Visual load effects on the auditory steady-state responses to 20-, 40-, and 80-Hz amplitude-modulated tones

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ABSTRACT

Ignoring background sounds while focusing on a visual task is a necessary ability in everyday life. If attentional resources are shared between modalities, processing of task-irrelevant auditory information should become attenuated when attentional capacity is expended by visual demands. According to the early-filter model, top-down attenuation of auditory responses is possible at various stages of the auditory pathway through multiple recurrent loops. Furthermore, the adaptive filtering model of selective attention suggests that filtering occurs early when concurrent visual tasks are demanding (e.g., high load) and late when tasks are easy (e.g., low load). To test these models, this study examined the effects of three levels of visual load on auditory steady-state responses (ASSRs) at three modulation frequencies. Subjects performed a visual task with no, low, and high visual load while ignoring task-irrelevant sounds. The auditory stimuli were 500-Hz tones amplitude-modulated at 20, 40, or 80 Hz to target different processing stages of the auditory pathway. Results from bayesian analyses suggest that ASSRs are unaffected by visual load. These findings imply that attentional resources are modality specific and that the attentional filter of auditory processing does not vary with visual task demands.

1. Introduction

In daily life, people need to be able to focus on a task while ignoring any task-irrelevant background noise. For example, people who work in an open-space office may have to work on a report while ignoring the background talk among co-workers. Because the capacity for processing information is limited [1], attentional processes seem necessary to attenuate or filter out task-irrelevant sounds during a visual task. However, researchers debate how attention is distributed to different senses (i.e., crossmodal attention) and whether attentional resources for processing information are modality specific [2–4] or share a common pool across modalities [5–11]. If there exists a common, supramodal pool of attentional resources, then processing of information within one modality should take up a substantial portion of resources and, therefore, processing of information from another modality should be attenuated.

The mechanisms and connectivity of the auditory pathway seem to provide numerous possibilities for attenuating irrelevant auditory information. According to the early-filter model [12], the auditory pathway consists of multiple dynamic and recurrent loops that may allow top-down attentional modulation of sounds by prefrontal cortex [12,13] and multi-sensory areas [14]. According to the adaptive filtering model [15], the stage of filtering depends on the attentional demand: If a task is difficult rather than easy, the filtering of irrelevant auditory information occurs early rather than late in the pathway.

One approach to studying crossmodal attention is to investigate the effects of attending to a visual task on auditory steady-state responses (ASSRs) to task-irrelevant sounds. ASSRs are brain responses to periodic, amplitude-modulated tones [16–18]. If the amplitude modulation has a 100% modulation depth and a modulation frequency of 40 Hz, the amplitude of the tone changes from 0 to its maximum and back to 0 (this is one cycle) 40 times per second. At this particular modulation frequency, the ASSR is usually the strongest [16, 18–20].

Notably, because ASSRs are often used in a clinical context, it is of practical importance to determine whether they are affected by selective attention, specifically concurrent visual load. For example, ASSRs are widely used in audiology to measure the auditory threshold of individuals who cannot provide a subjective response, such as preverbal children [17,21]. During clinical assessment, some individuals can potentially ignore the auditory stimuli and focus their attention elsewhere, particularly during a demanding visual task. Thus, it is relevant

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for this clinical context to investigate the extent to which ASSRs are sensitive to changes in crossmodal attention.

ASSRs seem to receive contributions from both subcortical and cortical sources [22–24], but the strength of these contributions seems to vary with the frequency of the amplitude modulation [23,25,26]. At 80 Hz and above, ASSRs are mainly generated in the brainstem [17,25,26] or thalamus [23]. At 40 Hz, ASSRs are generated mainly in the primary auditory cortex, particularly Heschl’s gyrus [25,27–31]. Below 40 Hz, ASSRs are mostly generated in the auditory cortex [23,25,32], possibly involving multiple generators across primary and secondary auditory cortices [26]. Furthermore, additional sources outside of the auditory pathway were identified for ASSRs at 4, 20, 40, and 80 Hz: left and right precentral gyrus, superior parietal lobe, and right occipital lobe [23]. Taken together, research suggests that the contribution of different neural generators to ASSRs changes hierarchically with the modulation frequency: For higher frequencies, subcortical generators such as brainstem and thalamus seem to be the main contributors, whereas for lower frequencies, cortical generators, that is primary and non-primary auditory cortex, seem to be the main contributors. Because of this variation in neural generators, it should be possible to use different modulation frequencies to investigate the stage of attentional filtering.

In many previous studies on the effects of crossmodal attention on ASSRs, subjects attended to visual stimuli and then to auditory stimuli, or vice versa (e.g., 33–36). However, because switching attention between modalities (e.g., visual vs. auditory) and switching attention between tasks (e.g., easy vs. difficult visual task) operate by different mechanisms [37–39], any effects in such study designs may be caused by changing attention between modalities and not between tasks. To ensure that an effect of task switching is not confounded by modality switching, the tasks should vary within the same modality (e.g., easy vs. difficult visual task), while information in another modality (e.g., auditory stimulation) is task-irrelevant and to be ignored.

Only a few studies have used task switching, and their results varied [3,40–46]. All studies examined the effects of manipulating visual task difficulty or load on 40-Hz ASSRs and, in one study, also on 20-Hz ASSRs [41]. The visual load manipulations were as follows: detecting versus discriminating a change in target brightness [40], reading versus performing a visual search task [41], passively viewing a map versus performing a search task on a map [42], detecting an easy versus difficult target [3], playing an easy versus difficult Tetris game [43], flying an airplane in a simulator during self-reported low versus high mental workload [44], and performing n-back tasks with different n [45,46].

Five of these studies showed statistically significant effects of visual load on 40-Hz ASSRs [42–46]. One study found significant effects only for (unexpected) occipital electrodes [40]. In two studies, effects were apparently not significant for 40-Hz ASSRs [3,41] or for 20-Hz ASSRs [41]. Although two more studies recorded 40-Hz ASSRs and manipulated visual load, effects of load were not analyzed specifically because these studies addressed other research questions [47,48]. Taken together, previous studies do not provide a clear answer as to whether ASSRs are affected by manipulations of visual load.

