NeuroImage 273 (2023) 120080

Contents lists available at ScienceDirect

NeuroImage

journal homepage: www.elsevier.com/locate/neuroimage

The effects of visual perceptual load on detection performance and event-related potentials to auditory stimuli

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ARTICLE INFO

Keywords:
Load theory
Perceptual load
Distraction
EEG

ABSTRACT

Load Theory states that perceptual load prevents, or at least reduces, the processing of task-unrelated stimuli. This study systematically examined the detection and neural processing of auditory stimuli unrelated to a visual foreground task. The visual task was designed to create continuous perceptual load, alternated between low and high load, and contained performance feedback to motivate participants to focus on the visual task instead of the auditory stimuli presented in the background. The auditory stimuli varied in intensity, and participants signaled their subjective perception of these stimuli without receiving feedback. Depending on stimulus intensity, we observed load effects on detection performance and P3 amplitudes of the event-related potential (ERP). N1 amplitudes were unaffected by perceptual load, as tested by Bayesian statistics. Findings suggest that visual perceptual load affects the processing of auditory stimuli in a late time window, which is associated with a lower probability of reported awareness of these stimuli.

1. Introduction

The question of the locus of selective attention has been occupying psychological and neuroscientific research for decades (e.g., Allport et al., 1972), with *Load Theory* being regarded as the dominant theory (Lavie, 1995; Lavie and Tsal, 1994). *Load Theory* suggests that all information is processed regardless of its relevance in situations of low load. In contrast, only relevant information is processed during high load, and irrelevant information is inhibited. Since a parametric or formalized definition of perceptual load is still missing (Murphy et al., 2016), it can only be defined in terms of different operationalizations related to the number, salience, and (spatial) arrangement of stimuli (Brockhoff et al., 2022; see also Neokleous et al., 2016).

While initially *Load Theory* was tested by behavioral experiments, where the decreased distractor interference on the main load task under high versus low load was described to constitute the load effect, many neuroscientific studies directly investigated how load manipulations affect stimulus processing, even if the stimulus was irrelevant for the main load task. Thus, several electroencephalographic studies investigated the effects of perceptual load on early (i.e., N1 amplitude) and late (i.e., P3 amplitude) event-related potentials (ERP) to task-unrelated stimuli. These studies yielded heterogeneous findings. Many unimodal studies (i.e., effects of visual load on task-irrelevant visual stimuli) showed that the N1/N170 amplitude was not affected by load (Intaitė et al., 2013; Kimura and Takeda, 2013; Müller-Bardorff et al., 2016; Schindler et al., 2020b, 2021a; S. 2021b). However, three studies also reported decreased N1/N170 responses (Rorden, 2008; Schindler et al., 2020a; S. 2021a), and one study even found increased N170 responses (Neumann et al., 2018). The P3 amplitude was most often reduced under high load (Intaitė et al., 2013; Müller-Bardorff et al., 2016; Rossi and Pourtois, 2014; Sawaki and Katayama, 2009; Schindler et al., 2020b), with only one study reporting no effect (Tiferet-Dweck et al., 2016) and two studies reporting opposite effects (Sawaki and Katayama, 2009; Sugimoto and Katayama, 2017). For crossmodal studies (i.e., effects of visual load on task-irrelevant auditory stimuli), the N1 amplitude was found to be either reduced (Molloy et al., 2015; Wiens et al., 2019) or not affected by high load (Sugimoto and Katayama, 2017). The P3 amplitude in these studies was decreased (Molloy et al., 2015, 2018; Zhang et al., 2006), increased (Sugimoto and Katayama, 2017), or not affected (Sculthorpe et al., 2008; Wiens et al., 2019) under high versus low load. Thus, early, and in contrast to the big picture on load studies (see Brockhoff et al., 2022), also late load effects occur inconsistently. Since the inconsistency of early effects might be, besides power problems, partly due to differences in study designs, future studies

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https://doi.org/10.1016/j.neuroimage.2023.120080.
Received 18 October 2022; Received in revised form 25 March 2023; Accepted 31 March 2023
Available online 1 April 2023.

should use controlled and systematized designs (see also Brockhoff et al., 2022).

Furthermore, a critical prediction from *Load Theory* is that the detection of task-irrelevant stimuli, at least threshold stimuli, should be reduced or even inhibited under conditions of high load. While studies examining awareness of stimuli do not necessarily rely on load manipulations, in several behavioral studies, inattentional blindness (Cartwright-Finch and Lavie, 2007; Macdonald and Lavie, 2008) and inattentional deafness (Macdonald and Lavie, 2011; Raveh and Lavie, 2015) was found under high versus low load. However, in none of these studies, the detection of task-irrelevant stimuli was completely inhibited. Interestingly, only Molloy et al. (2015) have targeted neural effects related to detecting auditory stimuli in a standard load paradigm. With magnetoencephalography, they found reduced early (aM100) and late responses (P3) to sounds and a decreased detection under high versus low load (88 versus 92 percent detection accuracy) and interpreted this as evidence for an association between reduced neural responses and awareness of sounds. However, this result remains to be replicated. Furthermore, in that study, there was a simultaneous onset of target and distractor stimuli and no control load conditions without distractors, which makes it difficult to separate effects of load on task-irrelevant stimuli from general load effects.

In the current study, we systematically investigated the effects of continuous perceptual load on the detection of auditory stimuli and their neural processing (i.e., ERPs). The continuous perceptual load paradigm is based on a previous study (Schindler et al., 2021b) and avoids the simultaneous onset of visual and auditory stimuli. To separate effects of visual perceptual load on auditory stimuli from general load effects, we compared conditions in which an auditory stimulus or no stimulus was presented. Moreover, we varied the intensity of auditory stimuli to investigate the role of stimulus strength. We hypothesized that high versus low perceptual load reduces the detection of auditory stimuli and early (N1) and late (P3) components of the ERP, most pronounced for stimuli at the detection threshold.

