No reliable effect of task-irrelevant cross-modal statistical regularities on distractor suppression

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Abstract:

Our sensory systems are known to extract and utilize statistical regularities in sensory inputs across space and time for efficient perceptual processing. Past research has shown that participants can utilize statistical regularities of target and distractor stimuli independently within a modality either to enhance the target or to suppress the distractor processing. Utilizing statistical regularities of task-irrelevant stimuli across different modalities also enhances target processing. However, it is not known whether distractor processing can also be suppressed by utilizing statistical regularities of task-irrelevant stimulus of different modalities. In the present study, we investigated whether the spatial (Experiment 1) and non-spatial (Experiment 2) statistical regularities of task-irrelevant auditory stimulus could suppress the salient visual distractor. We used an additional singleton visual search task with two high-probability colour singleton distractor locations. Critically, the spatial location of the high-probability distractor was either predictive (valid trials) or unpredictive (invalid trials) based on the statistical regularities of the task-irrelevant auditory stimulus. The results replicated earlier findings of distractor suppression at high-probability locations compared to the locations where distractors appear with lower probability. However, the results did not show any RT advantage for valid distractor location trials as compared with invalid distractor location trials in both experiments. When tested on whether participants can express awareness of the relationship between specific auditory stimulus and the distractor location, they showed explicit awareness only in Experiment 1. However, an exploratory analysis suggested a possibility of response biases at the awareness testing phase of Experiment 1. Overall, results indicate that irrespective of awareness of the relationship between auditory stimulus and distractor location regularities, there was no reliable influence of task-irrelevant auditory stimulus regularities on distractor suppression.

Keywords:
attention, attention capture, distractor suppression, cross-modal, statistical regularities

Introduction

Our senses are bombarded with a vast number of sensory stimuli, at any given moment, from the external world and our body. In order to efficiently manage metabolic resources, our brain prioritizes the task or goal-relevant sensory information and ignores the task-irrelevant information. The set of processes involved in this optimization is referred to as selective attention. Prominent theories of selective attention have proposed that the selection of information in the environment is mainly dependent on two types of processes: top-down (aka goal-dependent) and bottom-up (aka stimulus-dependent) processes (Egeth & Yantis, 1997; Theeuwes, 2010a). Recently, numerous empirical studies have indicated various cognitive factors which can neither be categorized into top-down goals nor bottom-up processes to determine attentional selectivity (Awh et al., 2012; Theeuwes & Failing, 2020). Many of these cognitive factors are collectively referred to as "history-driven" influences on selective attention (Theeuwes & Failing, 2020). They hypothesized that top-down, bottom-up, and history-driven signals are projected onto a feature map representing selection priority to determine the selective behaviour of organisms (Theeuwes & Failing, 2020). Pertinent to this paper, we focus on the role of statistical learning, a history-driven cognitive mechanism, in attentional selection (Awh et al., 2012; Theeuwes & Failing, 2020; Wang & Theeuwes, 2018b).

Frost et al. (2015) defined statistical learning as the "extraction of distributional properties from sensory input across time and space" (Frost et al., 2015). They suggested that statistical learning is one of the critical cognitive processes in the perceptual processing of sensory inputs (Frost et al., 2015). Multiple previous studies indicated that sensory systems utilize the statistical regularities in the sensory input for efficient perceptual processing (for review, see Frost et al., 2019). For instance, targets (task-relevant) that frequently appear at a particular spatial location in visual search displays are perceptually processed better than targets at infrequent search locations (Awh et al., 2012; Chun & Jiang, 1998; Geng & Behrmann, 2002, 2005; Jiang et al., 2013). Whereas recent studies also suggested that the salient distractors (task-irrelevant) that frequently appear at a particular spatial location in visual search displays are perceptually suppressed by showing their reduced interference in visual search task performance (faster RTs) compared to distractors at infrequent search locations to enhance the task efficiency (Duncan & Theeuwes, 2020; Failing, Feldmann-Wüstefeld, et al., 2019; Failing, Wang, et al., 2019; Li & Theeuwes, 2020; Lin et al., 2020; Theeuwes et al., 2018; Wang, Samara, et al., 2019; Wang & Theeuwes, 2018a, 2018b, 2018c). For example, Wang &