Furthermore, many of these previous studies have one or more limitations that challenge the robustness of the findings. First, several studies used visual tasks in which visual stimuli differed substantially among the load levels (e.g., a magazine article versus Landolt rings, or different speeds of Tetris). Thus, it is unresolved whether the obtained effects were caused by attentional processes or by physical differences between the loads. Second, in many studies, the selection of electrodes appears to have been data driven, that is, on the basis of visual inspection of the data. This practice has been shown to pose a strong risk for biased results [49–51].

In two recent studies with 40-Hz ASSRs, we tried to minimize these biases [52]. Study 1 used two levels of visual load (low and high), and Study 2 used four levels of visual load (no, low, high, and very high). In both studies, the visual stimuli were similar in all conditions, and flexibility in data processing and analysis was avoided by preregistering the hypotheses, method, and analyses (Study 1: https://doi.org/10.17605/OSF.IO/UYJVA, Study 2: https://doi.org/10.17605/OSF.IO/JVMFD). Furthermore, bayesian analyses were used to distinguish results that support the null hypothesis, support the alternative hypothesis, or are inconclusive [53]. In both studies, results provided moderate to extreme evidence for no effects of visual load on signal-minus-noise (SnN) measures of amplitude or intertrial phase coherence (ITC) to 40-Hz ASSRs.

Regarding the finding that visual load had no effect [52], one possible explanation is that the load manipulation was not strong enough. However, this is unlikely because several manipulation checks of load showed substantial differences among the visual conditions (i.e., behavioral performance, subjective workload ratings, and visual P3 to targets versus nontargets). Furthermore, similar tasks were used in previous research [3,54–56] and are considered to be prototypical manipulations of perceptual load [57]. Another possible explanation for no effect of load is that tones presented at 60 dB were hard to ignore. However, this sound presentation level was used in previous studies and is comparable to the average noise level of office conversations [58].

Finally, filtering may have occurred at a processing stage that was not detected by 40-Hz ASSRs [52]. On the one hand, if filtering occurs at the brainstem for easy tasks, then the 40-Hz ASSRs would be attenuated in all load conditions (i.e., low, high, and very high). However, this explanation seems unlikely because the ASSRs remained the same whether or not there was a visual task (i.e., ASSRs were the same for the three load conditions and the no load condition, in which subjects passively viewed the visual stimuli). On the other hand, if filtering occurs only after the stages that generate the 40-Hz ASSRs, then the 40-Hz ASSRs would not be attenuated.

To examine different stages of attentional filtering, the present study measured ASSRs to two other modulation frequencies aside from the 40-Hz ASSRs: a higher frequency (80-Hz ASSRs) and a lower frequency (20-Hz ASSRs). If filtering occurs very early in the pathway, there may be no differences among the visual conditions for 20-Hz or 40-Hz ASSRs but some differences for 80-Hz ASSRs. If filtering occurs in later stages of processing, there may be no differences among the visual conditions for 40-Hz or 80-Hz ASSRs but some differences for 20-Hz ASSRs.

In sum, we examined the effects of crossmodal attention on 20-Hz, 40-Hz, and 80-Hz ASSRs. The visual task had three load levels (no, low, and high) and was identical to the visual task in our previous study (i.e., Study 2 from [52]). Subjects were asked to detect a target in a rapidly changing stream of letters (low load and high load) or to passively observe the letter stream (no load). The letters varied in color, name, and capitalization. In low load, the target was a particular color regardless of name and capitalization. In high load, the target was a particular color-name combination regardless of capitalization. The visual stimuli were identical in all conditions but occurred in different proportions to keep a constant number of targets. Thus, any effects of the visual conditions were unlikely to be confounded by differences in visual stimulation. Simultaneously to the visual task, subjects were presented with tones that varied in amplitude modulation frequency (20, 40, or 80 Hz). To confirm that the load manipulation was strong, we measured several variables: behavioral performance in terms of reaction times to targets versus nontargets. Furthermore, subjective workload ratings, and visual P3 to targets versus nontargets [60]. We preregistered the study with regard to hypotheses, method, and analyses to minimize unintended differences between the results and the preregistration are noted below. The experiment was
programmed in Python (Version 2.7.14) [62] using the PsychoPy package (Version 1.85.3; [63]) for visual presentation and SoundDevice package (Version 0.3.10; [64]) for auditory presentation. Data were processed and analyzed with Python (Version 3.7.4 [62]), MNE-Python (Version 0.19.2 [65]), and R (Version 4.0.2 [66]) under R Studio (Version 1.3.1073 [67]).

Supplementary material is available at a university depository [68]. This material includes all raw data, scripts, and results of preregistered and exploratory analyses.

Twenty-five subjects (age \( M = 27.12 \), age \( SD = 4.97 \), 20 right-handed, 11 male) were recruited from local universities and through online billboards in Stockholm, Sweden. Participation was compensated with a 100-SEK gift voucher. Before the experiment, subjects provided written, informed consent in accordance with the Declaration of Helsinki. Ethical review and approval were not required for this study in accordance with local legal and institutional requirements. Subjects reported being between 18 and 40 years old, having no history of neurological or psychological illness, and having normal or corrected-to-normal vision and normal hearing. Hearing was tested at the beginning of the experiment with pure-tone audiometry at 500 Hz (relevant frequency for the study), 750 Hz, and 1000 Hz to ensure normal hearing (\( \leq 20 \) dB HL).

We preregistered that data collection would finish if the Bayes factor (BF) was \( > 3 \) after at least 20 subjects were retained and no later than after 60 subjects were retained or at the end of March 2020. Because not all relevant analyses showed \( BF > 3 \) after 20 subjects were tested, we continued testing. However, we were forced to stop testing in the middle of March 2020 because during the COVID-19 crisis, the department prohibited data collection involving human subjects. Importantly, the analyses of data from the recruited 25 subjects showed that BF was \( > 3 \) for all preregistered hypotheses except one (see supplementary material).

