Auditory White Noise Increases Visual Accuracy

Julian Keil[1], Madelaine-Rachel Dering[2], Ida Zimmermann[1], Merle Schuckart[1], Mira-Lynn Chavanon[3]

1 Biological Psychology, Christian-Albrechts-University Kiel, Germany

2 Medizinische Hochschule Hannover, Germany

3 Clinical Child and Adolescent Psychology, Faculty of Psychology, University of Marburg, Germany

Abstract

Perception fluctuates over time and depends on internal states, such as attention, fatigue, or arousal. Several studies indicate that concurrent stimulation can influence perception and cognition. However, the direction of this influence is under debate, with some experiments finding detrimental effects, whereas others find that noise can be beneficial. In two experiments, we examined the influence of auditory white noise on visual perception. We first extended previous findings on the beneficial influence of white noise stimulation on visual perception in a visual flanker task. We then used the audiovisual sound-induced flash illusion to extend this line of research and found a reduction of the illusion perception under white noise stimulation. Overall, we find that white noise improves perceptual accuracy, without changing response speed. This is in line with the Moderate Brain Arousal Model, which suggests that white noise stimulation should improve performance in attention tasks. Our findings indicate that concurrent, task-independent auditory stimulation can improve responses to visual target stimuli.

Keywords: Attention, Perception, White Noise, Resonance

Auditory White Noise Increases Visual Accuracy

Maintaining constant performance, even for long durations, is critical in many situations. However, action, perception, and cognitive control mechanisms such as attention fluctuate over time (Esterman & Rothlein, 2019). To optimize performance over time, it is therefore important to design tasks and interventions to counteract drifts and fluctuations. Exploring the options to modulate performance is a first step towards finding specific intervention and adaptation strategies. One of these options may be acoustic stimulation with white noise to increase arousal and enhance sensory processing and perception (Moss et al., 2004).

Adding noise to a signal can enhance the salience of a signal such that a certain threshold for information transmission can be reached with higher probability. This non-linear effect of noise on information transfer has been called “stochastic resonance” (SR, Moss et al., 2004). In auditory perception, pure tone detection thresholds can be lowered by continuous white noise stimulation (Zeng et al., 2000). Interestingly, there is evidence that stochastic resonance works across modalities, as indicated by continuous auditory noise improving visual signal detection (Manjarrez, Mendez, Martinez, Flores, & Mirasso, 2007) and visual contrast perception (Gleiss & Kayser, 2014). In electrophysiological studies, the latter finding was related to a decrease in occipital alpha power. Reduced alpha power in turn has been linked to cortical excitability and improved visual accuracy (Michail et al., 2021). In short, auditory and visual perception appear to benefit from adding auditory white noise. However, this noise is task-irrelevant, but can have a task-independent and even cross-modal effect, suggesting a modality-independent, general effect on arousal and cortical excitability.

To link SR, arousal, and attention, Sikström and Söderlund (2007) proposed the Moderate Brain Arousal Model (MBA). This model is based on observations of attenuated dopamine levels in attention-deficit/hyperactivity disorder (ADHD). The MBA predicts differences in attention depending on the dopamine (DA) level. Therein, one must differentiate between tonic and phasic DA activity. The former refers to low extracellular concentrations of DA, whereas the latter refers to release of DA from the axon terminals following action-potentials. Siktröm and Söderlund (2007) argue that tonic DA modulates the phasic neural reactivity, thereby influencing the critical excitation-inhibition balance (Plenz et al., 2021). Following the MBA, low tonic DA should lead to less, perhaps insufficient, neural excitability which may lead to poor signal transmission. To reach a sufficient signal transmission, neural excitability thus needs to be boosted by increased arousal. One way to increase the arousal is continuous exogenic stimulation. Importantly, based on the critical excitation-inhibition balance, the MBA proposes an optimal level of exogenic stimulation, with detrimental effects of too strong or too weak stimulation (i.e., inverted U-shaped relationship; see Sikström & Söderlund, 2007). Taken together, the MBA proposes that an optimal level of stimulation will increase the arousal and influence the tonic DA level, thereby facilitating cognitive control mechanisms such as attention and improving perception.

In order to evaluate the relationship between SR, arousal and attention proposed in the MBA, the empirical evidence for or against the model needs to be carefully examined and extended. In two experiments, we first aimed to replicate the critical findings of an influence of white noise stimulation on perception using a visual flanker task. Subsequently, we aimed to extend these findings to bistable audiovisual perception. The overall goal of the two experiments presented here was to elucidate the influence of white noise stimulation on visual perception. In both experiments, we examined responses to visual target stimuli in the context of incongruent, but task-irrelevant concurrent auditory stimulation. In the first experiment, the flanker task comprised congruent and incongruent visual stimuli with and without concurrent white noise stimulation. Participants typically are faster and more accurate in their responses to congruent vs. incongruent stimuli. Competing approaches conceptualize the congruent vs. incongruent difference as primarily stimulus and perception-driven interference, or interference aligned to the response level in terms of action control (Kopp, Rist & Mattler, 1996; Albrecht et al., 2008; McLoughlin et al., 2009; Ridderinkhof et al., 2021 for a review). If white noise improves perception, then responses to both congruent and incongruent stimuli should get faster and more accurate. In contrast, if white noise improves cognitive control, the difference between both stimulus categories should be reduced. In the second experiment, the sound-induced flash illusion (SIFI, Shams et al., 2000; Keil et al., 2020) comprised congruent and incongruent audiovisual stimuli. In this experiment different loudness levels of white noise stimulation were used to examine the relationship between noise level and perception. Again, participants typically are more accurate in their responses to congruent vs. incongruent audiovisual stimuli, and the critical combination of two auditory with one visual stimulus can induce the illusory perception of two visual stimuli. If white noise affects the influence of the auditory stimuli on visual perception (Andersen et al., 2004), then responses to incongruent audiovisual stimuli should improve linearly with increasing noise levels, resulting in less illusions. In contrast, if white noise improves cognitive control, then intermediate noise levels should lead to reduced illusion rates compared to low or high noise levels. In both experiments, we examined the perceptual errors induced by the concurrent incongruent stimulation. We hypothesize that white noise stimulation can increase the cortical excitability, which will facilitate the perceptual separation of target stimuli and concurrent distractors.

Experiment 1

The first experiment was aimed at testing the influence of white noise stimulation on attention-related parameters of visual perception. To this end, we used a visual flanker task in combination with and without auditory white noise stimulation. As an influence of white noise stimulation has already been shown in ADHD samples, we were especially interested in extending these findings to the influence of white noise on high-performing people with low scores on the ADHD index scale to the CAARS (Christiansen, Hirsch, Abdel-Hamid, & Kis, 2014).

Methods.

Participants.

In the first experiment, 31 male adult participants gave informed consent and participated in the study for partial course credit or in exchange for 25 €. The study was conducted in accordance with the 2008 Declaration of Helsinki and approved by the ethics committee of the Philipps-University Marburg (approval number: 2018-44k). Due to deviations in the experimental procedures (e.g., sleep deprivation, psychotropic substance intake, post-experimental control indicated deviation in SPL of white noise stimulation), data of seven participants were excluded from further analysis. The resulting sample (N=24) was screened for attention-deficit/hyperactivity symptomatology (i.e., inattentive-disorganized and hyperactive -impulsive symptoms) using the ADHD Index of the Conners' Adult ADHD Rating Scale Self-Rating (CAARS; Conners et al., 1999; German version: Christiansen, Hirsch, Abdel-Hamid, & Kis, 2014). The ADHD index is designed to measure the overall level of ADHD symptoms and serves as an economic screening instrument with only 12 items (4-point Likert responding; 0 = not at all/never to 3 = very much/very often) to distinguish adults with ADHD from a nonclinical group. The US-American and German versions displayed highly satisfactory psychometric properties (Christiansen, Hirsch, Abdel-Hamid, & Kis, 2014; Christiansen et al., 2012, 2011).