Theeuwes (2018a) adopted a well-established additional singleton visual search paradigm developed initially by (Theeuwes, 1991, 1992) with few modifications in their study. In the classic additional singleton visual search task, participants are asked to search for a shape singleton (a diamond among circles or vice versa) while ignoring a colour singleton distractor. Typically, a reduced visual search task performance (slower RTs) is observed in colour singleton present trials compared to colour singleton absent. This RT cost trials is considered evidence for selective attentional priority of colour singleton distractors (Luck et al., 2020; Theeuwes, 1992, 2010b). In their study, Wang & Theeuwes (2018a) have shown that if the salient colour-singleton distractor more frequently appears at a particular spatial location in visual search displays, its interference in visual search task performance is reduced (faster RTs) compared to distractors at infrequent search locations. Thus, learning statistical regularities of distractor locations modulates attentional processes to enhance task efficiency. Moreover, such distractor statistical regularities improved search performance without the participants' awareness, suggesting that learning distractor regularities is implicit and influences perception independent of top-down control (Duncan & Theeuwes, 2020; Wang & Theeuwes, 2018b, 2018c). However, in recent studies utilizing similar probabilistic tasks, testing the awareness of statistical regularities with more sensitive measures indicated the evidence of explicit knowledge of awareness (Giménez-Fernández et al., 2020; Vadillo, Linssen, et al., 2020). These studies cast doubts on the implicit nature of learning distractor statistical regularities in additional singleton tasks.

Further, studies also indicate that the learning of distractor statistical regularities can be non-spatial and feature-specific (Failing, Feldmann-Wüstefeld, et al., 2019; Stilwell et al., 2019). For example, Stilwell et al. (2019) showed that a distractor colour that appears in search displays more frequently was suppressed efficiently compared with a less frequent distractor colour (Stilwell et al., 2019). Although the mechanisms of such distractor suppression are far from clear, recent studies suggest that the experience of distractor statistical regularities induce anticipatory or pro-active modulations in the first feedforward sweep of information processing that de-prioritize the most probable distractor locations (Huang et al., 2021; Wang, Driel, et al., 2019). Overall, there seems to be enough evidence to support the notion that our brain learns and utilize statistical regularities of both task-relevant and task-irrelevant sensory stimuli for optimizing behaviour.

While investigations of most previous research focused on understanding how statistical learning of visual objects influences selective attention, fewer studies have investigated the effects of such learning in cross-modal contexts (Chen et al., 2020, 2021; Kawahara, 2007; Nabeta et al., 2002). For example, in a cross-modal context, Chen et al. (2020) required their participants to search for a visual target in a task-irrelevant tactile stimulus context. The spatial location of the visual search target in each trial was either predictable or unpredictable based on statistical regularities of tactile stimuli (stimulated on participants' fingertips) embedded in the experimental trials. The search RTs for the visual target were faster in predictive compared to the un-predictive tactile context in their experiment 2. This finding suggests that task-irrelevant, cross-modal stimulus context can be processed and is utilized for improving performance in a visual search task. Critically, the experimental investigations in previous studies focussed on whether and how task-irrelevant, cross-modal stimulus statistical regularities that are indicative of visual search target location influence task performance. The current study aimed to investigate whether and how task-irrelevant, cross-modal stimulus statistical regularities that are indicative of salient visual distractor location influence task performance. If so, it would imply that the attentional system can be flexibly modified based on the task-irrelevant, cross-modal stimulus, regularities irrespective of whether they indicate a target or a distractor in visual search tasks.

We conducted two experiments in this study. The first experiment was designed to test whether the study participants learn to utilize task-irrelevant auditory spatial regularities, simultaneously presented across search displays, indicating the salient visual distractor's likely location influence visual search task performance. The second study was designed to test whether the task-irrelevant auditory non-spatial and frequency-based regularities, simultaneously presented across search displays, indicating the salient visual distractor's likely location influence visual search task performance. We adopted the additional singleton visual search paradigm developed initially by Theeuwes (1991, 1992) with few modifications. We manipulated statistical regularities of colour singleton distractor locations along with auditory stimulus spatial (Experiment 1) and non-spatial frequency-based (Experiment 2) regularities synchronously presented across search displays (see the methods section for more details). Critically, the spatial location of a colour singleton distractor in each trial could be either predicted or unpredicted based on the task-irrelevant auditory stimulus statistical regularities. For testing awareness about the relationship between auditory and visual distractor location regularities, we used the confidence rating scale and ranking method, adapted with slight modifications from the study by Vadillo et al. (2020). The confidence rating scale and ranking methods are, arguably, more sensitive measures for testing awareness than dichotomous "Yes" or "No" responses and/or indicating a particular location where participants believe that the target/distractor appeared most frequently (Giménez-Fernández et al., 2020; Vadillo, Linssen, et al., 2020). First, at the end of the experiment, each participant had to indicate whether they noticed the relationship between auditory and visual distractor location regularities on a scale of 1 to 6 (1= "Definitely not"; 6= "Definitely yes"). Second, participants were asked to rank three locations on the search display to indicate the high probability visual distractor for each sound stimulus separately (See the methods section for more details). The first, second, and third-ranked locations were given a score of 3, 2, and 1, respectively, and for all other locations, the score was zero. We assigned these locations into five categories (0-4) depending on their distance from the corresponding auditory stimuli that match the likely location of a salient visual distractor that is a "high-probability valid distractor location (HpValD)". For each participant, we then combined the data of two sound stimulus conditions to calculate the mean scores obtained by location according to the five categories mentioned above (0-4). We then analysed the linear relationship between mean scores received by each location from its distance from the actual HpValD location to test the awareness of audio-visual statistical regularities.