2. Methods

2.1. Participants

For this study, fifty-two paid participants were recruited at the University of Muenster. As there was no explicit stopping rule, sample size was based on a rough estimate of previous studies using a similar task paradigm (Schindler et al., 2021b; Schlossmacher et al., 2020). Five participants were rejected due to problems with stimulus presentation and EEG recording, four participants did not understand the task correctly, and two participants chose not to finish the experiment, leading to a final sample size of 41 participants (15 males, 36 females; M_{age} = 25.78 years, SD_{age} = 4.42 years). All participants provided their written informed consent. They had normal or corrected-to-normal vision and audition and no neurological or psychiatric disorders history. Three participants were left-handed, one was two-handed, and the remaining 37 were right-handed. The study was approved by the medical ethics committee of the University of Muenster.

2.2. Stimuli

Visual stimuli chosen for the continuous task consisted of 20 red dots, four of each rotating on five concentric orbits (radius: 2.5°, 3.5°, 4.5°, 5.5°, and 6.5°) with a white fixation cross (25×8 pixels) in the center of a black background screen. On every concentric orbit, four dots were spaced equidistantly. The dots were smallest on the innermost ring (0.31°) and became larger in 0.05° steps towards the outermost ring (0.51°). Throughout the experiment, the dots rotated along the orbits (with a velocity of 1° per frame). The direction of rotation alternated between clockwise and counter-clockwise every second block. In the low perceptual load condition, a color change of the fixation cross from white to red (high contrast change) appeared, while in the high perceptual load condition, one randomly chosen dot changed its color from red to lighter red (low contrast change). Auditory stimuli were characterized by (1) babble noise and (2) beep stimuli. The free accessible babble noise was taken from the signal processing information database (Johnson and Shami, 1993) via http://spib.linse.ufsc.br/noise.html. The babbling noise was further processed by adding the same stream played backward to the original. The average sound pressure level (SPL) during the experiment amounted to 55 dB. Beep stimuli were sinusoidal tones with rise and fall times of 10 ms, a duration of 100 ms, and a frequency of 600 Hz. They were presented at three different volumes (low, medium, and high intensity) and additionally with zero intensity (“no sound”), each with a proportion of 25%. In each trial, one beep stimulus (or the “no sound” stimulus) was embedded in the babble noise at a pseudo-randomized time point between 500 ms after the onset of the rotating dots and 800 ms before their offset. The “no sound” stimulus served as a reference condition in the ERP analysis. The sound volume was determined in a behavioral pilot study (n = 10). To this end, participants had to respond to the high contrast color change (i.e., low perceptual load condition) while the above described auditory stimuli were played in the background. Participants were asked after each trial whether beep stimuli were perceived. The experimenter adjusted the sound volume manually until five participants detected the beep in about 50% of the trials. This volume was then multiplied by 0.5 and 2 to yield the three critical levels used in the main experiment (42 dB, 45 dB, and 48 dB SPL).

2.3. Procedure

Firstly, participants were required to complete a demographic questionnaire. After being prepared for the EEG, they completed a practice task in which participants were told to respond to the color change of the fixation cross (low perceptual load condition) or the color change of one rotating dot (high perceptual load condition). In addition, they were informed that the background babble noise would contain occasional beeps with varying sound volume levels. The instructions were designed to establish the color-change detection as the main task and the report of the auditory percept as a subordinate task. This was achieved by stating that the sounds had no relevance to the participants, whereas, for the visual task, they would receive or lose points for correct and incorrect responses, respectively. They were instructed that they would first have to respond to the color change, and after having received the point feedback, they would be asked to rate their perception of the sounds. The instructions repeated that participants would not receive or lose points for their sound ratings. After the practice task, the main experiment started, divided into 16 blocks (8 blocks for each load level) with self-controlled breaks with a maximum length of 3 min. The perceptual load level of the first block (low or high) was counterbalanced across participants. Within the experiment, load levels alternated. At the beginning of each block, participants were informed which color change they should detect. Instructions regarding the sound were not repeated. Each block contained 32 trials. Trials aborted due to excessive eye movement (detail on eye tracking see below) were added to the end of a block. Of the 512 trials, 25% of all trials contained a visual target. Fig. 1 shows the course of a trial. At the beginning of each trial, a white fixation cross was presented for 500 ms. Afterward, the rotating dots and the babble noise with the beep sound were presented for 2500 ms. The color change of the fixation cross in the low load condition was presented for 500 ms, while the color change of the dot in the high load condition was presented for 100 ms. Both changes appeared at a random time point within the 2500 ms of the rotation phase (but not in the first 500 ms and the last 500 or 100 ms, in the low and high load condition, respectively). Subsequently, the subjects were asked whether they could detect a color change. They received feedback for this answer (i.e., plus points for correct answers and minus points for incorrect answers) to emphasize the importance of the visual task. Points accumulated over the whole exper-

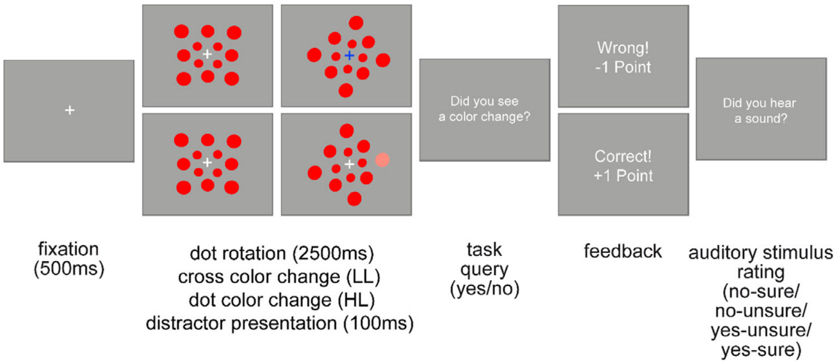

Fig. 1. Illustration of the experimental course.

iment. At the end of each trial, participants rated their subjective sound perception on a four-point scale, ranging from "no – certain" over "no – uncertain" and "yes – uncertain" to "yes – certain". After each block, participants also were presented with their total score (i.e., "You have scored x points out of maximum y points so far").