The present analysis focuses on the high performing participants. Therefore, analyses focused on the data of the 12 participants (mean +/- SD age = 22.33 +/- 1.67 years) with raw CAARS ADHD index scores below the group median. All participants had normal, or corrected-to-normal vision, and did not report any mental disorders or neurological diseases. Moreover, all participants were screened for behavior or events that could have influenced the dopamine system, such as caffeine consumption, illicit drug use or sleep quality and were tested between 9:30 am and 2 pm.

Task.

The first experiment consisted of a flanker task based on the procedure described in Albrecht et al. (2008, Figure 1), programmed in Presentation v18.3 (Neurobehavioral Systems, Berkeley, CA, USA). Each trial of the task comprised the presentation of a column of three arrowheads and required two-choice responding to the direction indicated by the central target with the index finger of the left or right hand, respectively. In congruent stimuli, target and flanker pointed into the same, while in incongruent stimuli they pointed into opposite directions. All triangles were presented in the center of a computer monitor, against light grey background. At the beginning of the trial, the flanker triangles were presented alone for 100 ms, followed by the conjoint presentation of flankers and target for another 150 ms. Within 1400 ms after target offset, the participants were asked to indicate the pointing direction of the target triangle using the left and right index fingers on an RB-840 response pad (Cedrus, San Pedro, CA, USA) as fast and accurate as possible. The task was presented in two sets, one with and one without white noise stimulation, with a 5-min. break in between. For each participant, the order of the sets was randomized. Each set comprised 10 blocks with 40 trials each (i.e., 10 right congruent, 10 left congruent, 10 right incongruent and 10 left incongruent) in random order. In line with the procedure by Albrecht et al. (2008), participants received written feedback on their performance after each block. With the feedback display, participants were instructed to respond more accurate in case of more than 10% errors in the congruent or more than 40% errors in the incongruent condition, or faster in case of less than 10% errors in the congruent or less than 40% errors in the incongruent condition. Prior to the start of the main experiment, participants were given two blocks of 12 trials to familiarize themselves with the task. Prior to, during and after the flanker task, EEG was recorded from 64 electrodes. Presentation of the EEG data is beyond the scope of the current report.

Apparatus.

Visual stimuli were presented on an 24'' TFT- screen with refresh rate of 60 Hz and a viewing distance of 70 cm. Auditory white noise at 78 dB (SPL; mono track, 44100 Hz sampling frequency with 32-bit float) was gated by an audio-mixer amplifier (Omnitronic LS622A) and presented to the participants using two room loudspeakers (JBL Control One, ±3dB, 80Hz – 20kHz) located approximately 2 m to each of the participants' ears. The sound level was checked before and after each test session by using a professional sound level meter. The sound level was chosen based on previous work in patients with ADHD (Usher & Feingold, 2000; Helps et al. 2014). These suggested the optimal level of stimulation for improving performance during tasks requiring executive attention and action control through SR-mechanism (Usher & Feingold, 2000; Helps et al. 2014), within the range of 70 to 85 dB WN.

Analysis.

The current analysis focused on the dependent variables median and standard deviation of reaction time (RT, congruent and incongruent visual stimuli), and accuracy, depending on the independent variables Congruence (congruent and incongruent visual stimuli) and Noise (white noise stimulation and no white noise stimulation). Accuracy was defined as the number of correct responses relative to all trials within one condition. For both dependent variables, repeated-measures 2x2 ANOVAs were performed. The Mauchly test was used to verify the assumption of sphericity and the Greenhouse-Geisser correction was applied, when necessary, to correct for non-sphericity. For these cases, the corrected degrees of freedom and p-values are reported. Generalized eta squared is used as a measure of effect sizes (Bakeman, 2005). Further analyses of the significant effects were performed using post-hoc paired t-tests. In addition, the interference effect, that is the change in the error rate and RTs between congruent and incongruent (congruent - incongruent) stimuli was compared between white noise stimulation and no white noise stimulation (Mullane et al., 2009).

If the data were not normally distributed (failing the Lilliefors test for normality of distribution) they were rank-ordered prior to the ANOVAs (Conover and Iman, 1981), and post-hoc Wilcoxon signed-rank tests were used to evaluate differences between conditions. The Holm-Bonferroni correction (Holm, 1979) was applied for the all the post-hoc pairwise comparisons. An alpha level of 0.05 is used for all statistical tests.

Results.

In the first experiment, we examined the accuracy and reaction times to congruent and incongruent stimuli in a flanker task with and without white noise stimulation. To this end, we computed repeated-measures ANOVAs with the factors Congruence (congruent and incongruent visual stimuli) and Noise (white noise stimulation and no white noise stimulation).

Accuracy.

Accuracy data were not normally distributed and therefore rank transformed. In the analysis of performance accuracy, we found a main effect of Congruence ($F(1,11) = 86.14$, $p < 0.001$, $\eta^2_G = 0.76$), indicating higher accuracy for congruent stimuli (Figure 2A, Table 1). However, we neither found a main effect of Noise ($F(1,11) = 3.98$, $p = 0.071$, $\eta^2_G = 0.05$), nor an interaction between Congruence and Noise ($F(1,11) = 0.076$, $p = 0.79$, $\eta^2_G < 0.01$). Further examination in terms of the interference effect, i.e., the accuracy difference between congruent and incongruent stimuli using a Wilcoxon signed-rank test revealed a smaller accuracy improvement from incongruent to congruent stimuli under white noise stimulation than without noise stimulation ($V = 7$, $p = 0.023$, Figure 2B), indicating superior accuracy to incongruent stimuli under white noise stimulation.

RTs.

In addition to perceptual accuracy, we also examined the reaction times. To this end, we computed the median and standard deviation of RTs across trials. For the median of RTs, in the comparison between conditions, we found a main effect of Congruence ($F(1,11) = 124.72$, $p < 0.001$, $\eta^2_G = 0.49$), indicating lower RTs for congruent stimuli (Figure 3A, Table 1). However, we neither found a main effect of Noise ($F(1,11) = 1.96$, $p = 0.19$, $\eta^2_G = 0.02$), nor an interaction between Congruence and Noise ($F(1,11) = 0.42$, $p = 0.53$, $\eta^2_G < 0.01$). Further examination in terms of the interference effect did not reveal a difference in RT change between the noise stimulation conditions ($t(11) = -0.64$, $p = 0.53$, Figure 3B). Standard deviation of RTs were not normally distributed and therefore rank transformed. Here, we found a main effect of Congruence ($F(1,11) = 25.34$, $p < 0.001$, $\eta^2_G = 0.34$). However, we found no main effect for Noise ($F(1,11) = 0.07$, $p = 0.79$, $\eta^2_G < 0.01$). Additionally, we found a significant interaction between Congruency and Noise ($F(1,11) = 7.85$, $p = 0.017$, $\eta^2_G = 0.02$). Further examination of the interaction in terms of the interference effect, i.e., the difference in standard deviation of RTs between congruent and incongruent stimuli revealed a smaller change in the standard deviation from incongruent to congruent stimuli under white noise stimulation than without noise stimulation ($t(11) = 2.80$, $p = 0.017$), indicating less reaction time variability under white noise stimulation.

Discussion.

In line with the literature (Mullane et al., 2009), we found increased accuracy, i.e., less errors, in congruent compared to incongruent trials. In contrast to our hypothesis, the influence of white noise on perception was not evident from the full-factorial ANOVA, possibly due to a ceiling effect in the congruent stimuli. However, when analyzing the change in performance from incongruent to congruent stimulation, we found that white noise stimulation led to a performance increase of about 5.3%, in line with the predictions of the Moderate Brain Arousal model (Sikström & Söderlund, 2007).