Nonetheless, in the analyses reported below, we deviated from the preregistration and included eight additional pilot subjects. Although these subjects participated before the study was formally preregistered, the procedure was similar to that in the actual study except for negligible differences (e.g., letter names and phase inversion differed; see supplementary material). Therefore, we decided to include these subjects because a larger sample is expected to provide a more accurate estimate of the true effect. Results were comparable for the smaller sample (see supplementary material).

The final sample size was 33 (age \( M = 27.09 \), age \( SD = 5.11 \), 27 right-handed, 13 male). All subjects fulfilled the preregistered hearing, vision, and health criteria. Preprocessing was the same for all subjects. No subject was excluded because of noisy EEG data.

### 2.1. Auditory stimuli

The auditory stimuli were amplitude-modulated tones with a carrier frequency (\( f_c \)) of 500 Hz and a modulation depth of 100%. Modulation frequencies (\( f_m \)) were 20.48 Hz, 40.96 Hz, and 81.92 Hz. These modulation frequencies can be resolved at a sampling frequency of 2048 Hz and were closest in frequency to 20, 40, and 80 Hz. The amplitude-modulated tones were presented continuously during the visual task. To minimize the response to the carrier frequency, the carrier frequency started with either the condensation or rarefaction phase. For each subject, the initial phase was assigned randomly and used in the first half of the visual task, whereas the other phase was used in the second half of the visual task. Tones were presented binaurally at 60 dB SL through in-ear tubephones (ER2; Etymotic Research Inc., IL; www.etymotic.com).

### 2.2. Procedure

#### 2.2.1. Visual detection task

Fig. 1 illustrates the experimental procedure. Subjects performed a visual detection task on a rapidly presented series of letters that varied in name, color, and capitalization. Subjects were instructed to respond to different features of the letters while ignoring the tone played continuously in the background. The amplitude-modulated tone started 200 ms before block onset and continued throughout the whole block.

The task was identical to that in a previous study (see Study 2 [52]). The visual stimuli were letters that differed in name (K, R, M, or H), color (red, blue, green, yellow, or violet), and capitalization (upper or lower). The height of the letters was 3.2° (in visual degrees), and each letter was presented on the screen for 100 ms at the beginning of each 500-ms trial. Subjects responded by pressing the space bar and were instructed to perform the task as accurately as possible. Behavioral responses were recorded in terms of pressing space bar to targets (i.e., hits) and to nontargets (i.e., false alarms), which were used to calculate \( d' \), and reaction times to hits.

Subjects performed 18 blocks of the visual task. Each block had one of three loads: in no load, there was no target, and subjects passively viewed the letters presented on the screen. In low load, the targets were letters of a determined color (irrespective of name and capitalization). In high load, targets were letters of two particular color-name combinations (irrespective of case). Each combination of load (no, low, and high) and modulation frequency (20, 40, and 80 Hz) was administered twice. For each set of the nine combinations of load and modulation frequency, block order was pseudorandomized for each subject with the restriction that each condition and each modulation frequency was used once within a set of three.

Each block took about two minutes and consisted of 247 trials. Of these trials, 48 were targets and 199 were nontargets in low load and high load (whereas all trials were nontargets in no load). The first 7 trials...
were always nontargets. Each target trial was separated from the next by 2 to 6 nontarget trials. For each subject, targets in the different conditions were chosen pseudorandomly to avoid conflicts. For example, if red was the target in low load, no other condition had a red target.

2.2.2. Self-reported workload

After each block of the visual detection task, subjects rated their perceived workload with regard to mental demand (i.e., “How mentally demanding was the task?”) and effort (i.e., “How hard did you have to work to accomplish your level of performance?”) on the NASA-Task Load Index (TLX) [59]. As in our previous study [52], the rating scale of the NASA-TLX was replaced with the Borg centiMax (CR100) scale [69], which has two advantages over the original scale. First, the Borg CR100 scale includes explicit verbal anchors (e.g., 100 on the scale refers to “maximal,” and 50 refers to “strong / heavy”). Second, although the scale has a maximum value, it allows subjects to use values above the maximum, which avoids ceiling effects. When rating their workload, subjects were instructed first to look at the verbal anchors of the Borg CR100 scale and then to choose a value. Before the experiment, they received detailed, written instructions on how to interpret the verbal anchors (e.g., “strong” was described as “The work is hard and tiring, but you can still continue. The effort and exertion is about half as hard as ‘Maximal’”). These instructions were also available to subjects during the experiment.

2.3. EEG recording

The EEG data were recorded with an Active Two BioSemi system (BioSemi, Amsterdam, Netherlands). Because the system is designed to record a maximum of eight single electrodes, six electrodes were recorded from standard 10/20 positions (Fpz, Fz, FCz, Cz, CPz, and Pz) and two electrodes from the tip of the nose and the cheek. Fpz, Fz, FCz, Cz, CPz, and Pz were recorded with pin electrodes in a 64-electrode EEG cap. Data from the tip of the nose and the cheek were recorded with flat electrodes attached with adhesive disks. Because previous studies on ASSRs have mainly reported electrodes in the vicinity of Fz, we pre-registered to analyze Fz and FCz. Furthermore, positions Cz, CPz, and Pz were commonly analyzed in previous studies on the visual P3 (as a load manipulation check). Because previous research on ASSRs used either the nose or the mastoids as reference, we picked the nose as reference. Two additional, system-specific positions were recorded with pin electrodes in the EEG cap (https://www.biosemi.com/faq/cmsdr1.htm). Data were sampled at 2048 Hz and filtered with a software high-pass filter at 0.1 Hz (Butterworth fourth degree two-pass filter) and a hardware low-pass filter at 417 Hz.