2.4. EEG recording and preprocessing

The brain's electrical activity was captured and recorded from 64 BioSemi active electrodes following the extended 10–20 system and using BioSemi's Actiview software (www.biosemi.com). Four additional electrodes were attached to record the horizontal and vertical eye movement. The recording sampling rate was 512 Hz. The software BESA research (Version 6.1, www.besa.de) was used for preprocessing. Offline data were re-referenced to average reference and filtered with a high-pass forward filter of 0.1 (6 dB/oct, Butterworth) and a 30 Hz low-pass zero phase filter (24 dB/oct, Butterworth). The automatic artifact correction implemented in BESA (Ille et al., 2002) was used to correct eye movement-related artifacts. A spline interpolation procedure was applied to interpolate noisy EEG channels. Data were segmented from 200 ms before auditory stimulus onset until 800 ms after auditory stimulus onset. Baseline correction used 200 ms before stimulus onset. The CMS/DLR Data were re-referenced to a common average reference. For each participant, on average, 4.63 electrodes were interpolated ($SD = 3.04$), and 5.51 percent of all trials were rejected ($SD = 6.23$) leading to a trial number of 362.83 on average ($SD = 23.91$). The trial number was not equalized between conditions.

2.5. Eye-tracking recording

We used an eye-tracker (EyeLink 1000, SR Research Ltd., Mississauga, Canada) for online tracking of the gaze position. If the gaze deviated by more than 3° from the fixation cross anytime during a trial, the current trial was aborted and added to the block's end. Participants were told to put their chin on a chin rest to reduce gaze deviation and head movements while the right eye was recorded. The recording sampling rate was 1000 Hz. An eye-tracker calibration procedure was automatically initiated using a five-point calibration procedure before starting the experiment. A new calibration procedure was carried out if the gaze was outside the desired gaze range more than 5 times.

2.6. Statistical analyses

The behavioral data analysis was conducted with MATLAB R2019b (https://de.mathworks.com). Two types of performance measures were calculated. For the visual task, the detection sensitivity (*d'*) was calculated for high and low load conditions and compared via a paired-sample *t*-test. Sound detection was quantified by *aZ*, i.e., the area under the receiver operating characteristic (ROC) curve, calculated from the proportion of hits and false alarms per level of confidence (Macmillan and Creelman, 2005). *Az* was determined for the two load and three sound volume conditions and ranges between 0.5 (chance performance) and 1 (perfect detection). Sound detection data were analyzed using a Repeated Measurement Analyses of Variance (ANOVA) with load (low load (LL) vs. high load (HL)) and sound volume (low volume vs. medium volume vs. high volume) as factors.

For EEG scalp data analysis and visualization, MATLAB R2019b (https://de.mathworks.com) and SPSS (https://www.ibm.com/de-de/analytics/spss-statistics-software) were used. The two components of interest (N1 and P3 amplitude) were identified by inspecting the time course of topographies of the grand average across all conditions except the "no sound" condition (see Fig. 2). Electrodes were chosen by eye inspection to cover the prominent bilateral frontal negative poles (F3, F4, F5, F6, FC3, FC4, FC5, FC6, C3, C4, C5, and C6) in case of the N1 amplitude, and the parieto-central positive poles (CP1, CP2, CP3, CP4, CPz, P1, P2, P3, P4, Pz, POz, PO3, and PO4) in case of the P3 amplitude. To identify the temporal intervals of interest, we inspected ERPs averaged across the above-mentioned sensor groups, separately for each sound volume but averaged across load levels. For the N1 amplitude, we observed an increase in peak latency with sound volume (Elberling et al., 1981; Keidel and Spreng, 1965). Thus, the peak of the N1 amplitude for the low volume sound was identified in the time range of 184 to 284 ms, for the medium volume sound in the time range of 155 to 255 ms, and for the high volume sound in the time range of 125 to 225 ms post-stimulus. The peak of the P3 amplitude was identified for all sound volumes in the same time range of 300 to 700 ms post-stimulus.

Since for the N1 the selection of intervals of interest depended on sound volume, the analysis of the main effect of sound volume on N1 amplitudes is circular (Kriegeskorte et al., 2009, 2010). However, the load effect and the interaction of load and sound are statistically independent of the main effect of sound volume. Therefore, we will not report any inferential statistics for the main effect of sound volume on the N1 amplitude.

To test the robustness of the analysis against the influence of subjective choices of sensors and intervals of interest, we performed a multiverse analysis (Steegen et al., 2016). For this purpose, the main analyses were repeated with different intervals and sensors, each representing a different reasonable choice. Since the N1 analysis is based on intervals around peak amplitudes, we tested two additional widths of this interval, 20 ms shorter or longer than the initially chosen 50 ms interval. The sensor selection described above contained 12 sensors of interest. We tested two further selections, involving 6 sensors less (FC3, FC4, C3, C4, C5, C6) or more (F3, F4, F5, F6, FC3, FC4, FC5, FC6, C3, C4, C5, C6, CP3, CP4, C1, C2) than the original selection. For the P3, we tested intervals 100 ms shorter and longer than described above (300 to 600 ms and 300 to 800 ms). The sensor selection described above already fully covered the positive pole of the P3 with 13 sensors. We therefore tested two smaller sensor groups, using 7 (P1, P2, Pz, POz, CPz, CP1, CP2),