Similar to the increase in accuracy, we found faster and less variable RTs in the congruent compared to the incongruent stimuli. Whereas white noise stimulation did not have any effect on the median of RTs between noise stimulation conditions, the interaction found between stimulus conditions and white noise stimulation in the comparison of RT standard deviations indicates that white noise stimulation reduced the reaction time variability.

Experiment 2

The second experiment was aimed at testing the influence of auditory white noise stimulation on cross-modal influences of visual perception. To this end, we used the audiovisual sound-induced flash illusion (SIFI, Shams et al., 2000; Keil, 2020) in combination with different levels of auditory white noise stimulation in a sample of healthy young male and female adults.

Methods.

Participants.

In the second experiment, 35 adult participants gave informed consent and participated in the study for partial course credit. The study was conducted in accordance with the 2008 Declaration of Helsinki and approved by the ethics committee of the German Psychological Society (approval number: KeilJulian2019-07-04VADM). All participants had normal or corrected-to-normal vision. Due to disruptions in the experimental procedures, data of one participant were excluded from further analysis. One participant was excluded due to reporting a previous neurological disease. One more participant was excluded for not responding to more than one third of the trials. Previous studies have shown that there is considerable inter-individual variability regarding the perception of the SIFI (see Keil, 2020 and Hirst et al., 2020 for reviews). For the second experiment, we therefore focused on healthy participants that could reliably identify stimulation with two visual stimuli. Based on this, 12 participants that had an incorrect response in more than one third of the trials with two visual stimuli in isolation (A0V2) were excluded. Thus, the final sample for the second experiment comprised 20 participants (14 female, mean +/- SD age = 25.1 +/- 6.8 years).

Task.

The second experiment comprised the sound-induced flash illusion (SIFI, Shams et al., 2000, Keil, 2020, Figure 4), in combination with different loudness levels of white noise, programmed in lab.js (Henninger et al., 2020). In the SIFI task, zero, one, or two visual flashes are paired with zero, one, or two auditory clicks. The participants' task is to report the number of perceived visual stimuli (0, 1 or 2) while ignoring the auditory clicks. The SIFI consists of the perception of two visual stimuli following the incongruent audiovisual stimulation with two auditory and one visual stimulus (A2V1). Visual stimuli were presented below the center of a computer monitor, against light grey background. Throughout the trial, a fixation cross was presented at the center of the screen. Auditory stimuli were presented synchronously to the visual stimuli. Within 1700 ms after the onset of the first stimulus, the participants were asked to indicate the number of perceived visual stimuli using the right hand using the keys B, N, and M on a keyboard. Importantly, instructions did not require fast responses.

Apparatus.

Visual stimuli were presented for 13 ms on a 21.5 inch LCD screen at 75 Hz refresh rate with a viewing distance of 60 cm. Auditory white noise was presented at different sound levels via Sennheiser on-ear headphones. The noise loudness was chosen based on the recommendations by Söderlund et al. (2007; 2010) for moderate loudness. The task-relevant auditory clicks had a duration of 10 ms with a frequency of 1000 Hz, presented at 80 dB(SPL). White noise was presented at 59.6 db(SPL) in the baseline block, and at 63, 66.5, 69.3, 72.2, 74.1, 76, and 78 db(SPL) in the seven noise blocks. Thus, the signal-to-noise ratio between the clicks and the noise changed across the blocks from 1.48 in the baseline block to 1.40, 1.32, 1.27, 1.22, 1.19, 1.16 and 1.12 in the seven noise blocks. All participants started with the baseline block, and the order of the seven noise blocks was randomized between participants. Importantly, reduced click loudness should reduce the likelihood of the illusion (Andersen et al., 2004).

Analysis.

The current analysis focused on the dependent variables median reaction time (RT) and accuracy to incongruent audiovisual stimuli (A2V1), depending on the independent variable Noise (Baseline and seven levels of white noise stimulation). In case of incongruent audiovisual stimulation (A2V1), an error indicates the perception of the illusion, and therefore reduced accuracy indicates increased illusion rates. For both dependent variables, repeated-measures one-way ANOVAs were performed with a focus on the stimuli eliciting the SIFI (A2V1). The Mauchly test was used to verify the assumption of sphericity and the Greenhouse-Geisser correction was applied when necessary, to correct for non-sphericity. For these cases, the corrected degrees of freedom and p-values are reported. Generalized eta squared is used as a measure of effect sizes (Bakeman, 2005). Further analyses of the significant effects were performed using post-hoc paired t-tests.

If the data were not normally distributed (failing the Lilliefors test for normality of distribution) they were rank-ordered prior to the ANOVAs (Conover and Iman, 1981), and post-hoc Wilcoxon signed-rank tests were used to evaluate differences between conditions. The Holm-Bonferroni correction (Holm, 1979) was applied for the all the post-hoc pairwise comparisons. An alpha level of 0.05 was used for all statistical tests.

Results.

In the second experiment, we examined the illusion rate and reaction times to incongruent audiovisual stimuli in the sound-induced flash illusion with and without different levels of white noise stimulation. Importantly, the illusion rate is the inverse of the accuracy. To this end, we computed repeated-measures one-way ANOVAs with the factor Noise (no white noise in the baseline, and seven levels of white noise loudness).

Accuracy.

Illusion rates in the incongruent A2V1 condition were not normally distributed and therefore rank transformed. In the analysis of illusion rates, we found a main effect of Noise ($F(4.41,83.79) = 6.22$, $p_{GG} < 0.001$, $\eta^2_G = 0.076$), indicating lower illusion rates, i.e. higher accuracy for white noise stimulation (Figure 5, Table 2). Further comparisons between the conditions using Wilcoxon signed-rank tests with Bonferroni correction for multiple comparisons revealed lower illusion rates in the second ($V = 136$, $p = 0.013$), third ($V = 151$, $p = 0.013$), fourth ($V = 135$, $p = 0.016$) and sixth ($V = 135$, $p = 0.016$) noise level compared to the baseline condition. All other comparisons, and the comparisons between the noise levels were not significant. We further explored the influence of the noise level on the illusion rate using linear mixed effect models (package 'nlme' in R). A quadratic model ($F(1,138) = 35.43$, $p < 0.001$) fit the data better than a linear model (F1,139) = 4.27, $p = 0.04$), as indicated by the Akaike Information Criterion (AIC quadratic model = 1537.11, AIC linear model = 1564.37), further highlighting the u-shaped relationship between noise level and illusion perception (Table 3). Accuracy did not change with white noise stimulation in any other audiovisual stimulus combination.

RTs.

In contrast to the reduction in illusion rates, we did not find changes in RTs to the incongruent audiovisual A2V1 stimuli due to white noise stimulation ($F(4.25,80.77) = 0.931$, $p_{GG} = 0.45$, $\eta^2_G = 0.014$, Figure 6, Table 2).

Discussion.

Similar to previous reports (see Keil, 2020 for a review), we found roughly bistable perception, albeit with large variability between participants. In line with our hypothesis, white noise stimulation reduced the likelihood to perceive the illusion, i.e., in line with the first experiment, we found increased accuracy during white noise stimulation. Post-hoc exploration indicated a quadratic relationship between noise level and illusion rate, and a visual inspection of the data suggests the lowest illusion rate with intermediate noise levels (Figure 4). The latter observation is in line with the Moderate Brain Arousal model (Sikström & Söderlund, 2007). Previously, Andersen et al. (2004) reported that reducing the loudness of the auditory stimulus should decrease the SIFI illusion rate. However, whereas we find a general reduction of illusion rates with white noise stimulation compared to the baseline condition (i.e., a reduced loudness difference between the background noise and the auditory stimuli), we find the largest reduction of the illusion with intermediate background noise.