Hypothesis:

This study tests the hypothesis regarding whether and how task-irrelevant, cross-modal stimulus statistical regularities indicating the salient visual distractor's likely location in search displays influence search task performance in terms of response times (RTs). The graphical representation of the hypotheses is presented in Figure 1. We also tested participants' awareness of the relationship between auditory and visual distractor location regularities for Experiments 1 and 2.

Hypothesis #1: We hypothesized that if participants learn to utilize auditory stimulus statistical regularities to anticipate the likely location of a salient visual distractor (colour singleton distractor) in search displays, the distractor locations indicated by the auditory stimuli (valid distractor location trials) are perceptually suppressed by pro-active modulations in the first sweep of information processing to optimize the search efficiency (Huang et al., 2021; Wang, Driel, et al., 2019). The response times (RTs) were expected to be shorter for conditions where auditory stimuli match the likely location of a salient visual distractor that is "high-probability valid distractor location (HpValD)" compared to the condition where auditory stimuli do not match the likely location of a salient visual distractor that is "high-probability invalid distractor location (HpInValD)" condition.

Hypothesis #2: We hypothesized that if the participants are aware of the relationship between auditory and visual distractor location regularities, we expected that the score received by each location linearly decreases as its distance from the actual HpValD location increases.

Manipulation Checks: We have included ND ("No Distractor") with no sound stimuli trials and LpD ("Low probability distractor locations") with uninformative sound conditions as manipulation checks. The former condition associated with the search trials having no salient colour singleton and no sound stimulus — should produce faster search RTs compared to HpValD and HpInValD conditions. While the latter condition associated with the appearance of the salient visual distractor in infrequent search locations having uninformative sound stimulus — should produce slower search RTs compared to HpValD and HpInValD conditions.

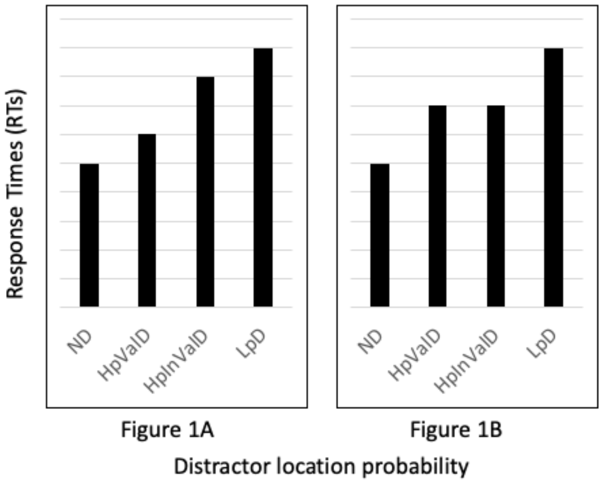

Figure 1. *Possible Experimental Outcomes. (1A) If auditory statistical regularities induce suppression of high probability valid distractor location processing, shorter RTs are expected in HpValD as compared to the HpInValD condition. (1B) If auditory regularities did not affect visual search behaviour, RTs are expected to be the same for HpValD and HpInValD conditions. ND ("No Distractor") = Distractor absent trials; HpValD (High probability valid distractor location)- high probability distractor location indicated by auditory regularities; HpInValD ("Hight probability invalid distractor location")= high probability distractor location not-indicated by auditory regularities. LpD ("Low probability distractor locations") = Low probability distractor locations with uninformative sound.*

Sampling plan:

Justification for the sample size to test hypothesis #1: The sample size was determined based on an a priori power analysis. In a previous study that is similar to the current experiments, Failing et al. (2019) reported an effect size of d = 0.602 by taking a difference between colour-match and colour-mismatch trials at two high-probability distractor locations. Relying on the effect size from the previous study at face value for an a priori power analysis is not recommended, as this might lead to underpowered studies (Dienes, 2021; Perugini et al., 2014). Therefore, to guard against the underpowered study, we determined the smallest effect size of interest as the lower limit of an 80% confidence interval for the effect size, by following the advice of Perugini et al. (2014).