2.4. EEG preprocessing

2.4.1. ASSR

To capture the ASSRs, the first two minutes of each block were divided into 77 epochs of 1.5625 s each. The first epoch started with the onset of the tone. The 1.5625-s epoch duration was chosen because for each frequency of interest (20.48, 40.96, and 81.92 Hz), one cycle fits in the epoch an integer number of times (e.g., one cycle of 40.96 Hz fits 64 times in 1.5625 s, 1/40.96 = 1.5625). Additionally, this epoch duration provides a satisfactory frequency resolution when the signal is transformed into the frequency spectrum (Δf = 0.64 Hz). Tone onset was identified with a Cedrus StimTracker (Cedrus Corporation, San Pedro, CA). The electrodes Fpz, Fz, FCz, Cz, CPz, and Pz were re-referenced to the tip of the nose, and Fpz was also re-referenced to the cheek electrode to detect vertical and horizontal eye movements.

For each subject, amplitude ranges (i.e., max minus min) within individual epochs were extracted, and the distribution of these ranges was visually inspected to exclude apparent extreme values. Cutoffs were adjusted individually to retain as many trials as possible while reducing the potential effects of extreme values. Because epochs were long (1.56 s) and consecutive epochs in a block covered two minutes of continuous data, eye blinks were inevitable and were not regarded as extreme values unless a subject had only a few of them. In fact, because even the lowest frequency of interest (20.48 Hz) is much higher than that of eye blinks (< 3 Hz), the ASSR measurements should be unaffected by eye blinks. Inspection was unbiased because it was blind to the load level and the amplitude modulation frequency [70]. After the artifact rejection, at least 73 epochs (94.8% of 77) were retained per block for each subject.

For each of the 18 blocks and each preregistered electrode (Fz and FCz), a mean waveform was computed across all retained epochs for each condition (i.e., load by modulation frequency). These mean waveforms were converted into amplitude spectra with fast Fourier transform (FFT). For each individual epoch in each condition, the phase was derived from complex components of the Fourier transform. The intertrial phase coherence (ITC) represents the phase coherence over the individual epochs in each condition and can range between 0 (no coherence) and 1 (perfect coherence). For each condition, the SmN for both amplitude and ITC was calculated as the difference between the value at the frequency of interest and the mean value from the 16 neighboring frequencies (eight on each side but omitting the two immediate neighbors on each side). The data for amplitude and ITC for all individual frequencies are supplementary material.

2.4.2. Visual P3

To capture the visual P3, epochs were extracted from 100 ms before letter onset to 500 ms after letter onset. Baseline correction was applied to each epoch by subtracting the mean amplitude of the 100-ms interval before letter onset. As in the preprocessing of the ASSRs, the data were re-referenced to the tip of the nose, and Fpz was re-referenced to the cheek electrode to detect eye movements. Because the epochs were much shorter for the visual P3 than for the ASSRs, and the visual P3 is a slow wave, the artifact rejection was more conservative than the one used during preprocessing of the ASSRs. Artifact rejection was unbiased because it was blind to load and modulation frequency [70]. After artifact rejection, the mean number of epochs was at least 43.3 (90.2% of 48) for targets and 171.6 (86.2% of 199) for nontargets in any block of low or high load.

To calculate the visual P3, mean amplitudes were extracted for the interval between 300 and 400 ms after the onset of the letters across electrodes Cz, CPz, and Pz. For low load and high load, the visual P3 was defined as the difference between targets and nontargets.

2.5. Statistical analysis

As preregistered, the BF was computed from bayesian one-sample t tests of difference scores. We preferred t tests to ANOVAs because in the analysis of factorial designs, t tests can be used to address specific, informative questions with contrast analyses [71].

The BF was computed to measure the relative strength of evidence in support of the alternative hypothesis versus the null hypothesis [53, 71–74]. The BF compares the likelihood of the data given an alternative hypothesis with the likelihood of the data given the null hypothesis. For example, a BF01 = 3 indicates that the data are three times more likely under the alternative hypothesis than the null hypothesis, whereas a BF10 = 3 indicates that the data are three times more likely under the null hypothesis than the alternative hypothesis. Although the BF is a continuous measure, we adopted an interpretation presented in Wagenmakers, Love, et al. [73]: 1 < BF < 3 reflects anecdotal evidence, 3 < BF < 10 moderate evidence, 10 < BF < 30 strong evidence, and 30 < BF < 100 very strong evidence. Because with anecdotal evidence, results are inconclusive as to whether there is an effect [53], we use the terms anecdotal and inconclusive interchangeably.

We hypothesized that ASSRs (i.e., amplitude SmN and ITC SmN) are unaffected by visual load. Specifically, we hypothesized that there would be no effect of task (no minus low load), no effect of load (low
3. Results

Below, we report only the main results. The supplementary material includes these main results together with additional results such as mean values (and confidence intervals) for each condition and for difference values between conditions, grand mean event-related potentials (ERPs), BF analyses, and exploratory ANOVAs.

3.1. Manipulation check of visual load

As a manipulation check of visual load, we analyzed behavioral performance (d’ and reaction times to hits), visual P3 (targets vs. non-targets), and subjective ratings of workload.

3.1.1. Behavioral performance

A response between 200 and 1000 ms after onset of a visual target was counted as a hit, whereas a response outside of this interval was counted as a false alarm. Although the specific interval for a hit was not preregistered, it was identical to that used in our previous study [Study 2 in 52]. Fig. 2 shows the mean differences in the signal-detection index d’ and in reaction times to hits between low and high load for 20-Hz, 40-Hz, and 80-Hz modulation frequencies. For each modulation frequency, subjects performed better (d’ \( M_{\text{diff}} > 1.78 \)) and were faster (RT \( M_{\text{diff}} > 115 \text{ ms} \)) during low load than during high load. In Fig. 2, the means and 95% confidence intervals overlap closely, suggesting no apparent differences between frequencies. In support, exploratory repeated-measures ANOVAs of load (low and high) and modulation frequency (20, 40, and 80 Hz) did not suggest an interaction (all \( p > .53 \); all BF\(_90 > 9 \) with a Cauchy prior of \( r = 0.5 \) for \( d’ \) or for reaction time).