In contrast to the illusion rates, we did not find a systematic influence of white noise stimulation in the critical incongruent audiovisual condition (A2V1). This mirrors the results of experiment 1, in which also no effects of white noise stimulation on RTs were found.

General Discussion

Behavioral performance fluctuates over time (Esterman & Rothlein, 2019). Using white noise stimulation to increase arousal could enhance sensory processing, perception, and cognition (Moss et al., 2004). According to the Moderate Brain Arousal Model an optimal level of stimulation will increase the arousal and influence the tonic DA level, thereby improving perception (Sikström & Söderlund, 2007). Similarly, Aihara et al. (2010) propose an interaction between internal and external noise, in that external noise will improve perception if the internal noise is suboptimal. In two experiments, we tested the predictions of the MBA on visual perception, and we hypothesized that white noise stimulation will facilitate the perceptual separation of targets and distractors and thus optimize perception. First, we used a visual flanker task accompanied either with or without auditory stimulation to replicate the beneficial influence of white noise stimulation. We then extended this question to examine the influence of auditory white noise stimulation on a bistable audiovisual illusion. Overall, our results confirm our hypothesis of a beneficial influence of auditory white noise stimulation on performance. In the first experiment, we found a larger accuracy improvement from incongruent to congruent stimuli under white noise stimulation than without noise stimulation. In the second experiment, we found lower illusion rates, that means higher detection accuracy, under white noise stimulation than without noise stimulation.

A beneficial influence of white noise stimulation on different aspects of perception and cognition has been shown before. In an examination of visual contrast detection, increasing levels of continuous white noise stimulation systematically reduced the visual detection threshold (Gleiss & Kayser, 2014). In addition to decreasing luminance and contrast thresholds, auditory white noise also improved tactile perception (Lugo et al., 2008). However, strong auditory noise can also have a detrimental effect of the detection of weak visual signals, resulting in an inverted-u shaped relationship (Manjarrez et al., 2007). In line with the interaction between internal and external noise (Aihara et al., 2010), the optimal noise level also differed between participants. A similar inverted-u shaped relationship between noise and visual perception was found following transcranial random noise stimulation (Van der Groen & Wenderoth, 2015). Further support for the interaction between internal and external noise and the MBA comes from research on ADHD. For example, comparing children with and without ADHD in a visual Go/NoGo task indicated that white noise stimulation normalized the rate of omission errors of the children with ADHD (Baijot et al., 2016). Similarly, auditory white noise had a positive effect on the cognitive performance of children with ADHD, but a detrimental effect on the control group (Söderlund et al., 2007). In summary, in line with the idea of SR, noise stimulation appears to be beneficial for perception and cognition across a range of experimental paradigms. However, the influence of noise appears to depend on the individual internal state.

In line with the literature, we found an overall positive effect of auditory white noise stimulation on visual perception across the two experiments. Whereas we only used one level of noise in the first experiment, we used multiple noise levels in the second experiment. Post-hoc comparisons between the different noise levels and the baseline without noise stimulation indicated that the strongest effect was found with intermediate noise levels. However, in contrast to previous studies (Manjarrez et al., 2007; Gleiss & Kayser, 2014), we did not find pronounced differences between the noise levels. Despite using similar noise levels as previous studies, it is possible that interindividual differences, e.g., DA levels or cognitive flexibility between the participants overshadow the inverted-u relationship between noise level and performance (Cools & D'Esposito, 2011). Future studies could therefore pay closer attention to the individual performance to estimate the single participants' optimal noise level. In the analysis of the performance increase from incongruent to congruent stimuli, we found that auditory noise stimulation led to a larger improvement compared to no auditory noise stimulation. This finding from a flanker task extends previous evidence regarding the beneficial influence of noise stimulation on perception to a task involving higher-order cognitive processes. Importantly, in a Go/NoGo experiment, Baijot et al. (2016) did not find changes in performance in the control group. Moreover, in a memory task, Söderlund et al.

(2007) found a decrease in performance in the control group. Thus, the influence of white noise on cognitive processes beyond perception appears to be more diverse, with a possible inverted u-shaped relationship between noise level and performance, in which the optimal noise level differs between individuals. As in the second experiment, future studies could therefore extend the current findings to multiple levels of white noise stimulation and different experimental tasks to delineate the influence of white noise stimulation on various aspects of perception and cognition. In summary, our results confirm the proposed relationship between SR, arousal, and perceptual performance. However, closer examination of the optimal noise level in different tasks and between individuals is needed.

While the two experiments presented here extend the previous findings to new paradigms, the current results are limited. The sample in the first experiment is very small and the effects are relatively weak. To gain more confidence in the effect of auditory white noise stimulation on visual perception in the flanker task, the experiment should thus be replicated in a larger sample. Moreover, multiple noise levels should be used to allow a more detailed analysis. Whereas the second experiment used multiple noise levels, only small differences between the noise levels could be found. This might be due to the heterogeneous responses of the participants. Future studies should therefore again collect larger samples and examine individual performance optima. Moreover, future studies could also explore alternative types of auditory stimulation, such as pink noise or music.

Conclusion

In two experiments, we confirm our hypothesis that auditory white noise stimulation has a beneficial influence on visual perception. The current findings are in line with the idea of stochastic resonance and the predictions of the Moderate Brain Arousal model. Auditory stimulation could therefore be a promising way to optimize perception and performance.

Acknowledgement

Experimental code to replicate the second experiment, cleaned data for both experiments and R-code to reproduce the analyses is available in the public GitHub-Repository https://github.com/juliankeil/SIFINoise

References

Aihara, T., Kitajo, K., Nozaki, D., & Yamamoto, Y. (2010). How does stochastic resonance work within the human brain?–Psychophysics of internal and external noise. *Chemical Physics*, *375*, 616–624. http://doi.org/10.1016/j.chemphys.2010.04.027

Albrecht, B., Brandeis, D., Uebel, H., Heinrich, H., Mueller, U. C., Hasselhorn, M., et al. (2008). Action Monitoring in Boys With Attention-Deficit/Hyperactivity Disorder, Their Nonaffected Siblings, and Normal Control Subjects: Evidence for an Endophenotype. *Biological Psychiatry*, *64*(7), 615–625. http://doi.org/10.1016/j.biopsych.2007.12.016

Baijot, S., Slama, H., Söderlund, G., Dan, B., Deltenre, P., Colin, C., & Deconinck, N. (2016). Neuropsychological and neurophysiological benefits from white noise in children with and without ADHD. *Behavioral and Brain Functions*, 1–13. http://doi.org/10.1186/s12993-016-0095-y

Bakeman, R. (2005). Recommended effect size statistics for repeated measures designs. *Behavior Research Methods*, *37*(3), 379–384. http://doi.org/10.3758/bf03192707

Christiansen, H., Kis, B., Hirsch, O., Philipsen, A., Henneck, M., Panczuk, A., Pietrowsky, R., Hebebrand, J., Schimmelmann, B. (2011). German Validation of the Conners Adult ADHD Rating Scales–self-report (CAARS-S) I: Factor Structure and Normative Data. *European Psychiatry, 26*(2), 100-107. doi:10.1016/j.eurpsy.2009.12.024

Christiansen, H., Kis, B., Hirsch, O., Matthies, S., Hebebrand, J., Uekermann, J., Abdel-Hamid, M., Kraemer, M., Wiltfang, J., Graf, E., Colla, M., Sobanski, E., Alm, B., Rösler, M., Jacob, C., Jans, T., Huss, M., Schimmelmann, B.G., Philipsen, A. (2012). German validation of the Conners Adult ADHD Rating Scales (CAARS) II:

Reliability, validity, diagnostic sensitivity and specificity. *European Psychiatry, 27*(5), 321-328. doi:10.1016/j.eurpsy.2010.12.010

Christiansen, H., Hirsch, O., Abdel-Hamid, M., & Kis, B. (2014). Conners Skalen zu Aufmerksamkeit und Verhalten für Erwachsene (CAARStm). Göttingen, Germany: Hogrefe.