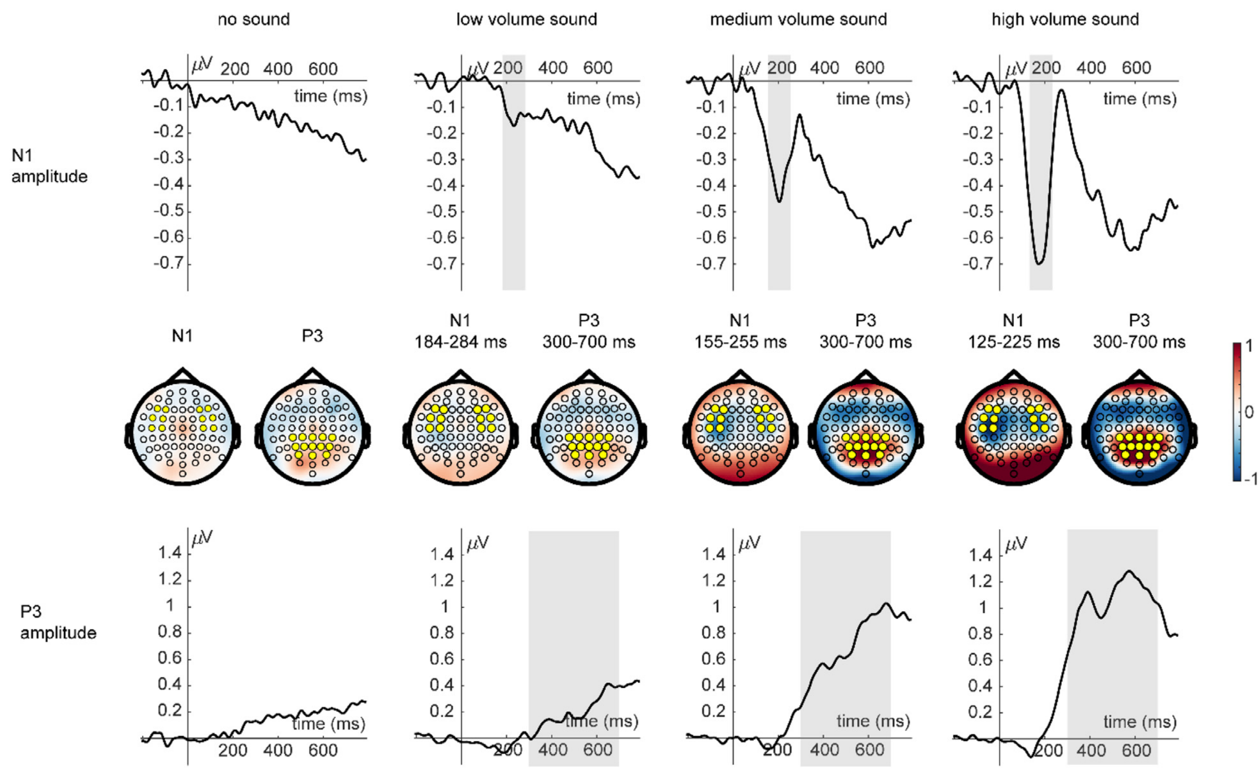

Fig. 2. ERP of the grand average ($n = 41$) for the two load conditions and the four sound volume conditions in the N1 time range (top row) and in the P3 time range (bottom row) with topographies (middle row). Sensors of interest are highlighted in yellow.

or one sensor (Pz). We calculated p-values for the main effects of load and sound volume and their interaction for each of the nine analyses per component.

To examine main effects of load and interaction effects of load and sound volume, we first subtracted the "no sound" condition from each sound condition and then computed an ANOVA with load (LL vs. HL) and sound volume (low vs. medium vs. high) for the N1 amplitude and the P3 amplitude.

All statistical tests used the conventional a priori threshold of $p <$ .05, and partial eta-squared ($\eta_p{}^2$) was used to describe the effect sizes. In case of non-significant results (i.e., $p \geq .05$) and in line with current recommendations (Dienes, 2016; Keysers et al., 2020; Wiens and Nilsson, 2017), we applied Bayesian statistics to quantify the likelihood of the null hypothesis. Bayes factors (*BF*) were computed using JASP (https://jasp-stats.org/download/). The null hypothesis was specified as a point-null prior (i.e., standardized effect size $\delta = 0$). The alternative hypothesis was defined as a Jeffreys-Zellner-Siow (JZS) prior, i.e., a folded Cauchy distribution centered around $\delta = 0$ with the scaling factor $r = 0.707$. This scaling factor assumes a roughly normal distribution. BF_{10} quantifies how much more likely the alternative hypothesis is compared to the null hypothesis, whereas BF_{01} indicates the likelihood of the null hypothesis compared to the alternative hypothesis. Following the guidelines of Jeffreys (1961), evidence for the respective hypothesis was interpreted as inconclusive for $BF < 3$, moderate for $BF \geq 3$, strong for $BF \geq 10$, very strong for $BF \geq 30$, and extreme for $BF \geq 100$.

3. Results

3.1. Ratings and behavioral results

Task performance. In the visual task, the *d'* was higher in the low (LL, $M = 4.54$, $SD = 0.52$; Fig. 3a) compared to the high load condition (HL, $M = 1.57$, $SD = 0.96$; Fig. 3a). More precise answers were given under LL ($t\,(40) = 19.32$, $p < .001$).

Table 1
Means (*M*) and standard deviations (*SD*) for the sound detection (*aZ*) for the different sound volume conditions.

	low volume sound *M (SD)*	medium volume sound *M (SD)*	high volume sound *M (SD)*
low load	0.57 (0.07)	0.87 (0.1)	0.95 (0.05)
high load	0.57 (0.08)	0.83 (0.12)	0.93 (0.08)

Sound detection. For an overview on the response pattern, Fig. 4 depicts the mean distribution of the four response categories, which are included in the calculation of *aZ*. Table 1 shows means and standard deviations of aZ for the different sound volume conditions. Concerning the sound detection, a repeated-measures ANOVA with load and sound volume as factors showed main effects of load ($F\,(1,40) = 11.71$, $p = .001$, $\eta_p{}^2 = 0.23$; Fig. 3b) and sound volume ($F\,(2,80) = 536.17$, $p < .001$, $\eta_p{}^2 = 0.93$; Fig. 3b) as well as an interaction of load and sound volume ($F\,(2,80) = 4.75$, $p = .011$, $\eta_p{}^2 = 0.11$; Fig. 3b). Concerning the sound volume, post hoc tests (p values are corrected with the Benjamini-Hochberg procedure) revealed that the accuracy of sound detection increased as the sound volume increased (low vs. medium volume: $t\,(40) = -22.81$, $p < .001$; medium vs. high volume: $t(40) = -7.98$, $p < .001$). Since our hypotheses only specified the direction of the load effect but not the minimal sound level at which it occurred, we used post-hoc tests to compare the load effect between sound volume levels. We report Benjamini-Hochberg-corrected critical alpha levels (α_{BH}) and label significant p-values with an asterisk(*). The post-hoc tests revealed that the load effect increased from low to medium volume ($t\,(40) = 2.67$, $p^* = .0108$; $\alpha_{BH} = 0.017$) and decreased from medium to high volume ($t\,(40) = -2.21$, $p^* = .0329$; $\alpha_{BH} = 0.033$). No significant difference in