3.1.2. Visual P3

Fig. 3 shows grand mean ERPs to the onset of visual stimuli, and Fig. 4 shows the mean visual P3 differences between low and high load for all three modulation frequencies.

The visual P3 was substantially larger in low load than in high load (\( M_{\text{diff}} > 6.0 \mu V \)). In Fig. 4, the means and 95% confidence intervals overlap closely, suggesting no differences between frequencies. In support, exploratory repeated-measures ANOVA of load (low and high) and modulation frequency (20, 40, and 80 Hz) did not suggest an interaction (\( p = .82; \text{BF}_{90} = 9.8 \) with a Cauchy prior of \( r = 0.5 \)).

3.1.3. Workload ratings

For each modulation frequency, low load was more demanding than no load (mental demand \( M_{\text{diff}} > 8 \), effort \( M_{\text{diff}} > 10 \)), and high load was not reasonably exceed the values during no load. Specifically, the difference between no load and another condition (e.g., no load minus high load) could not reasonably be larger than the starting value during no load; that is, the no load condition would define an upper limit of the maximum effect. For example, if \( +0.24 \mu V \) was the mean amplitude SmN during no load, a difference of no load minus low load equal to \( +0.24 \mu V \) would mean that low load eliminated the ASSRs. Because we assumed that values for no load would be similar between studies, we preregistered the specific values for no load from the previous study as upper limits in the BF analyses.

However, the actual data (see below) suggested that these preregistered upper limits were unreasonable: The values obtained during no load varied between modulation frequencies and were much smaller for 80 Hz than for other frequencies. To adhere to the original goal of using reasonable, informed alternative hypotheses, we deviated from the preregistration and used the actual SmN values during no load or low load to define the upper limits. Separately for each measure (amplitude and ITC) and modulation frequency, the alternative hypothesis was modelled as a uniform distribution from 0 to the mean SmN of no load (or low load for the comparison between low and high load). Accordingly, the effect was modelled to vary between 0 and the maximum value obtained at no load (or low load). The preregistered analyses are supplementary material.

The BF’s for the bayesian one-sample t tests were computed with Aladins R scripts [75]. The likelihood was modeled as a t distribution. For all mean differences, we also report the 95% confidence intervals to facilitate an estimation approach [71].

3. Results

As preregistered, the alternative hypotheses in the BF analyses were modeled as a uniform distribution with reasonable, informed upper limits. In all analyses, the lower limit was zero, but the upper limit was defined on the basis of the results of a previous study that used the same load manipulation [Study 2 in 52]. Thus, the alternative hypothesis was between 0 and +0.24 \( \mu V \) for amplitude SmN and between 0 and +0.37 for ITC SmN. The upper limits matched the mean values during no load in the previous study. We assumed that any effects of task or load could not reasonably exceed the values during no load. Specifically, the difference between no load and another condition (e.g., no load minus high load) could not reasonably be larger than the starting value during no load; that is, the no load condition would define an upper limit of the maximum effect. For example, if \( +0.24 \mu V \) was the mean amplitude SmN during no load, a difference of no load minus low load equal to \( +0.24 \mu V \) would mean that low load eliminated the ASSRs. Because we assumed that values for no load would be similar between studies, we preregistered the specific values for no load from the previous study as upper limits in the BF analyses.

Fig. 2. Mean d’ and reaction time (RT) differences between low and high visual load averaged across blocks for 20-Hz, 40-Hz, and 80-Hz modulation frequencies.
more demanding than low load (mental demand $M_{\text{diff}} > 12$, effort $M_{\text{diff}} > 12$). For each comparison, the 95% CIs did not include zero (mental demand $LL_{\text{diff}} > 3$, effort $LL_{\text{diff}} > 5$). Fig. 5 shows the mean ratings of mental demand and effort during no, low, and high load for all three frequencies. The means and 95% confidence intervals overlap closely, suggesting no apparent differences between frequencies. In support, exploratory repeated-measures ANOVAs of load (no, low, and high) and modulation frequency (20, 40, and 80 Hz) did not suggest an interaction ($all \ p > .22; all \ BF_{01} > 18$ with a Cauchy prior of $r = 0.5$) for mental demand or effort.

Taken together, the results from behavioral performance, visual P3, and workload ratings showed that for each modulation frequency, high load was more demanding than low load. The workload ratings also suggest that no load was the least demanding. Furthermore, results suggest no differences among modulation frequencies.

### 3.2. Amplitude SmN

Fig. 6 shows mean amplitude SmN (and confidence intervals) for all load conditions (no, low, and high) and the differences among conditions for the three modulation frequencies.

#### 3.2.1. 20-Hz ASSR

Fig. 7 shows the grand mean ERPs (top panel) and mean amplitude spectra (bottom panel) averaged across two electrodes (Fz and FCz) for the three load conditions. The amplitude of the frequency of interest (20.48 Hz) was larger than the amplitudes of the neighboring frequencies (SmN $> 0.34 \mu V$). Figs. 6 and 7 suggest that the SmN did not differ among the load conditions. In support, the bayesian analyses provided moderate to strong evidence for no effect of task, load, or the combination of task and load ($BF_{01} > 6.77$ for all comparisons).

#### 3.2.2. 40-Hz ASSR

Fig. 8 shows the grand mean ERPs (top panel) and mean amplitude spectra (bottom panel) averaged across two electrodes (Fz and FCz). The amplitude of the frequency of interest (40.96 Hz) was larger than the amplitudes of neighboring frequencies (SmN $> 0.44 \mu V$). The bayesian analyses provided moderate evidence for no effect of task (no minus low; $BF_{01} = 4.44$), moderate evidence for no effect of load (low minus high; $BF_{01} = 7.83$), and anecdotal evidence for no combined effect of task and
load (no minus high; BF\textsubscript{01} = 1.74).