Conners, C.K., Erhardt, D., Sparrow, E.P., Conners' Adult ADHD Rating Scales (CAARS). North Tonawanda: Multi-Health Systems; 1999.

Conover, W. J., & Iman, R. L. (1981). Rank transformations as a bridge between parametric and nonparametric statistics. *The American Statistician*, *35*(3), 124–129. http://doi.org/10.1080/00031305.1981.10479327

Cools, R., & D'Esposito, M. (2011). Inverted-U-shaped dopamine actions on human working memory and cognitive control. *Biological Psychiatry*, *69*(12), e113–25. http://doi.org/10.1016/j.biopsych.2011.03.028

Esterman, M., & Rothlein, D. (2019). Models of sustained attention. *Current Opinion in Psychology*, *29*, 174–180. http://doi.org/10.1016/j.copsyc.2019.03.005

Gleiss, S., & Kayser, C. (2014). Acoustic Noise Improves Visual Perception and Modulates Occipital Oscillatory States. *Journal of Cognitive Neuroscience*, *26*(4), 699–711. http://doi.org/10.1371/journal.pone.0037190

Helps, S. K., Bamford, S., Sonuga-Barke, E. J. S., & Söderlund, G. B. W. (2014). Different Effects of Adding White Noise on Cognitive Performance of Sub-, Normal and Super-Attentive School Children. *PloS One*, *9*(11), e112768–10. http://doi.org/10.1371/journal.pone.0112768

Henninger, F., Shevchenko, Y., Mertens, U., & Kieslich, P. J. (2019). lab. js: A free, open, online study builder. *Psyarxiv.com*

Hirst, R. J., McGovern, D. P., Setti, A., Shams, L., & Newell, F. N. (2020). What you see is what you hear: Twenty years of research using the Sound-Induced Flash Illusion. *Neuroscience & Biobehavioral Reviews*, *118*, 759–774. http://doi.org/10.1016/j.neubiorev.2020.09.006

Holm, S. (1979). A simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics*, *6*(2), 65–70. http://doi.org/10.2307/4615733

Kopp, B., Rist, F., & Mattler, U. (1996). N200 in the flanker task as a neurobehavioral tool for investigating executive control. *Psychophysiology*, *33*(3), 282–294. http://doi.org/10.1111/j.1469-8986.1996.tb00425.x

Manjarrez, E., Mendez, I., Martinez, L., Flores, A., & Mirasso, C. R. (2007). Effects of auditory noise on the psychophysical detection of visual signals: cross-modal stochastic resonance. *Neuroscience Letters*, *415*(3), 231–236. http://doi.org/10.1016/j.neulet.2007.01.030

McLoughlin, G., Albrecht, B., Banaschewski, T., Rothenberger, A., Brandeis, D., Asherson, P., & Kuntsi, J. (2009). Performance monitoring is altered in adult ADHD: a familial event-related potential investigation. *Neuropsychologia*, *47*(14), 3134–3142. http://doi.org/10.1016/j.neuropsychologia.2009.07.013

Moss, F., Ward, L. M., & Sannita, W. G. (2004). Stochastic resonance and sensory information processing: a tutorial and review of application. *Clinical Neurophysiology*, *115*(2), 267–281. http://doi.org/10.1016/j.clinph.2003.09.014

Mullane, J. C., Corkum, P. V., Klein, R. M., & McLaughlin, E. (2009). Interference control in children with and without ADHD: a systematic review of Flanker and Simon task performance. *Child Neuropsychology : a Journal on Normal and Abnormal Development in Childhood and Adolescence*, *15*(4), 321–342. http://doi.org/10.1080/09297040802348028

Plenz, D., Ribeiro, T. L., Miller, S. R., Kells, P. A., Vakili, A., & Capek, E. L. (2021, February 18). Self-Organized Criticality in the Brain.

Ridderinkhof, K. R., Wylie, S. A., Wildenberg, W. P. M., Bashore, T. R., & Molen, M. W. (2020). The arrow of time: Advancing insights into action control from the arrow version of the Eriksen flanker task, 1–22. http://doi.org/10.3758/s13414-020-02167-z

Shams, L., Kamitani, Y., & Shimojo, S. (2000). Illusions. What you see is what you hear. *Nature*, *408*(6814), 788. http://doi.org/10.1038/35048669

Sikström, S., & Söderlund, G. (2007). Stimulus-dependent dopamine release in attention-deficit/hyperactivity disorder. *Psychological Review*, *114*(4), 1047–1075. http://doi.org/10.1037/0033-295X.114.4.1047

Söderlund, G. B. W., Sikström, S., Loftesnes, J. M., & Sonuga-Barke, E. J. (2010). The effects of background white noise on memory performance in inattentive school children. *Behavioral and Brain Functions*, *6*(1), 55–10. http://doi.org/10.1186/1744-9081-6-55

Söderlund, G., Sikström, S., & Smart, A. (2007). Listen to the noise: noise is beneficial for cognitive performance in ADHD. *Journal of Child Psychology and Psychiatry*, *48*(8), 840–847. http://doi.org/10.1111/j.1469-7610.2007.01749.x

Usher, M., & Feingold, M. (2000). Stochastic resonance in the speed of memory retrieval. *Biological Cybernetics*, *83*(6), L11–6. http://doi.org/10.1007/PL00007974

van der Groen, O., & Wenderoth, N. (2016). Transcranial Random Noise Stimulation of Visual Cortex: Stochastic Resonance Enhances Central Mechanisms of Perception. *The Journal of Neuroscience : the Official Journal of the Society for Neuroscience*, *36*(19), 5289–5298. http://doi.org/10.1523/JNEUROSCI.4519-15.2016

Zeng, F. G., Fu, Q. J., & Morse, R. (2000). Human hearing enhanced by noise. *Brain Research*, *869*(1-2), 251–255. http://doi.org/10.1016/s0006-8993(00)02475-6

Tables

Table 1

Mean Accuracy and RTs in Experiment 1

Congruency	Noise	Accuracy (SD)	RT (SD)
Incongruent	No Noise	0.72 (0.20)	342.09 (48.65)
Congruent	No Noise	0.98 (0.02)	277.84 (30.72)
Incongruent	White Noise	0.77 (0.14)	352.44 (26.98)
Congruent	White Noise	0.99 (0.01)	284.51 (29.59)

Note: Values represent means and SD of the dependent variables (accuracy and median RT) across participants.

Table 2

Mean Illusion Rate and RTs in Experiment 2

Condition	Block	Noise Level db(SPL)	Illusion Rate (SD)	RT (SD)
A2V1	Baseline	59.6	0.64 (0.32)	795.29 (211.73)
	Noise 1	63.0	0.36 (0.34)	786.53 (246.01)
	Noise 2	66.5	0.35 (0.38)	778.28 (269.17)
	Noise 3	69.3	0.36 (0.39)	716.83 (201.25)
	Noise 4	72.2	0.36 (0.36)	750.95 (248.61)
	Noise 5	74.1	0.39 (0.36)	768.00 (215.57)
	Noise 6	76.0	0.39 (0.34)	812.94 (277.43)
	Noise 7	78.0	0.45 (0.32)	788.15 (227.82)

Note: Values represent means and SD of the dependent variables (illusion rate and median RT) across participants.