The determined effect size of interest was 0.332, estimated using the Shiny R web app (Maxwell et al., 2018). Conducting an a priori power analysis with effect size d = 0.332, given alpha = 0.02 and power ≥ 90%, in a two-tailed matched-sample t-test, yields a minimum of 121 participants required to test hypothesis #1 for each proposed experiment (calculated using G*Power 3.1). This sample size is considerably larger than the typical experiments conducted using the additional singleton tasks (an average of around 26 participants in (Failing, Feldmann-Wüstefeld, et al., 2019; Wang & Theeuwes, 2018a, 2018b, 2018c)).

Justification for the sample size to test hypothesis #2: The sample size was determined based on an a priori power analysis. Most previous studies utilized dichotomous “Yes” or “No” responses and/or indicating a particular location where participants believe that the target/distractor appeared most frequently to test awareness of statistical regularities and concluded that the statistical learning is unconscious (e.g., in studies by (Failing, Feldmann-Wüstefeld, et al., 2019; Wang & Theeuwes, 2018b)). However, recent studies indicated that using a confidence rating scale and ranking methods are, arguably, more sensitive measures for testing awareness (Giménez-Fernández et al., 2020; Vadillo, Linssen, et al., 2020). Utilizing these sensitive measures to test awareness of statistical regularities in probabilistic cuing search tasks, the Vadillo et al. (2020) study indicated that participants are not unaware of the statistical regularities. Their study reported an effect size of Cohen's h = 0.57 for their meta-analysis of Experiments 1 and 2. However, choosing the effect size from the previous study at face value for an a priori power analysis is not recommended, as this leads to underpowered studies (Dienes, 2021; Perugini et al., 2014). To guard against the underpowered study, we determined the smallest effect size of interest as the lower limit of an 80% confidence interval for the effect size, by following the advice of Perugini et al. (2014).

The determined effect size of interest was 0.426, estimated using Shiny R web app (Maxwell et al., 2018). Conducting an a priori power analysis with effect size of d = 0.426, given alpha = 0.02 and power ≥ 90%, in a two-tailed matched-sample t-test yields a minimum of 75 participants required to test hypothesis #2 for each proposed experiment (calculated using G*Power 3.1).

Participant selection criteria:

Selected participants reported normal hearing and colour vision and normal or corrected to normal visual acuity with an age range from 18 to 35 years. Additionally, we tested whether the participants could discriminate the spatial location of sound (left and right) in experiment 1. In Experiment 2, we tested whether participants could discriminate between two different sound frequencies (500Hz & 1000Hz). A short two-alternative forced choice, 20 auditory-only trials were presented to the participants to judge the sound location (e.g., Left or Right) or sound frequency (e.g., Low or High). Those participants who showed a minimum of 75% accuracy were selected for participation in the experiment. Selected participants provided informed consent before they participated in the study. The experimental procedures were approved by the Institutional Ethics Committee (IEC) of the Indian Institute of Technology Gandhinagar, India.

Materials:

The experiments were conducted in a dim-lit room. All the experimental stimuli were created and presented using MATLAB with Psychophysics Toolbox extensions (Brainard, 1997). The visual stimuli were shown on an LCD monitor with a black background. Figure 2 shows the schematic of a visual search display consisting of eight shapes (e.g., one diamond and seven circles) presented on an imaginary circle with a radius of 4 degrees centred at the white fixation cross (1×1 degree). Each unfilled shape (circle subtended with 1-degree radius, diamond subtended with 2 × 2 degrees) contains an embedded grey line (0.3 × 1.5 degrees, RGB:127/127/127) oriented either horizontally or vertically. The colour of the shapes in the search displays were red (RGB: 255/0/0) and green (RGB: 0/255/0). For example, the displays contain one circle in red, and the remaining all shapes in green or vice versa (50% probability). The auditory stimulus in Experiment 1 was a burst of white noise (50ms duration) presented via speakers placed on the left and right sides of the LCD screen. In experiment 2, auditory stimuli consist of two pure tones (50ms duration) with 500Hz or 1000Hz frequency presented via headphones. The sound level was adjusted for each participant according to their comfort at the beginning of the experiment and was kept constant throughout the experiment.

Experiment 1:

Experiment 1 aimed to test whether participants learn to utilize the task-irrelevant auditory stimulus spatial regularities, simultaneously presented across search displays, indicating salient visual distractor 's likely location influences visual search task performance. We hypothesized that if participants learn to anticipate the salient distractor locations indicated by the auditory stimuli (valid distractor location trials), the valid distractor locations would be perceptually suppressed according to the pro-active distractor suppression account, thereby impairing the distractor interference in visual search tasks (Huang et al., 2021; Wang, Driel, et al., 2019).

