = 542.13 ms, *SD* = 142.79 ms).

A Bayesian Paired Samples T-test analysis on the standard deviations of the reaction times revealed a Bayes Factor of 18.4. Thus, there is strong evidence that the standard deviations of the reaction times are higher in the cognitive load condition (*M* = 123.76 ms, *SD* = 29.59 ms) than in the control condition (*M* = 87.43 ms, *SD* = 24.94 ms).

Discussion

The current study investigated the effect of cognitive load on auditory susceptibility (as reflected in the fP3 amplitude) in the absence of other potential influences, such as visual or manual demands. In addition, the study investigated the effect of actively responding to sounds (referred to as “response requirement”) on auditory susceptibility and its interaction with cognitive load. The results show decisive evidence for a reduced auditory susceptibility (as reflected in the reduced fP3 peak amplitude) during conditions of cognitive load (cf. Molloy et al., 2015; Scheer et al., 2016; Van der Heiden et al., 2018, 2020; Wester et al., 2008), conform prior expectations. The results further suggest that response requirement has no main effect, nor an interaction effect with cognitive load, on auditory susceptibility. This is in contradiction with prior expectations and previous studies (e.g. Scheer, Bülthoff, & Chuang, 2018; Van der Heiden et al., 2018; Wester et al., 2008).

Comparison of the different cognitive load conditions showed that auditory susceptibility was highest in the control blocks (containing the oddball paradigm without verb generation stimuli), suggesting that humans are more susceptible to audio when not experiencing cognitive load. This finding also seems to be reflected in the results of the reaction time analysis. Although the evidence for the average reaction time analysis is considered as anecdotal and therefore does not allow for conclusions, the average reaction times seem higher during the cognitive load blocks (containing the oddball paradigm and the verb generation task) than the control blocks (cf. Van der Heiden et al., 2018). Furthermore, there was conclusive evidence for a higher variability in reaction times during cognitive load, indicating an increase in occasional lapses of attention (cf. Wester et al., 2008). Together, these results may indicate that the manipulation of cognitive load using the verb generation task succeeded and that cognitive load can affect auditory susceptibility without influences of visual or manual task requirements.

The comparison of the control under load condition and cognitive load condition within the cognitive load block revealed no differences, indicating that auditory susceptibility was equally reduced during moments where participants were generating a verb and between those moments. This finding seems to be reflected in the results of the reaction time analysis as well. The slightly higher reaction times and the increased variability in reaction times, measured during the control under load condition, may reflect residual cognitive load caused by preceding verb generation trials and thereby possibly explain why no evidence was found for differences in auditory susceptibility within this block. However, the evidence for the comparison of auditory susceptibility in the control under load condition and cognitive load condition is considered as anecdotal evidence and therefore does not allow for conclusions.

Still, the results differ from a previous study by Van der Heiden et al. (2020), where significant differences were found while solely using blocks similar to the cognitive load blocks from the current experiment. A potential cause of these deviating results, and the lack of conclusive evidence, may be the differences in the experimental design. The experiment contained a larger number of verb generation trials within one cognitive load block (36 out of 80 trials) than Van der Heiden et al. (2020) (24 out of 80 trials). These additional verb generation trials may have induced additional cognitive load or lingering cognitive load between the trials, resulting in cognitive distraction. Another difference is the number of nouns that were followed by a novel. In the previous study (Van der Heiden et al., 2020), half of the nouns were followed by a novel, which may have unconsciously caused a higher expectancy of the novels after hearing a noun and thereby affecting the fP3 amplitude. In the current experiment only four of the nouns were followed by a novel in order to keep the distribution of standards and novels around 80% and 20%, respectively, and thereby to maintain the relatively unexpectedness of the novels.

The anecdotal evidence for the null effect of response requirement on auditory susceptibility does not allow for firm conclusions. The ability to interpret these results remains therefore limited. However, for now the results suggest that actively responding to sounds has no effect on humans' susceptibility to audio nor does it interact with cognitive load induced by generating a verb. Therefore, it seems more likely that the positive effect of response requirement found in previous studies (Scheer et al., 2018; Van der Heiden et al., 2018; Wester et al., 2008) was due to directing attention towards auditory information and making this information task-relevant, and not due to preventing underload. The auditory version of the verb generation task in this experiment also required such direction of attention towards the auditory information and thereby may have created the same positive effect. However, again, the evidence found is not compelling enough and therefore more data is needed to create a better understanding of the effect of response requirement, leaving this question open for potential future work.

Due to the regulations in response to the Covid-19 pandemic, the data collection ended before the predetermined number of participants was met. The use of Bayesian statistics for the analyses partly alleviated this problem by providing insight into the strength of the evidence. However, these analyses showed that the evidence for the majority of the effects was not strong enough, meaning that more data or replication is needed to be able to make any firm conclusions regarding these effects. It remains therefore important for future work to find more conclusive evidence to eliminate the current uncertainties.

Another potential problem is that during prior inspection of the experiment, technical issues arose which may have affected the results. Inspection of pilot data showed inconsistencies between the timing of the markers in the EEG data and the actual timing of the presented stimuli, with differences ranging from 3 ms to 20 ms. This problem seemed to be resolved after a change in the technical setup and further inspections between the experiments also showed no signs of abnormalities in the timing. However, detailed timing control data was not collected during the experiments. Therefore, it is not certain whether all problems were resolved. Future studies can look into gaining even better control and calibration over such timing issues.

Future work may build upon this study by addressing the shortcomings in the design and improving these. For example, being able to use shorter blocks in which cognitive load is induced or using fewer verb generation trials might reduce the chance of participants developing fatigue. Another option is to also present deviants in conjunction with a noun, to allow for a more extensive comparison of reaction times between conditions. In addition, this may provide more insight into the experienced cognitive load during and between verb generation trials and thereby possibly explain why no differences were found within the cognitive load blocks. Future work may also look further into the performance of the verb generation task, for example by comparing the response times in verb generation trials followed by a standard or by a novel.

In conclusion, cognitively demanding tasks can diminish humans' susceptibility towards auditory signals, solely due to mental processes. Demanding tasks can further interfere with reaction times, as reflected by the increased variability in reaction times during a cognitively demanding task. Further research is needed to test whether actively responding to deviant sounds also affects the susceptibility to auditory signals and how this may interact with induced cognitive load.

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