At face value, the anecdotal evidence for no combined effect of task and load (BF\textsubscript{01} = 1.74) is inconsistent with our previous report of strong evidence for no combined effect on 40-Hz ASSRs (BF\textsubscript{01} = 27.2 in Study 2 [52]). To estimate the strength of evidence across all data (i.e., previous and the present study) and for all effects (i.e., task, load, and combined), we added the present data to those from our previous studies [52]. In the previous studies, Study 1 included low load and high load, and Study 2 included no load, low load, and high load. To calculate the BF, the alternative hypothesis was modelled as a uniform distribution from zero to a reasonable upper limit (i.e., mean level at no load or low load). When combined, the data provided strong evidence for no effect of task (BF\textsubscript{01} = 10.07), strong evidence for no effect of load (BF\textsubscript{01} = 10.07), and moderate evidence for no combined effect of task and load (BF\textsubscript{01} = 3.79).

### 3.2.3. 80-Hz ASSR

Fig. 9 shows the grand mean ERPs (top panel) and mean amplitude spectra (bottom panel) averaged across two electrodes (Fz and FCz) for all loads. The amplitude of the frequency of interest (81.92 Hz) was slightly larger than the amplitudes of neighboring frequencies (SmN > 0.09\textmu V). The bayesian analyses provided strong evidence for no effect of task (BF\textsubscript{01} = 11.53), anecdotal evidence for no effect of load (BF\textsubscript{01} = 2.80), and moderate evidence for no combined effect of task and load (BF\textsubscript{01} = 4.25).

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**Fig. 5.** Mean ratings of self-reported mental workload and effort (NASA-TLX) for no, low, and high load, averaged across blocks for 20-, 40-, and 80-Hz modulation frequencies.

**Fig. 6.** Means and 95% CIs of amplitude signal minus noise (SmN) for all load conditions (no, low, and high), for the effect of task (no-low), the effect of load (low-high), and the combined effect of task and load (no-high) for 20-, 40-, and 80-Hz ASSRs. Individual subjects’ values are plotted as circles, and the thin lines connect all values for each individual.
Fig. 7. Grand mean event-related potentials (ERPs) (top) and mean amplitude spectra (bottom) of 20-Hz ASSRs, averaged across all blocks and electrodes (Fz, FCz) for no, low, and high visual load. The gray interval highlights the neighboring frequencies used to calculate the noise level.

Fig. 8. Grand mean event-related potentials (ERPs) (top) and mean amplitude spectra (bottom) of 40-Hz ASSRs, averaged across all blocks and electrodes (Fz, FCz) for no, low, and high visual load. The gray interval highlights the neighboring frequencies used to calculate the noise level.
3.3. Intertrial phase coherence SmN

Fig. 10 shows mean ITC SmN (and confidence intervals) for all load conditions (no, low, and high) and the differences between conditions for the three modulation frequencies. In support, the bayesian analyses provided moderate to strong evidence for the null hypothesis for all comparisons ($BF_{01} > 9.73$).

3.3.1. 20-Hz ASSR

ITC at the frequency of interest (20.48 Hz) was larger than ITC at the neighboring frequencies (SmN > 0.17). Fig. 10 suggests that the SmN was similar for the load conditions (no, low, and high). In support, the bayesian analyses provided moderate to strong evidence for the null hypothesis for all comparisons ($BF_{01} > 9.73$).
3.3.2. 40-Hz ASSR

ITC at the frequency of interest (40.96 Hz) was larger than ITC at the neighboring frequencies (SnM > 0.32). The bayesian analyses provided anecdotal evidence for no effect of task (BF\text{01} = 1.64) and moderate evidence for no effect of load (BF\text{01} = 4.23). However, as suggested in Fig. 10, ITC tended to decrease from no to high load. Thus, the evidence was strong (BF\text{01} = 12.66) for a combined effect of task and load on ASSR.

As for the amplitude SmN, we combined the present ITC data with that of our previous studies [52]. The bayesian analyses provided strong evidence for no effect of task (BF\text{01} = 12.38), anecdotal evidence for no effect of load (BF\text{01} = 1.09), and anecdotal evidence for the combined effect of task and load (BF\text{01} = 1.56).

3.3.3. 80-Hz ASSR

ITC at the frequency of interest (81.92 Hz) was slightly larger than ITC at the neighboring frequencies (SnM > 0.10). The bayesian analyses provided moderate evidence for no effect of task (BF\text{01} = 3.27), anecdotal evidence for no effect of load (BF\text{01} = 2.25), and anecdotal evidence for the combined effect of task and load (BF\text{01} = 1.50).

3.4. Data check for floor effects

Because the SnM for the three modulation frequencies varied considerably among subjects (see Figs. 6 and 10), we explored whether there were any relationships between the level of the values during no load (starting values) and the size of the combined effect (no load minus high load). Results suggested no relationships for any ASSR (see supplementary material).

4. Discussion

The current study examined effects of task (no minus low load), load (low minus high load), and their combination (no minus high load) on amplitude SnM and ITC SnM of 20-Hz, 40-Hz, and 80-Hz ASSRs. For 20-Hz ASSRs, bayesian analyses provided strong evidence that manipulations of visual load had no effect on either amplitude SnM or ITC SnM. For 40-Hz ASSRs, the strength of evidence was moderate for no effect of either task or load on amplitude SnM and for no effect of task on ITC SnM; however, there was strong evidence for a combined effect of task and load on ITC SnM. For 80-Hz ASSRs, the strength of evidence was moderate to strong for no effect of task on amplitude SnM or ITC SnM and was moderate for no combined effect on amplitude SnM. Manipulation checks confirmed that for each modulation frequency, load had substantial effects on behavioral performance and visual P3. Also, subjective workload ratings showed that all three conditions (no, low, and high load) differed in mental demand and effort. Results suggested no differences between the modulation frequencies.

4.1. 20-Hz ASSR

Bayesian analyses provided moderate to strong evidence for no effect of task, load, or their combination on amplitude SnM (BF\text{01} > 6.77) or ITC SnM (BF\text{01} > 9.73). These results replicate and extend previous reports of a statistically nonsignificant effect of load on 20-Hz ASSRs [41]. First, a statistically nonsignificant result does not necessarily provide evidence for no effect [76], whereas the present results support the conclusion that load has no effect. Second, the present results show that task and the combination of task and load have no effect, either. These results suggest that 20-Hz ASSRs are not attenuated.