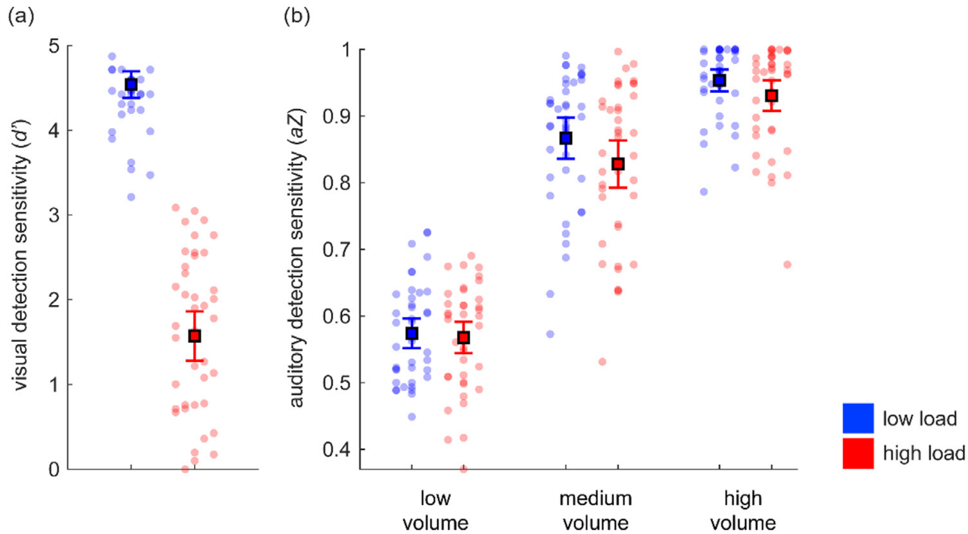

Fig. 3. (a) Detection sensitivity (d') for the visual task in the two load conditions, and (b) detection sensitivity (aZ) for the auditory stimuli in the low, medium, and high volume conditions and the two load conditions. Error bars depict the 95% confidence interval of the mean. Small dots represent individual data points.

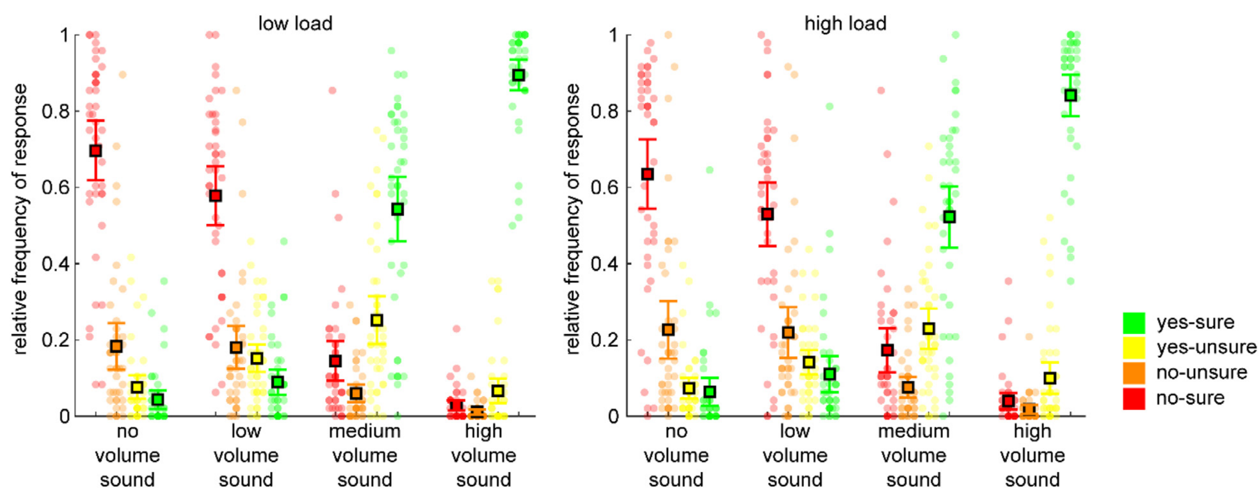

Fig. 4. The four response categories' mean distribution for each sound condition and the two load conditions. Error bars depict the 95% confidence interval of the mean. Small dots represent individual data points.

Table 2
Average amplitudes (M; in µV) and standard deviations (SD) per condition and component.

		low volume sound *M (SD)*	medium volume sound *M (SD)*	high volume sound *M (SD)*
N1	low load	−0.05 (0.36)	−0.31 (0.46)	−0.52 (0.55)
	high load	−0.04 (0.28)	−0.27 (0.42)	−0.52 (0.53)
P3	low load	0.05 (0.41)	0.44 (0.56)	0.79 (0.75)
	high load	−0.02 (0.41)	0.57 (0.67)	0.99 (0.73)

load effects was found from low to high volume (t (40) = 1.44, p = .1585; α_{BH} = 0.05).

3.2. ERPs

The main ERP analysis is based on the difference between the ERPs to the sounds presented at three intensities under two load conditions and the corresponding "no sound" conditions under two load conditions. Means and standard deviations for each component and condition are shown in Table 2.

N1. For the N1 amplitude, the main effect for load and the interaction of load and sound volume were not significant (all $p \geq .79$). A Bayesian repeated-measures ANOVA revealed that the most likely model only includes the main effect of sound volume (BF_M = 25.83). There was moderate evidence against the additional inclusion of the load term (BF_{01} = 6.99) and very strong evidence against the additional inclusion of the load and interaction term (BF_{01} = 83.33). At each sound volume level, we observed moderate evidence for the absence of a load effect (low volume, HL – LL: BF_{01} = 5.913; medium volume, HL – LL: BF_{01} = 4.983; high volume, HL – LL: BF_{01} = 5.928).

P3. For the P3 amplitude, the main effect for load was not significant (p = .29). A Bayesian repeated-measures ANOVA also showed that the main effect of load did not differ from the null model (BF_{01} = 3.66). The interaction of load and sound volume was significant (F (2,80) = 3.61, p = .032, η_p^2 = 0.08; Fig. 5).

Again, we used we used post-hoc tests to compare the load effect between sound volume levels applying Benjamini-Hochberg-corrected critical alpha levels. The post-hoc tests revealed that the load effect increased from low to high (t (40) = −2.42, p^* = .01; α_{BH} = 0.017) and from low to medium volume (t (40) = −2.14, p^* = .019; α_{BH} = 0.033). However, no significant difference in load effects was found from medium to high volume (t (40) = −0.58, p = .281; α_{BH} = 0.05). Individual amplitude differences are depicted in Fig. 6 to illustrate the distribution of the effects of load and sound volume on the N1 and the P3.