Procedure and design for Experiment 1:

Each trial started with a fixation cross and was presented until the trial ends. 500ms after the fixation cross onset, the visual search display was presented for 2000ms or until the participant makes a response (<2000ms). The participants were instructed to search for a shape singleton in displays. For example, participants were asked to search for a diamond shape among circles or vice versa and respond to the line segment's orientation embedded in that target shape. If the orientation of the line segment was horizontal, the participants were required to press the "Z" key, and if the line segment was vertical, the participants were required to press the "M" key as soon as possible. Participants were asked to press the response key quickly and accurately. The target (shape singleton) was present in all the trials, and the target was either circle or diamond with equal probability. A blank display presented with intertrial interval (ITI) was randomly determined between 500ms to 750ms. The timed-out responses were considered as incorrect responses. In cases of incorrect responses and timed-out responses, feedback was provided to the participants with white text "Incorrect response" or "Timed-out", respectively, at the center of the LCD screen for 1000ms. Feedback was not provided for the correct responses. Two critical design factors were important in the experiment regarding the experimental manipulations of additional (color) singleton distractor location and the auditory stimulus across the trials.

Additional singleton distractor and search target manipulations: All search elements were red or green with equal probability in one-sixth of the trials ("distractor-absent trials"). In the remaining trials, one of the distractors had the same shape as other distractors but with a unique color (red among green distractors or vice versa with equal probability). These trials were labelled as additional singleton distractor-present trials or simply "distractor-present trials". The additional singleton distractors were presented at any one of the eight search locations in distractor present trials. However, the additional singleton distractors were more likely to appear in two search locations (31.25 % each) and less likely (6.25 %) in each of the remaining six search locations in the search display. The high probability distractor locations were positioned such that one of the high probability distractor locations is on the left hemifield and the other is on the right hemifield with a maximum distance between them (i.e., they are at opposite locations on the imaginary circle). These two high-probability distractor locations were fixed for each participant and counterbalanced across participants. Figure 2 shows the schematic illustration of search displays. The target appears with equal probability and randomly in the distractor-absent trials at each search location. However, in distractor present trials, the target's location was randomly determined such that it does not coincide with the additional singleton distractor location.

Auditory stimulus manipulations: No auditory stimulus was presented to the participants for the distractor-absent trials. However, for the distractor-present trials, an auditory stimulus was presented simultaneously with the search display. There were two critical manipulations in the auditory stimulus presentations. First, when the additional singleton distractor appears in one of the two high-probability search locations, the auditory stimulus was more likely (80 %) presented at the spatially congruent side of the distractor location (left or right hemifield) and less likely (20 %) presented at the spatially incongruent side. Second, when the additional singleton distractor appears at one of the low-probability distractor locations, the auditory stimulus was presented by both left and right-sided speakers. Thus, the auditory stimulus is virtually perceived to be coming from the center of the search display. This makes the auditory stimulus uninformative about the distractor location in the search display.

The combination of the additional singleton distractor and auditory stimulus manipulations in the trials generate the following four different experimental conditions:

a) No distractor trials with no auditory stimulus ("no-distractor" condition)
b) Distractor appears in one of the two high probability locations with auditory stimulus location match ("high-probability valid distractor location")
c) Distractor appears in one of the two high-probability locations with auditory stimulus location mismatch ("high-probability invalid distractor location")

d) Distractor appears in one of the low-probability locations with the uninformative auditory stimulus (“low-probability distractor location”)

The experiment started with 20 practice trials and 6 experimental blocks of 192 trials each. The color of the additional singleton (red or green) and the orientation of the line segment (horizontal or vertical) embedded in the target shape were presented randomly with equal probability in each experimental block. A 30-second break was given to participants after completing each experimental block.

Testing participants’ awareness of statistical regularities: To determine whether participants were aware of the relationship between auditory and visual distractor location regularities, all participants had to answer forced-choice questions at the end of the experiment (See supplementary materials section). First, participants were asked to indicate whether they had noticed regularities in the sound location such that the sound stimulus location most frequently matched the color distractor location in display on a rating scale from 1 to 6. Second, participants were informed that each sound stimulus location (Left or Right) was most frequently matched with a specific color distractor location in display and were asked to rank three such locations for each sound stimulus location separately. The rating scale and ranking methods are, arguably, more sensitive measures for testing awareness than dichotomous “Yes” or “No” responses and/or indicating a location where participant believes that the target/distractor appeared most frequently (Giménez-Fernández et al., 2020; Vadillo et al., 2020).