Table 3

Summary of the linear mixed model analysis

Factor	Beta	Std. Error	DF	t-value	p-value
Linear Model					
Block	-1.76	0.85	139	-2.07	0.04
Quadratic Model					
Block	-20.53	3.24	138	-6.32	< 0.001
Block ^2	1.84	0.31	138	5.95	< 0.001

Figures

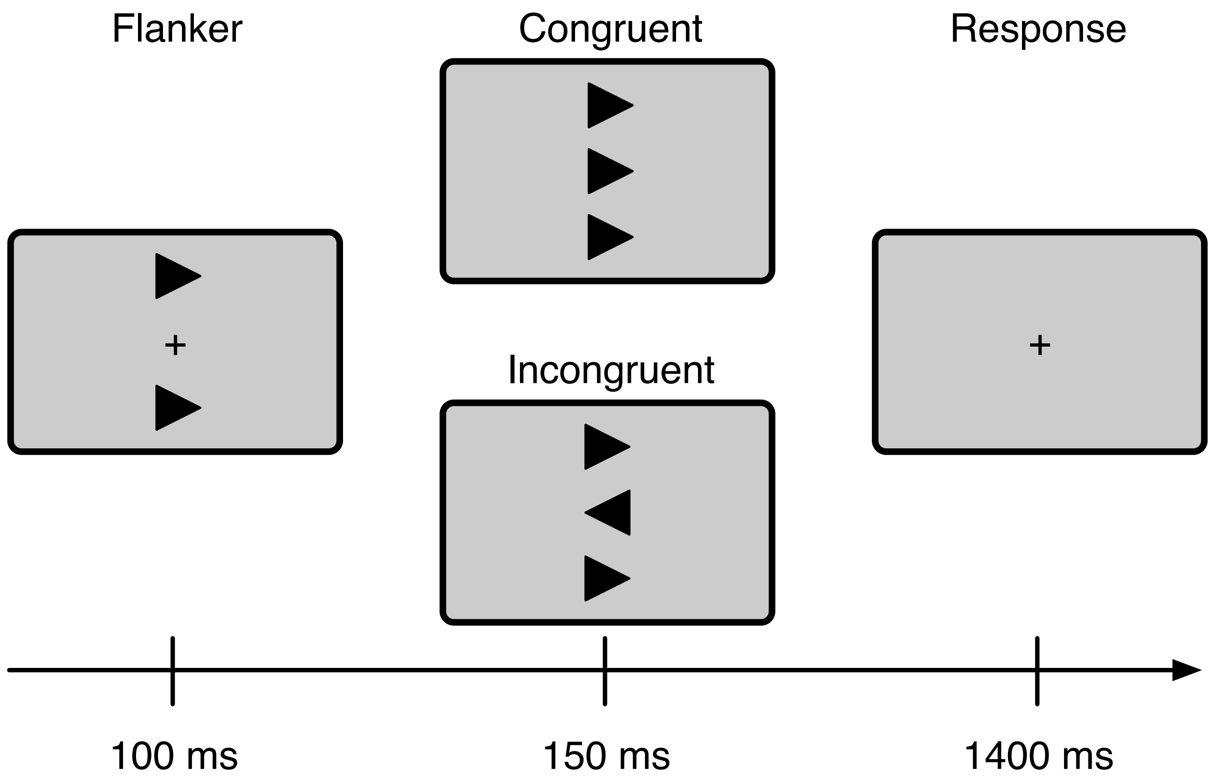

Figure 1. Experimental setup in the flanker task. Each trial started with the presentation of the flanking stimuli above and below a central fixation cross for 100ms. Next, either a congruent (i.e. an arrowhead pointing to the same direction as the flanker stimuli) or and incongruent (i.e. an arrowhead pointing to the opposite direction as the flanker stimuli) was presented between the flanker stimuli for 150 ms. Participants had 1400 ms to give their response before the next trial started.

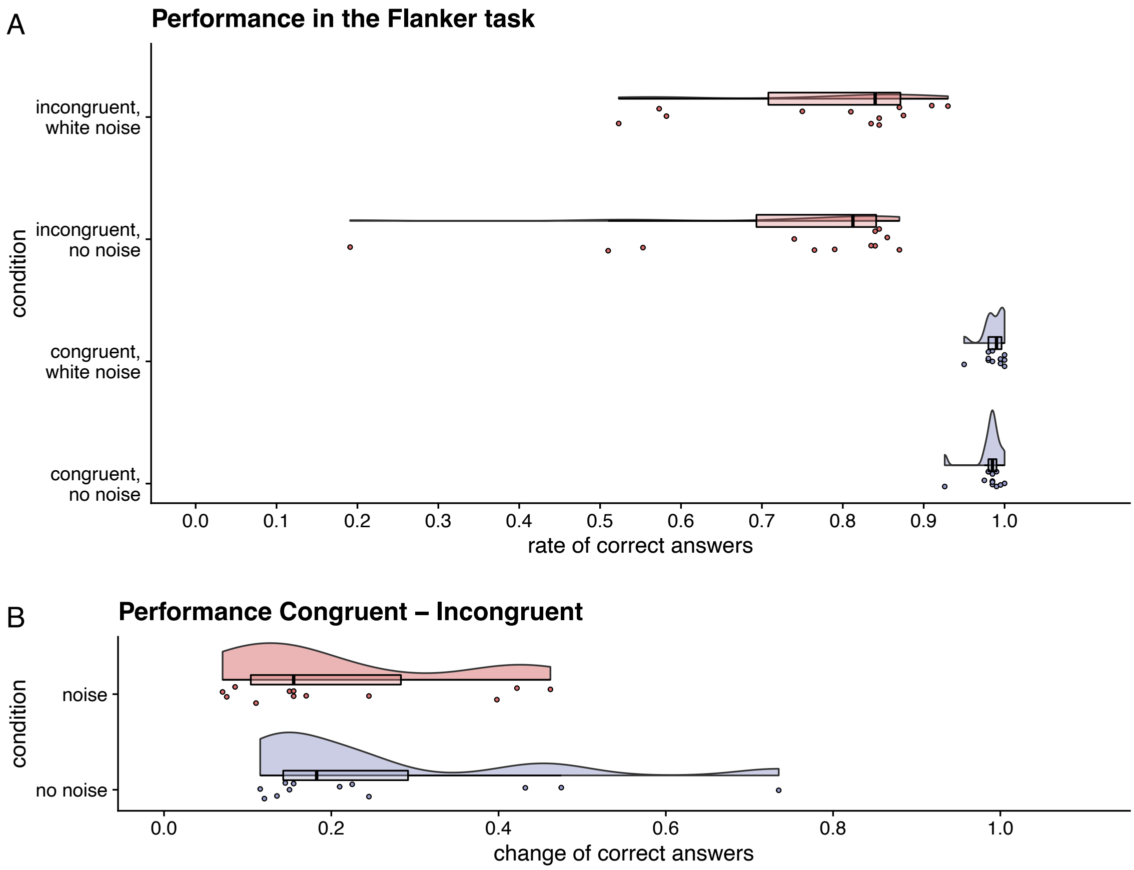

Figure 2. Performance in the flanker task. (A) The rate of correct answers for each combination of the factors Congruence and Noise. (B) The change in performance as the difference between congruent and incongruent stimuli for the two noise levels.