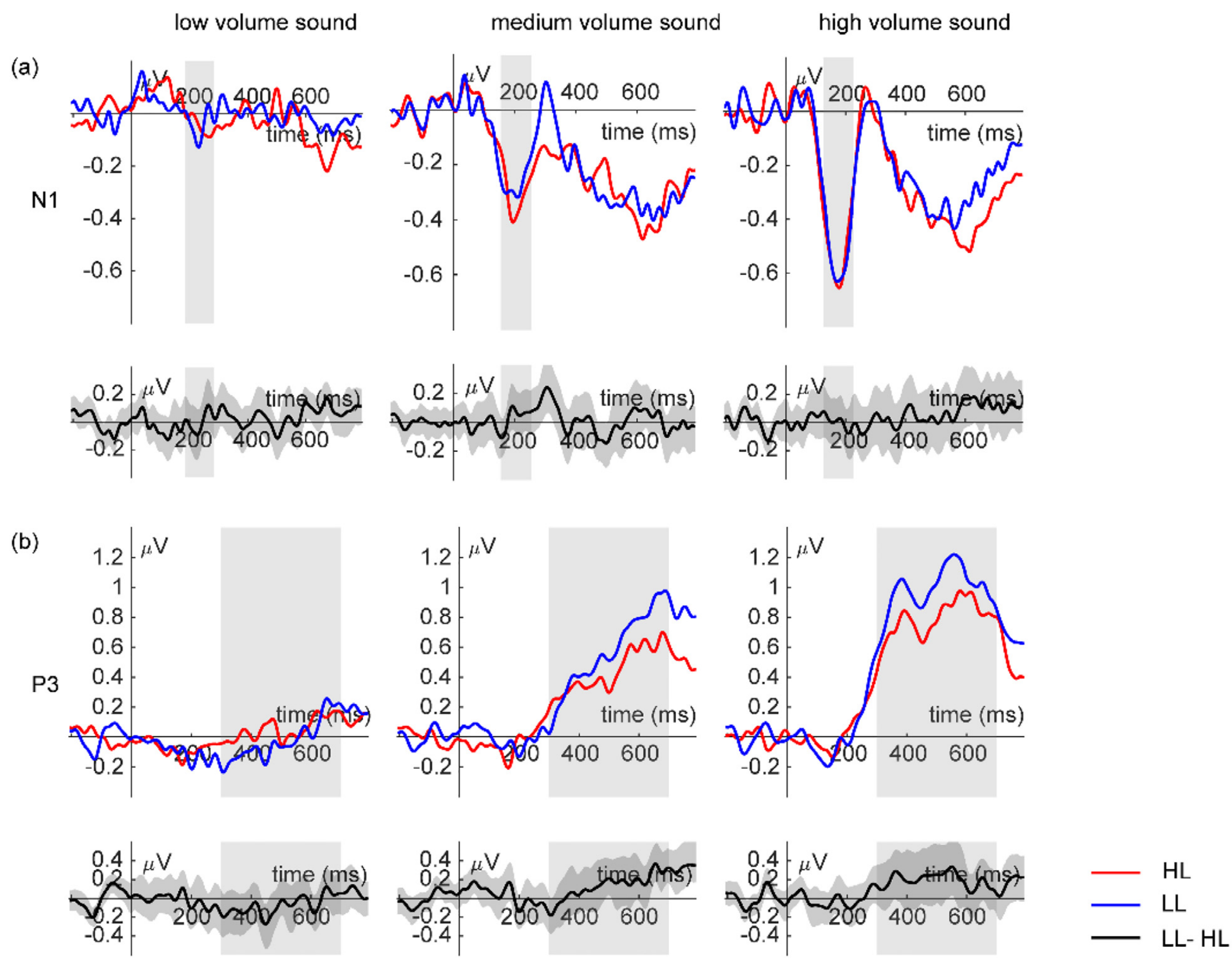

Fig. 5. ERPs (n = 41) for the two load conditions (LL, HL) and the three sound volume conditions (low, medium, high) in (a) the N1 time range and (b) the P3 time range.

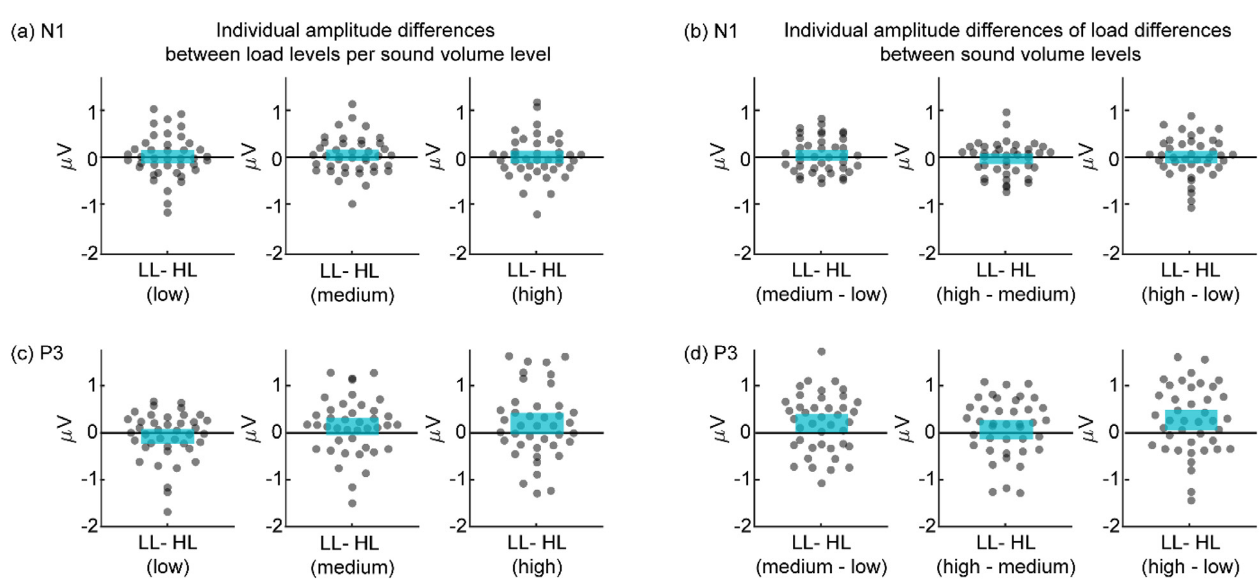

Fig. 6. Individual amplitude differences for the N1 and P3. (a) and (c) Differences between load levels separated by sound volume level. (b) and (d) Differences of load differences between sound volume levels. The blue area depicts the 96% confidence interval around the mean difference.