Because 20-Hz ASSRs are mainly generated in the auditory cortex [23,25,26,32], filtering may occur only beyond the auditory cortex. However, this explanation would be inconsistent with findings that load affects activations related to figure-ground segregation in the auditory cortex, as measured with magnetoencephalography [77]. Another explanation is that filtering occurs in all conditions (including no load) and that the 20-Hz ASSRs are attenuated similarly for all conditions. According to the adaptive filtering model [15], filtering occurs early in the pathway for highly demanding tasks and late for less demanding tasks. Our results would fit with this theory if it is assumed that although the stage of the filter varied with load, the effects of these filters on the auditory cortex were similar for all conditions.

4.2. 40-Hz ASSR

For amplitude SnM and ITC SnM, the results of the bayesian analyses varied. For amplitude SnM, results provided moderate evidence for no effect of task (BF\text{01} = 4.44) or load (BF\text{01} = 7.83) but only anecdotal evidence for no combined effect of task and load (BF\text{01} = 1.74). For ITC SnM, results provided moderate evidence for no effect of load (BF\text{01} = 4.23) and only anecdotal evidence for no effect of task (BF\text{01} = 1.64); contrary to these results, there was strong evidence for a combined effect of task and load (BF\text{01} = 12.66).

In two recent studies, we used similar load manipulations and recorded 40-Hz ASSRs [52]. Results provided moderate to extreme evidence for no effect of visual load on SnM measures of either amplitude or ITC. These results should be more robust than the present findings for several reasons: The sample sizes were larger (N = 43 to 45 in Study 2, vs. N = 33 in the present study), the blocks were longer (three instead of two minutes), and each visual condition was repeated in four blocks (rather than two). Exploratory analyses of these previous studies suggested that effects did not vary within or among blocks.

To obtain the best estimate of the true effect, we combined the current data with those of the previous two studies. For the effect of load, we used data from Study 1 and Study 2 [52]. For the effect of task and the combined effect of task and load, we used only data from Study 2 because Study 1 lacked a passive viewing condition (i.e., no load). For the amplitude SnM, the combined data provided moderate evidence for no effect of task, load, or their combination (3.79 < BF\text{01} < 10.07). For the ITC SnM, the combined data provided strong evidence for no effect of task (BF\text{01} = 12.38) but only anecdotal evidence for no effect of load (BF\text{01} = 1.09) and for a combined effect of task and load (BF\text{01} = 1.56).

Regarding amplitude SnM, the moderate to strong evidence for no effect suggests that the amplitude of 40-Hz ASSRs is unaffected by manipulations of task, load, or their combination. This fits with the statistically nonsignificant results reported by Parks et al. [3]. Although the present findings do not rule out the possibility that a stronger load manipulation could have an effect, manipulation checks showed substantial load effects in terms of behavioral performance, visual P3, and subjective workload ratings. Furthermore, in other studies that found load effects on physiological measures other than ASSRs, the manipulations of load and their effects on behavioral performance were similar to those in the present study [3,54-56].

Regarding ITC SnM, there was strong evidence for no effect of task but only anecdotal evidence for no effect of load and for a combined effect of task and load. With anecdotal evidence, results are inconclusive as to whether there is an effect [53]. However, an estimation approach suggests that the maximum effect size (i.e., upper limit of 95% CI) on ITC SnM is 0.028 for the load effect and 0.038 for the combined task and load effect. Although these effects may be theoretically important, it is unclear whether their effect sizes are of practical importance.

A previous study found that with an increase in load in an n-back task, the phase-locking index (PLI) decreased [45]. PLI was calculated in the same way that ITC was calculated in the current study except that it was expressed as a signal-to-noise ratio (rather than a difference score of signal minus noise). However, a drawback of the signal-to-noise ratio is that it may be unreliable when noise levels are close to zero [52]. Another study also associated an increase in load with a decrease in PLI, but only when load changed from no load to a 2-back task and not vice versa [46]. In that study, PLI reflected only the signal frequency even though it is beneficial to consider signal strength relative to the noise (i.
e., SmN or signal-to-noise ratio). Notably, our results do not suggest that the overall signal strength was weak in our study; instead, the overall signal strength in the present study (means between 0.4 and 0.5) tended to be larger than that in the other studies (means close to 0.26 in [45], between 0.3 and 0.4 in [46]). Furthermore, a combined sample size of 121 subjects across our present and previous studies [52] was not enough to determine whether there was an effect of load, which suggests that examining this question requires a huge sample size. If publication biases (i.e., significant findings are more likely to get published [78]) can be assumed, then it is likely that published, positive findings do not reflect the true effect. Thus, the present findings emphasize the need for large sample sizes to resolve whether there is a load effect on ITC SmN.

Three explanations for no effect of visual load manipulation on 40-Hz ASSRs seem plausible. First, because the primary auditory cortex is the main generator of 40-Hz ASSRs [25,27–31], these ASSRs should not be attenuated if filtering occurs beyond the primary auditory cortex. However, previous findings showed that load affects the primary auditory cortex [77]. Second, filtering for all conditions (including no load) occurs at or before the primary auditory cortex, and thus 40-Hz ASSRs are attenuated in all conditions. This explanation is consistent with the adaptive filtering model [15] if it is assumed that the effects of filtering are similar at the primary auditory cortex. Third, because 40-Hz ASSRs are generated by brainstem and thalamus as well as primary auditory cortex [25,26], differences among the visual load conditions may not be detected if the combined effects of load on these neural generators are small.

4.3. 80-Hz ASSR

Results of the bayesian analyses provided moderate to strong evidence for no effect of task on amplitude SmN ($BF_{10} = 11.53$) or ITC SmN ($BF_{10} = 3.27$). There was also moderate evidence for no combined effect of task and load on amplitude SmN ($BF_{01} = 4.25$). The strength of evidence was only anecdotal for any other effects. However, as shown in Figs. 6 and 10, the overall levels of amplitude SmN and ITC SmN were low. If overall levels are low, it is possible that there were floor effects: If levels are low during no load, they cannot decrease further with high load. However, there was no apparent relationship between an individual’s SmN level during no load and the individual’s change in SmN level with high load (see supplementary material).