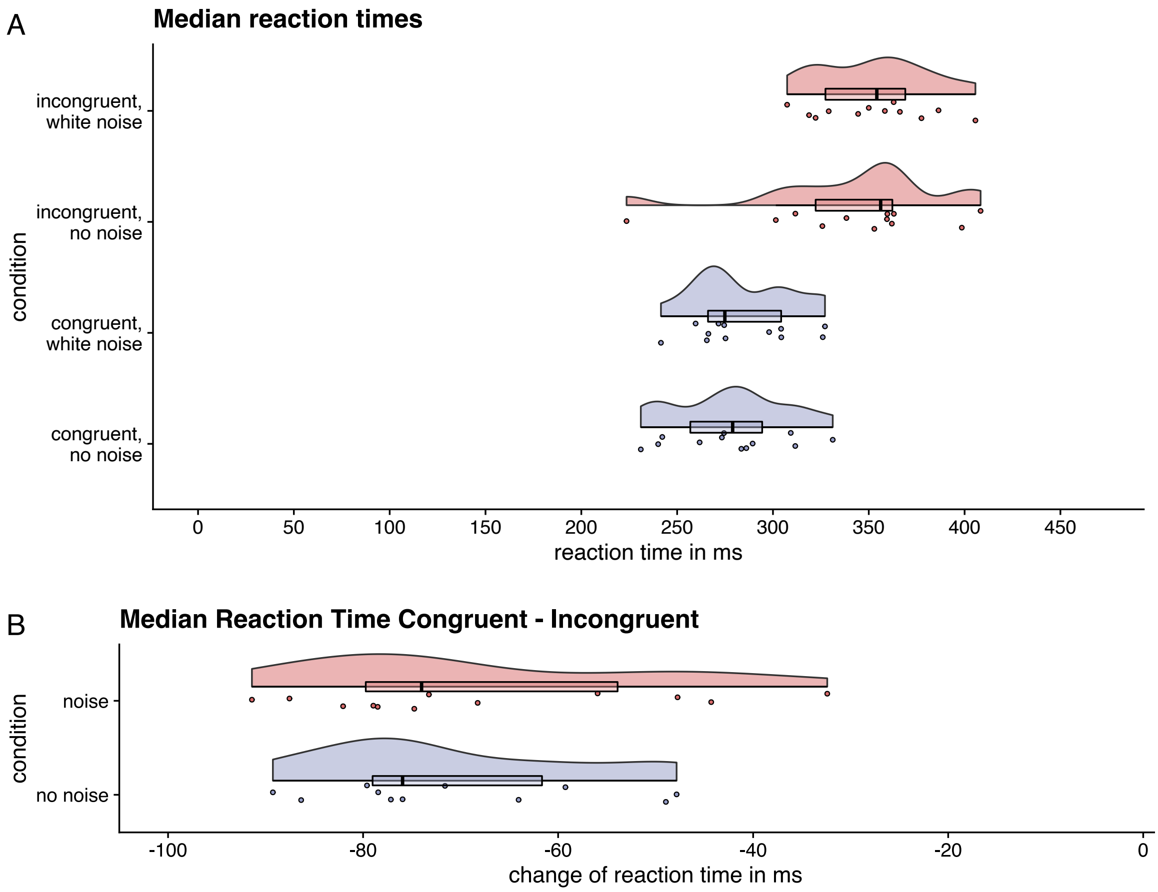

Figure 3. Reaction times in the flanker task. (A) The median RTs for each combination of the factors Congruence and Noise. (B) The change in RTs as the difference between congruent and incongruent stimuli for the two noise conditions.

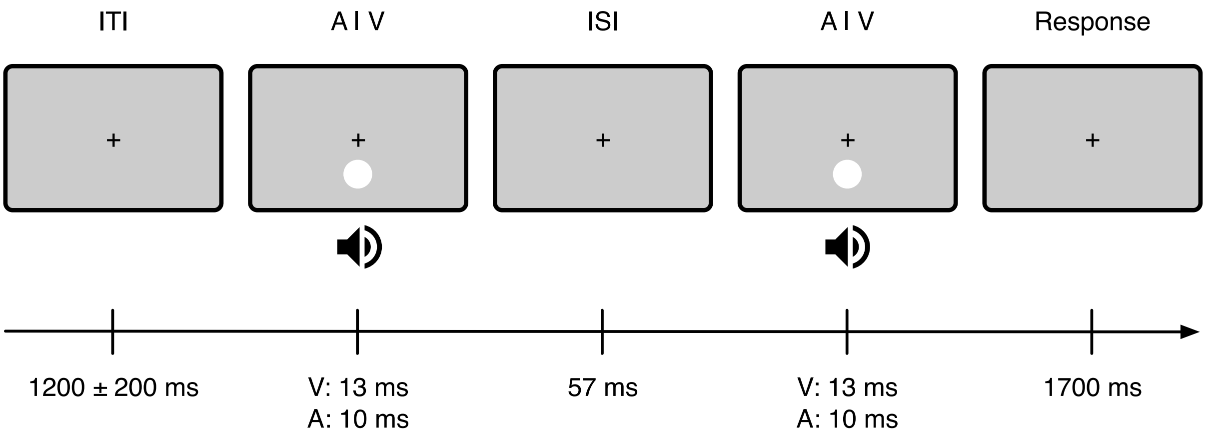

Figure 4. Experimental setup in the SIFI task. Each trial started with the presentation of the fixation cross for 1200 ± 200 ms. Next, the auditory and/or visual stimulus was presented (V: 13 ms, A: 10 ms). Following an inter-stimulus interval (ISI) of 57 ms (180 ms in case of A2V1late trials), the second auditory and/or visual stimulus was presented. Audiovisual stimuli were either congruent (i.e. the same number of auditory and visual stimuli) or and incongruent (i.e. different numbers of auditory and visual stimuli). Participants had 1700 ms to give their response before the next trial started.