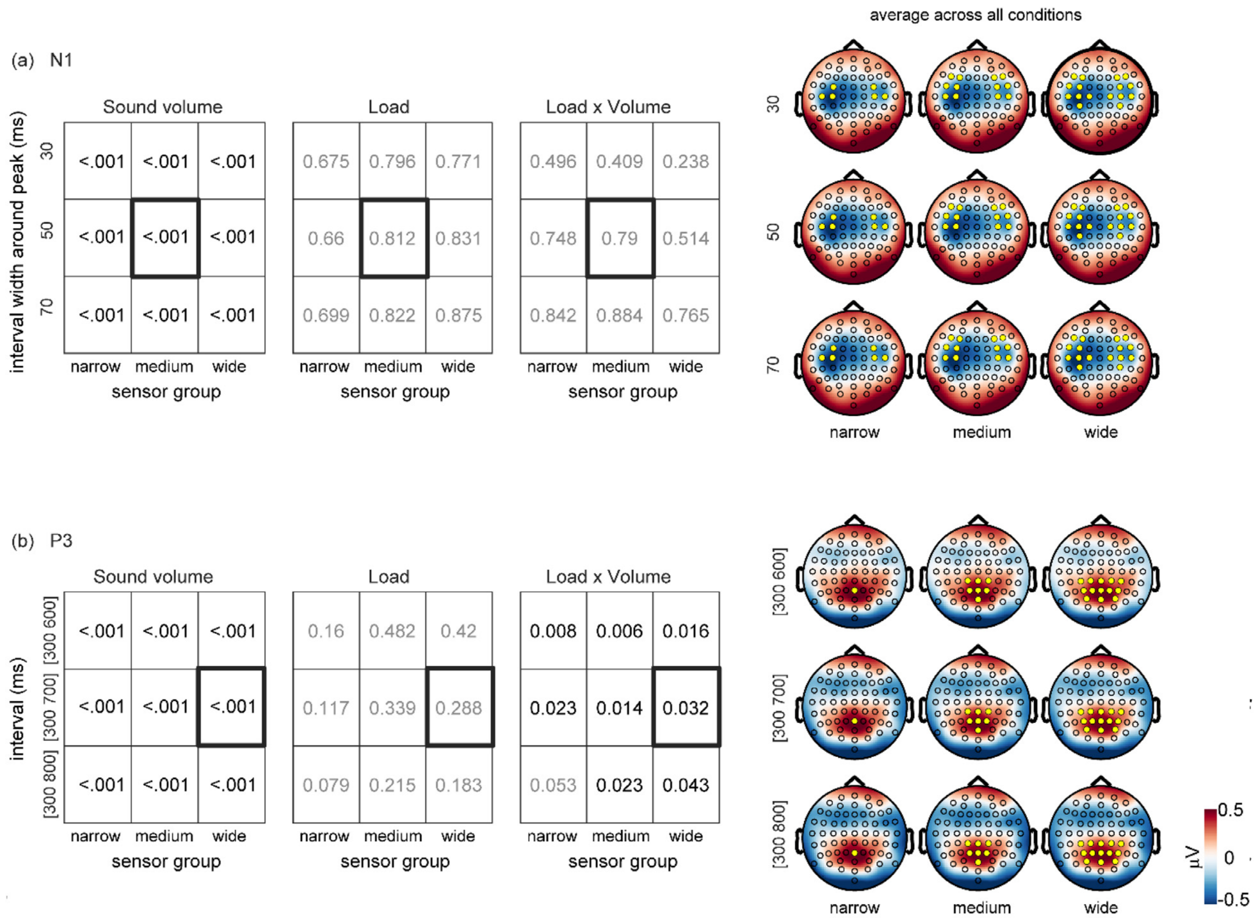

Fig. 7. Results from the multiverse analysis for (a) the N1 and (b) the P3. The tables contain *p*-values for the main effects of sound volume and load and the interaction of load and volume. Each row in each table represents a different choice of the selected interval of interest, and each column has a different sensor selection of interest (see Methods). All *p*-values ≥ 0.05 are printed in gray, and all *p*-values < 0.05 are printed in black. A black frame in each table highlights the interval and sensor selection used for the analysis presented above. Following the same arrangement of rows and columns, the topographies on the right depict the average across all conditions. Selected sensors are highlighted in yellow.

The multiverse analysis revealed that the statistical significance did not change in all but one tested alteration of sensor and interval selections (see Fig. 7). For the N1, sound volume effects were always significant (all $p < .001$; but see Methods regarding potential problems of circularity), while load effects and the interaction of load and volume were never significant (all $p \geq .66$ and $p \geq .238$, respectively). For the P3, sound volume effects were again always significant (all $p < .001$), while load effects were never significant (all $p \geq .079$). The interaction of sound volume and load was significant in eight out of nine cases (all $p \leq 0.043$). The interaction failed to reach significance with the narrowest sensor group selection and the longest interval selection ($p = .053$).

4. Discussion

This study investigated effects of continuous visual perceptual load on auditory stimulus processing. We found (i) a reduced sound detection under high versus low load for the middle and high volume sound, (ii) no effect of load on N1 amplitudes for all sound volumes, and (iii) a decreased P3 amplitude under high versus low load for the middle and high volume sound.