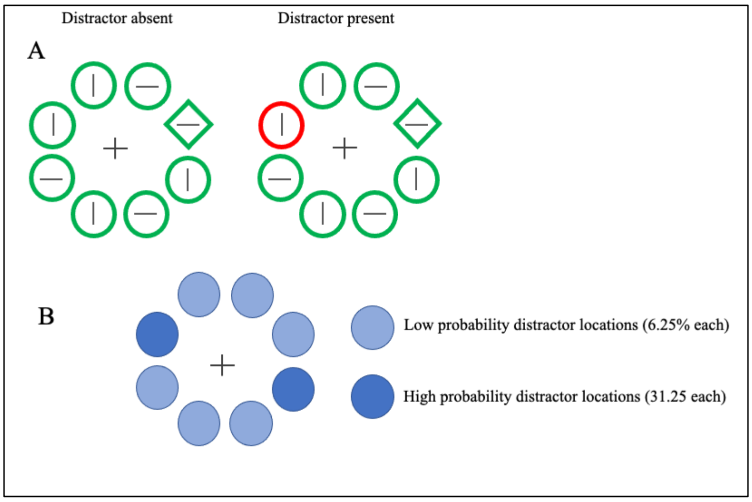

Figure 2. *(A) Schematic illustration of search displays. The participant's task is to search for a Shape-singleton. In distractor present trials, participants will be instructed to ignore the colour-singleton distractor. (B) Schematic illustration of spatial regularities of distractors. Low-probability distractor locations are shown in light blue, and high-probability distractor locations are shown in dark blue. Note: the schematic display is not drawn to the scale/color.*

Experiment 2:

Experiment 2 aimed to test whether the study participants learn to utilize the task-irrelevant auditory non-spatial, frequency-based statistical regularities, simultaneously presented across search displays, indicating salient visual distractor's likely location influence visual search task performance. Like Experiment 1, we hypothesized that the salient distractor locations indicated by the auditory stimuli (valid distractor location trial) would be perceptually suppressed according to the pro-active distractor suppression account, thereby impairing the distractor interference in visual search tasks (Huang et al., 2021; Wang, Driel, et al., 2019).

Procedure and Design for experiment 2:

The experimental procedure and design were same as Experiment 1, except the following changes to auditory stimulus presentations. In Experiment 2, auditory stimuli consist of two pure tones (50ms duration) with either 500 or 1000 Hz frequency presented via headphones. No auditory stimulus was presented to the participants for distractor-absent trials. However, for distractor-present trials, an auditory stimulus was presented simultaneously with the search display. There were two critical manipulations in the auditory stimulus presentations. First, when the additional singleton distractor appears in one of the two high-probability search locations, the auditory stimulus was more likely to be (80%) presented with one of the two pure tones (e.g., 500Hz frequency tone) and less likely to be (20%) presented with the other pure tone (e.g., 1000Hz frequency tone) and vice versa. Second, when the additional singleton distractor appears at one of the low probability distractor locations, the auditory stimulus was a noise burst with a 50ms duration.

Like Experiment 1, the combination of the additional singleton distractor and auditory stimulus manipulations in the trials generate the following four different experimental conditions:

a) No distractor trials with no auditory stimulus (“no-distractor” condition)
b) Distractor appears in one of the two high probability locations with auditory stimulus feature match (“high-probability valid distractor location”)
c) Distractor appears in one of the two high- probability locations with auditory stimulus feature mismatch (“high-probability invalid distractor location”)
d) Distractor appears in one of the low-probability locations with the uninformative auditory stimulus (“low-probability distractor locations”)

Testing participants’ awareness of statistical regularities: The questionnaire for the experiment 2 was similar to Experiment 1 mentioned above, except that we used text sound pitch, either high or low, instead of the text mentioning the right or left sound locations.

Participant and data replacement:

Any of the following criteria were used to replace a given participant in both Experiments:

1) The participant performed the task with less than 75% accuracy. This would suggest that the participant is either not engaged in the task or not understood the instructions.
2) Any participant voluntarily chooses not to perform the task at any time before completing the experiment.

Data analysis:

Identical but separate data analysis performed for Experiments 1 and 2. The incorrect responses and response times (RTs) shorter than 200ms were discarded before performing statistical analysis on RT data. If assumptions of normality and sphericity are violated, appropriate non-parametric tests and sphericity corrections (Greenhouse-Geisser correction) were applied to the statistical results.

Analysis of Response times (RTs): As mentioned in Figure 1, the relevant comparison was to test whether auditory regularities influence distractor suppression. For this comparison, we used paired t-tests to compare experimental conditions of "high-probability valid distractor location" and "high-probability invalid distractor location".