Because 80-Hz ASSRs are generated in the brainstem [17,25,26], one explanation for no effect of task or of load on amplitude SmN or ITC SmN is that at the level of the brainstem, all irrelevant information is already filtered out even during no load. However, this explanation is inconsistent with the adaptive filtering model [15]: If filtering for less demanding tasks (i.e., no load condition) occurs already at the level of the brainstem, there is little possibility for the filter to move lower in the pathway with increased task demand, unless it moves all the way to the cochlea. This should be possible through the medial olivocochlear (MOC) efferent projections from the superior olivary complex in the brainstem to the outer hair cells in the cochlea [79–81]. Because changes in otoacoustic emissions reflect the modulation of cochlear activity by MOC efferents [80], otoacoustic emissions can be used to examine whether crossmodal attention affects the cochlea. Results of two recent studies suggest that otoacoustic emissions are unaffected by whether subjects attend auditory or visual modality [82,83]. However, in these studies, attention conditions switched between modalities (i.e., attend auditory vs. visual), whereas in the current study, attention conditions switched between tasks (i.e., attend to different visual load tasks while auditory stimuli are always to be ignored). Although it is unclear whether the results can be generalized to task-switching designs, these findings suggest that crossmodal attention has no effect on otoacoustic emissions. As such, they are inconsistent with the adaptive filtering model.

Another explanation is that early filtering at the level of the brainstem does not occur because common load manipulations are not strong enough. If this is true, extreme load manipulations appear necessary because the present study manipulated load similarly to other studies that found effects of load on other measures [3,54–56].

4.4. General discussion

For all bayesian analyses with conclusive evidence ($BF > 3$), results suggested that manipulations of visual load have no effect on amplitude SmN or ITC SmN to 20-Hz, 40-Hz, or 80-Hz ASSRs. If the present results are correct in that visual load has no effect on ASSRs, they support the idea that auditory processing and visual processing use separate pools of resources [2–4,84,85]. However, the present results do not rule out the possibility that filtering occurs already in the brainstem for all conditions (even during passive viewing). Thus, they may be consistent with the early-filter model [12] because top-down attentional modulation can occur even at very early stages of processing. However, if filtering already occurs at the brainstem during passive viewing, this explanation is inconsistent with the adaptive filtering model [15], as the filtering stage should be dynamic and vary with the attentional demand of the relevant task.

Although the adaptive filtering model does not seem to apply to crossmodal attention, it appears to be correct for intramodal attention. Several recent intramodal studies showed a substantial attenuation of ASSRs when the auditory information was not attended compared to when it was attended [32,86–90]. This ability of the auditory system to attenuate task-irrelevant information in the intramodal attention design but not in the crossmodal attention design supports the idea of separate, modality-specific attentional resources [2–4,84,85].

In the present study, bayesian analyses were conducted to measure the strength of evidence for or against effects of visual load. For 20-Hz ASSRs, the evidence for no effect was moderate to strong. For 40-Hz ASSRs, the strength of evidence across the present and previous data [52] was moderate to strong for no effect of task, load, or their combination on the amplitude SmN and was strong for no effect of task on the ITC SmN. However, it was only anecdotal with regard to a load effect and a combined task and load effect on ITC SmN to 40-Hz ASSRs. Because the strength of the evidence remained anecdotal even with 121 subjects (across studies), these findings suggest that effect sizes are small and that collecting enough evidence therefore requires very large sample sizes. Notably, the 95% CI may be useful to estimate an upper limit of the effect. For example, the estimated maximum effect size of the combined effect of task and load on ITC SmN is 0.038. Because current theories are not explicit about effect sizes, it is unclear whether this effect is theoretically important. Also, it is unclear whether this effect size is of practical importance. For 80-Hz ASSRs, results may need to be interpreted with caution. As shown in Figs. 6 and 10, overall levels of amplitude SmN and ITC SmN were low for 80-Hz ASSRs, and several subjects did not show any 80-Hz ASSRs at all, consistent with other research on ASSRs [91]. Future research should preregister the criterion that subjects will be included only if they show clear evidence of ASSRs, although it will be difficult to define a reasonable threshold value (e.g., 0.1 SmN for amplitude). Notably, exploratory analyses of the present data did not suggest any floor effects: Across subjects, there was no apparent relationship between SmN levels during no load and change in SmN levels with high load.

Because ASSRs do not require subjective responses, they are used in audiology to measure the auditory threshold of individuals who cannot provide a response [17,21]. Because some individuals might direct their attention elsewhere during clinical assessments, it is clinically relevant to investigate whether ASSRs are sensitive to visual load. The present results suggest that visual load has no effect on the amplitude and ITC of 20-, 40-, or 80-Hz ASSRs. If these responses are unaffected by whether individuals engage in a low or high visual load task or no task, results of clinical assessments should be unaffected by the directed visual attention of the tested individuals.
4.5. Conclusion

The present study used a task-switching design to manipulate crossmodal attention. Individuals were asked to ignore auditory stimuli while attending to visual tasks that differed in load (no, low, and high). For all bayesian analyses with conclusive evidence, results showed that manipulations of visual load have no effect on amplitude SmN or ITC SmN to 20-Hz, 40-Hz, or 80-Hz ASSRs. Because no auditory filtering was detected at any tested processing stage, these findings are inconsistent with the adaptive filtering model. Thus, the findings support the idea of separate processing resources for auditory and visual information. However, these results cannot be generalized to intramodal designs (e.g., attending or ignoring a particular auditory stream) or other cross-modal designs (e.g., switching modality between auditory and visual).

Because previous research showed that in intramodal designs, ASSRs are affected by attention manipulations, the adaptive filtering model may apply to designs other than task switching.

Declaration of Competing Interest

None.

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