The behavioral data showed that high continuous perceptual load versus low load leads to reduced detection of the sounds. The effects are small in absolute terms but statistically robust. This finding is consistent with the results of Molloy et al. (2015), who also found reduced detection of sounds under high load in a non-continuous load design. However, the load effects found do not support the claim of load effects being an all-or-nothing phenomenon ("irrelevant information will be excluded from processing", Lavie and Tsal, 1994, p.185) since in our study and Molloy et al. (2015), "inattentional deafness" could only be observed in a small number of trials. Most importantly, differential effects of load were observed only in conditions where detection accuracy was already very high (see Fig. 3b). Thus, given our data and also related to previous studies targeting inattentional blindness (Cartwright-Finch and Lavie, 2007; Macdonald and Lavie, 2008) or deafness (Macdonald and Lavie, 2011; Raveh and Lavie, 2015), we see little supported for load effects leading to absent stimulus processing. Therefore, it does not seem possible to induce complete blindness or deafness by high perceptual load across many trials. This has strong implications for *Load Theory*, for example, by defining effects in relative terms. Several other authors have also criticized the term exhaustion of processing capacity, as it seems unlikely that there is absolute exhaustion of processing capacity but a dynamic relationship between the specific task load, the relevance, and the salience of distractor stimuli might better explain the task load occurrence (see also Konstantinou et al., 2014; Straube et al., 2011).

The electrophysiological data showed a load-independent N1 amplitude irrespective of sound volume. Several previous perceptual load studies also found no effects (in the visual domain: Intaitė et al., 2013; Kimura and Takeda, 2013; Müller-Bardorff et al., 2016; Schindler et al., 2020b, 2021a, 2021b; in the auditory domain: Sugimoto and Katayama, 2017). However, there are also studies suggesting decreased (in the visual domain: Rorden, 2008; Schindler et al., 2020a, 2021a; in the auditory domain: Wiens et al., 2019) or even increased early processing of task-irrelevant stimuli (in the visual domain: Neumann et al., 2018). In all these studies, there are differences concerning the choice, expectancy, and timing of stimuli and the continuity and type of the load manipulation. In the study of Molloy et al. (2015), which found an early load effect, load and distractor stimuli had a simultaneous onset, which might represent a critical difference to our continuous load design. Furthermore, our study compared responses to auditory stimuli against load conditions without stimuli to control for general effects of load. We used a relatively large sample size compared to previous studies, which might have reduced reporting of an unreliable early effect. However, at least for the study of Molloy et al. (2015), MEG might reveal effects not seen with EEG data since MEG and EEG respond to different dipoles of electromagnetic fields (Hansen et al., 2010; Luck, 2014). It remains unclear whether early effects are unreliable or dependent on specific experimental factors.

Regarding late ERP data, there was an interaction between load and sound volume in the form of load effects for the medium and high volume sound, which is in line with previous perceptual studies. Those studies most often showed decreased late processing of task-irrelevant stimuli (in the visual domain: Intaitė et al., 2013; Müller-Bardorff et al., 2016; Rossi and Pourtois, 2014; Sawaki and Katayama, 2009; Schindler et al., 2020b; in the auditory domain: Molloy et al., 2018; Zhang et al., 2006) with only few studies showing no influence of load on late processing (in the visual domain: Sculthorpe et al., 2008; Tiferet-Dweck et al., 2016; in the auditory domain: Wiens et al., 2019) or increased late processing (in the visual domain: Sawaki and Katayama, 2009; Sugimoto and Katayama, 2017, in the auditory domain: Sugimoto and Katayama, 2017). The P3 amplitude has been discussed to represent attention, decision-making, and confidence during detection designs (Dellert et al., 2021; Herding et al., 2019; Palmer et al., 1994; Pitts et al., 2014; Schlossmacher et al., 2020; 2021; Twomey et al., 2015). Moreover, there is evidence that the P3 amplitude seems to reflect the depth of conscious processing, encoding, and thus the degree of reportability of stimuli (Dellert et al., 2021; Pitts et al., 2018). In our design, these processes likely seem to affect later detection performance, as the P3 effects mirror the results at the behavioral level. The detection and the P3 amplitude were reduced only for the medium and high volume sound but not for the low volume sound. Therefore, visual perceptual load affects the processing of auditory stimuli in a late time window, which is associated with a lower probability of reported awareness of these stimuli.

We would like to note some limitations of our study. In our study, load was continuously manipulated. Preliminary findings suggest that the timing of load and auditory stimuli onset might play an important role on early neuronal effects. Therefore, future studies should systematically vary the onset of load and task-irrelevant stimuli. In this context, it would also be interesting to consider different phases of the task (i.e., encoding, maintenance, and probe) to understand better which specific stage of auditory processing is affected by load. Although the visual task was established as the main task, the instruction to additionally respond to the auditory stimuli created a dual-task-like situation, possibly introducing task-related multisensory interference effects (Shaw et al., 2020). Our analysis excludes a contamination by task-switching effects because only trials without a visual target were analyzed. However, continuous effects of "task mixing" (Shaw et al., 2020) may have influenced the results and should be examined in future studies with actually task-irrelevant auditory stimuli. Finally, we only realized two load levels to understand at which levels of stimulus intensities, load affects processing the most. Thus, in future studies it would be interesting to investigate distractor effects for the medium intensity using a parametric manipulation of load, to detail which load level leads to differential processing and whether there are upper or lower boundaries. At last, it remains to be considered how different neuroscientific methods (e.g., MEG, EEG, fMRI) might lead to different outcomes and how methods could be combined to gain more reliable insights into the load-dependent modulation of neural activity.

5. Conclusion

This study explored detection and neural processing of auditory stimuli during a continuous visual task alternating between low and high load. Depending on stimulus intensity, decreased detection and late ERP responses (P3) to auditory stimuli were found under high versus low load. Findings suggest that visual perceptual load affects the processing of auditory stimuli in a late time window, which is associated with a lower probability of reported awareness of these stimuli.

Data and code availability statement

Data and code are available on the Open Science Framework accessible via https://osf.io/phav2/.

Declaration of Competing Interest

None

Credit authorship contribution statement

Laura Brockhoff: Conceptualization, Methodology, Formal analysis, Visualization, Writing – original draft. **Elisa Adriana Elias:** Investigation, Formal analysis, Writing – original draft. **Maximilian Bruchmann:** Conceptualization, Methodology, Software, Formal analysis, Visualization, Writing – review & editing. **Sebastian Schindler:** Conceptualization, Methodology, Formal analysis, Writing – review & editing. **Robert Moeck:** Software. **Thomas Straube:** Conceptualization, Methodology, Writing – review & editing, Supervision.

Acknowledgments

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The authors declare no competing interests. We acknowledge support from the Open Access Publication Fund of the University of Münster.

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