Analysis of participants' awareness of regularities: We calculated the mean rating for Question #1 in the questionnaire for the awareness test (see the supplementary materials). As mentioned in the methods above, all participants were asked to rank three locations for each sound stimulus condition separately (Question #2 & Question #3). The first, second, and third-ranked locations were given scores of 3, 2, and 1, respectively. The remaining locations were given the score of zero. We assigned these locations into five categories (0-4) depending on their distance from the corresponding HpValD location. For example, 0 corresponds to the HpValD location, 1 corresponds to two locations immediately next to the HpValD location, and so on. For each participant, we then combined the data from Question #2 & Question #3 to calculate the mean scores obtained by location according to the five categories mentioned above (0-4). To analyse the data used a linear mixed-effects model with a random intercept for participants to determine a linear relationship between scores obtained by each location and their distance from the HpValD location (0-4).

Predicted Outcomes:

The experimental question was whether the task-irrelevant auditory regularities indicative of the additional singleton location in the visual search display modulates the search efficiency. Suppose the auditory regularities indeed generated the predictions for the likely distractor location. In that case, these distractor locations (in "high-probability valid distractor location") could be perceptually suppressed, and the RTs in those trials expected to be shorter than invalid distractor locations (in "high-probability invalid distractor location" trials).

Likewise, in Experiment 2, RTs were expected to be shorter for high-probability valid distractor location trials (indicated by sound feature) than for high-probability invalid distractor location trials. Figure 1 shows the graphical representation of experimental predictions.

Results and Discussion of Experiment 1:

Pre-registered analysis:

In accordance with participant selection criteria, a total of 132 participants who were able to discriminate the spatial location of sound (left and right) with a minimum of 75% accuracy were recruited for the Experiment 1 (Mean % accuracy ± SEM: 97.8030 ± 0.3697). Out of these, we excluded the data of 8 participants who failed to achieve a minimum of 75% overall accuracy in the search task (pre-registered criteria). The remaining data from 124 participants were included for further analysis. Although we pre-registered to have a minimum sample of N = 121 for Experiment 1 , our total sample that included for the statistical analysis was N=124 after counter-balancing the two High-probability Distractor Locations in the search displays across participants. We performed statistical tests after we collected the data of 124 participants who achieved a minimum of 75% overall accuracy in the search task.

Mean correct RTs were used for the statistical testing after removal of incorrect responses (including timed-out trials, 9.47% of total trials) and response times shorter than 200ms (0.4% of total trials). All the statistical analyses were performed using JASP, an open-source statistical software (Team, 2022). In cases where the sphericity assumption was violated for tests of repeated measures of ANOVA, the reported p-values are Greenhouse-Geisser corrected. Similarly, in cases where the assumption of normality was violated (Shapiro-Wilk test) for paired t-tests, the reported p-values were obtained by Wilcoxon signed-rank tests. In accordance with the pre-registered analysis plan, a statistical significance threshold of 0.02 was used to interpret the results.

RT analysis:

The paired samples T-test between mean RTs of experimental conditions HpValD and HpInValD revealed a non-significant difference between them (HpValD: 1022.227ms ± 12.340 SEM; HpInValD:1023.794ms ± 12.637 SEM; $t(123) = 0.624$, $p = 0.691$, $r_b = 0.041$). These results indicate that the valid distractor locations (distractor appears in one of the two high probability locations with auditory stimulus location match) were not perceptually suppressed relative to the invalid distractor locations (distractor appears in one of the two high probability locations with auditory stimulus location mismatch). Figure 3 shows the mean RTs and percent of incorrect responses for all experimental conditions in Experiment #1.

Awareness test:

Figure 4 provides the responses received by participants for Question #1 in the Questionnaire for testing awareness of statistical regularities. When participants were asked whether they had noticed that a given sound location frequently matched with a distractor location in search displays, the modal response was “probably yes”. The average response (± SD) on a scale of 1 to 6 is 3.298 ± 0.1145 SEM. Overall, participants were less confident in their responses in both directions.

Following the pre-registered protocol, we calculated the mean scores obtained by each location based on five categories (0-4) for each participant. Figure 5 (Left panel) summarizes mean scores for each of the five categories (0-4). A linear mixed effects model with random intercepts for participants indicated that the mean scores for each location were significantly decreased linearly as a function of its distance from the HpValD location ($b= -0.136$, $t(618)= -8.113$, $p < 0.001$). These results suggest that the participants are aware of the relationship between auditory stimulus location and visual distractor location regularities in Experiment #1.