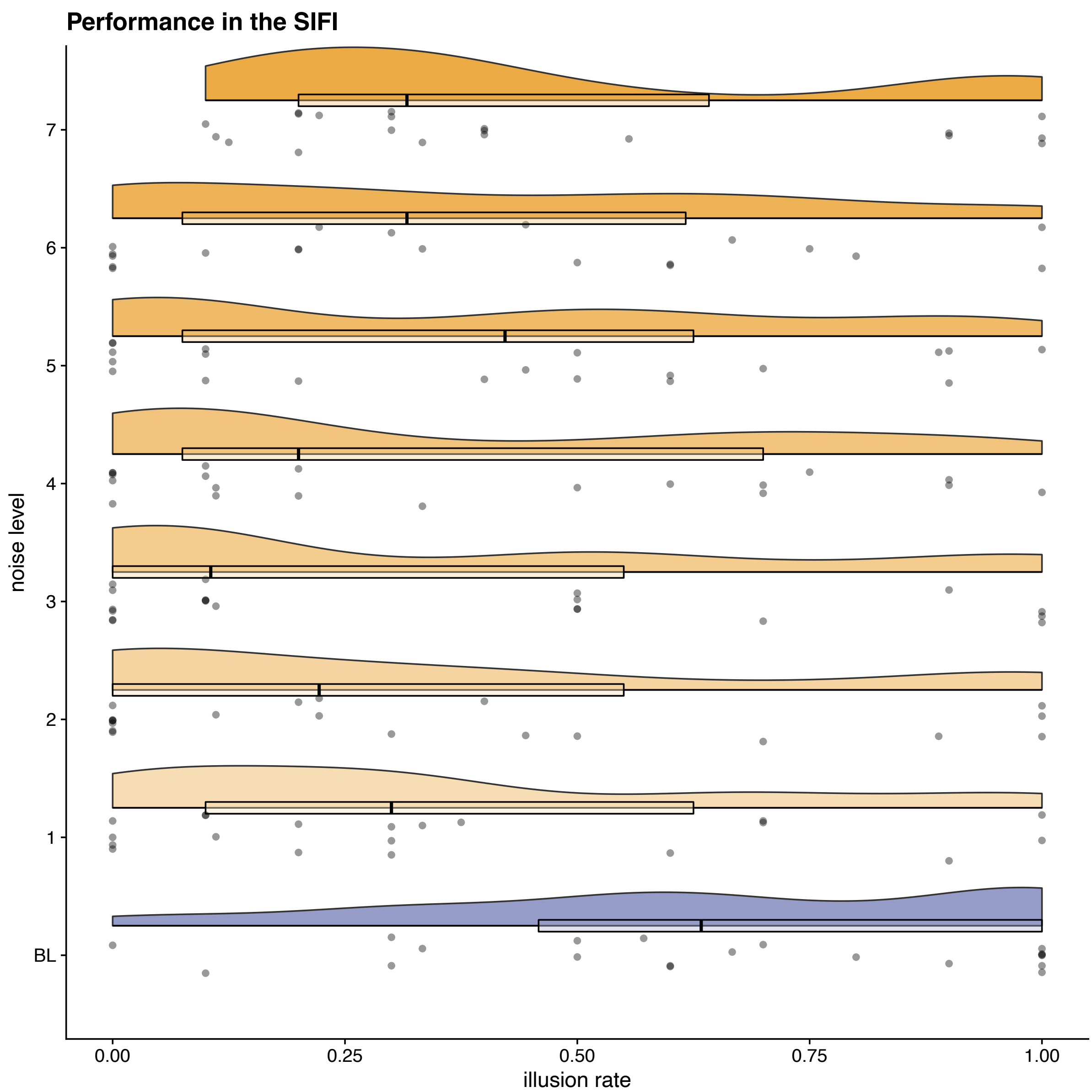

Figure 5. Illusion rates following incongruent audiovisual stimulation with two auditory and one visual stimulus (A2V1).

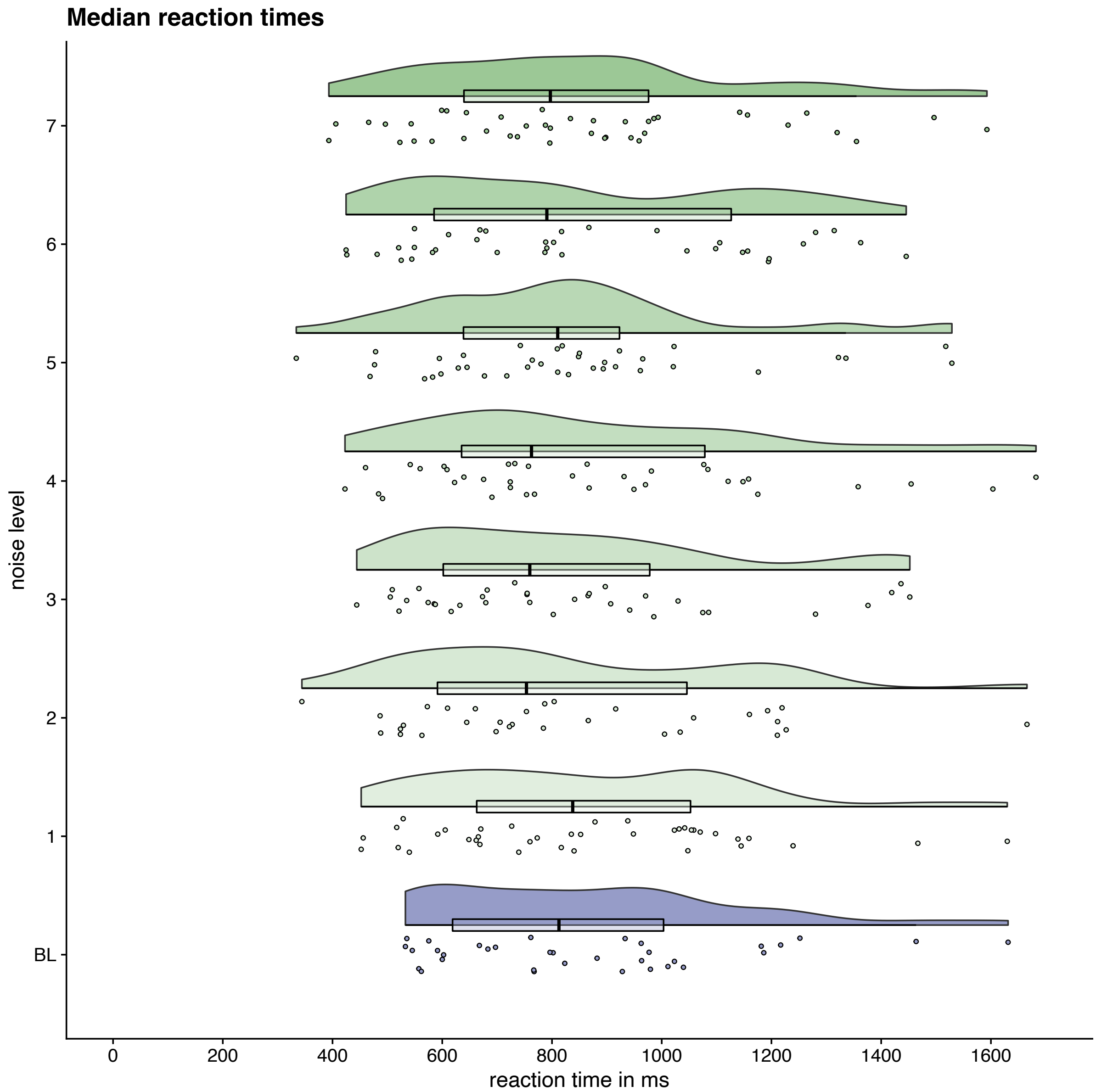

Figure 6. Reaction times following incongruent audiovisual stimulation with two auditory and one visual stimulus (A2V1). The median RTs for each level of the factor Noise.

Supplement

Supplementary Table 1

Lilliefors test results for experiment 1

Dependent Variable	Accuracy D	Accuracy *p*	Median RT D	Median RT *p*	Standard-deviation RT D	Standard-deviation RT *p*
Incongruent, No Noise	0.29	0.006**	0.171	0.428	0.25	0.037*
Congruent, No Noise	0.305	0.003**	0.127	0.859	0.25	0.036*
Incongruent, White Noise	0.254	0.032*	0.118	0.915	0.222	0.104
Congruent, White Noise	0.226	0.092	0.218	0.12	0.204	0.183

Note: D represents the maximal absolute difference between the empirical data distribution and the normal distribution. If the p-value is below the critical alpha level, the hypothesis of normality has to be rejected. * indicates $p < .05$, ** indicates $p < .01$.

Supplementary Table 2

Lilliefors test results for experiment 2

Block	Response	D	*p*
Baseline	0	0.538	0**
	1	0.164	0.172
	2	0.167	0.151
Noise 1	0	0.451	0**
	1	0.206	0.025*
	2	0.183	0.076
Noise 2	0	0.538	0**
	1	0.19	0.058
	2	0.182	0.08
Noise 3	0	0.463	0**
	1	0.254	0.001**
	2	0.287	0**
Noise 4	0	0.508	0**
	1	0.234	0.005**
	2	0.224	0.01**
Noise 5	0	0.509	0**
	1	0.171	0.128
	2	0.198	0.039*
Noise 6	0	0.524	0**
	1	0.129	0.517
	2	0.136	0.436
Noise 7	0	0.464	0**

Block	Response	D	*p*
	1	0.247	0.002**
	2	0.258	0.001**

Note: D represents the maximal absolute difference between the empirical data distribution and the normal distribution. If the p-value is below the critical alpha level, the hypothesis of normality has to be rejected. * indicates $p < .05$, ** indicates $p < .01$.