Non-Pre-registered analysis:

We explored whether colour singleton distractors interfere with search task when the distractor is present in low and high-probability distractor locations (regardless of sound stimulus manipulations in the experiment) relative to the distractor-absent trials. This exploratory analysis was intended to see whether the data replicated the distractor suppression effects typically observed in prior studies (e.g., Wang & Theeuwes, 2018). For each participant, we calculated mean search RTs for distractor absent trials (ND), distractor-present trials in low probability locations (LpD), and distractor-present trials in high probability locations (HpD; combined HpValD and HpinValD trials). Mean RTs were submitted to a one-way repeated-measures of ANOVA with the experimental condition of interest (ND vs. LpD vs. HpD) as a factor. The analysis indicated a significant main effect of condition, $F(2, 246)= 664.12$, $p < 0.001$, partial $\eta^2 = 0.844$. Relative to mean RTs on no-distractor trials (944.1ms

$\pm$ 12.118 SEM), the mean RTs were significantly slower in the HpD condition (1022.55ms $\pm$ 12.537 SEM, $p < 0.001$, $r_b = 0.981$), and LpD condition (1059.461ms $\pm$ 12.410 SEM, $p < 0.001$, $r_b = 0.999$). Moreover, RTs in the LpD condition were significantly slower than RTs in the HpD condition ($p < 0.001$, $t(123) = 16.197$, Cohens' d= 1.455). A similar analysis was conducted on the percentage of incorrect responses in each condition of interest. The one-way repeated measures of ANOVA indicated a significant main effect of condition, $F(2, 246) = 166.053$, $p < 0.001$, partial $\eta^2 = 0.574$. Relative to the percentage of incorrect responses on no-distractor trials (6.746% $\pm$ 0.482 SEM), incorrect responses were significantly higher in the HpD condition (9.761% $\pm$ 0.574 SEM, $p < 0.001$, $r_b = 0.910$), and LpD condition (11.136% $\pm$ 0.600, $p < 0.001$, $r_b = 0.967$). Moreover, the percentage of incorrect responses were significantly higher in the LpD condition than in the HpD condition ($p < 0.001$, $t(123) = 7.278$, Cohens' d= 0.654). This pattern of results indicates that the response time differences among conditions were not due to the speed-accuracy trade-off. Overall, results indicate that the singleton distractors indeed capture attention and interfere with search tasks indicated by slower RTs in search displays when the distractor was present compared to when it was absent. Further, this effect was improved when distractors were present in high-probability locations compared to low-probability locations which indicates the better suppression of distractors at high-probability locations compared to low-probability locations.

We conducted paired t-test on the mean percent of incorrect responses between HpValD and HpInValD conditions to check if the observed non-significant difference in mean RTs of HpValD and HpInValD were due to speed-accuracy trade-off. We found a non-significant difference in the mean percent of incorrect responses between HpValD condition (9.511% $\pm$ 0.528 SEM) and the HpInValD condition (9.590% $\pm$ 0.559 SEM, $p = 0.696$, $t(123) = 0.313$, Cohens' d = 0.028). These results indicate that the non-significant difference in mean response times between HpValD and HpInValD was not a consequence of the speed-accuracy trade-off.

Next, we conducted one-way repeated measures of ANOVA on mean RTs in all experimental conditions (ND vs. HpValD vs. HpInValD vs. LpD). This analysis was intended to test whether the data passed the pre-registered outcome-neutral criteria (i.e., absence of floor and ceiling effects). There was a main effect of experimental condition, $F(3, 369) = 436.441$, $p < 0.001$, partial $\eta^2 = 0.780$. Bonferroni corrected post-hoc test revealed that RTs were significantly faster in ND compared to all other conditions (all $p < 0.001$), and RTs were significantly slower in LpD compared to all other conditions (all $p < 0.001$). Similarly, the mean percentage of incorrect responses was significantly lower in ND compared to all other conditions (all $p < 0.001$), and the percentage of incorrect responses were significantly higher in LpD compared to all other conditions (all $p < 0.001$). These results indicate that data passed the pre-registered outcome-neutral criteria and ensure that the experimental results can test the stated hypothesis proposed in the pre-registered protocol.

Next, RT performance analysed in terms of epochs rather than taking mean performance per experimental condition. The epoch-wise analysis would reveal if there are any significant RT differences between valid and invalid distractor location trials as the duration of Experiment progresses. The mean RT performance was then calculated across six consecutive experimental blocks per condition (valid and invalid distractor trials) for each participant. Figure 7 (left panel) in shows the mean RTs as a function of epochs, separately for valid and invalid distractor trial conditions. We submitted mean RTs to repeated measures of ANOVA with factors Validity (Valid vs. Invalid distractor trials) and Epochs (1 to 6). The results revealed a significant main effect of Epoch, $F (5, 615) = 299.131$, $p < .001$, $r_b = 0.709$. However, there was no significant main effect of Validity ($p = 0.324$) or Validity × Epoch interaction ($p = 0.904$) on the mean RTs. These results indicate that RT performance did not significantly differ between the valid and invalid distractor location trials across Epochs, corroborating the lack of evidence supporting distractor suppression effects by statistical regularities of cross-modal stimuli.

Finally, we conducted Bayesian paired samples t-test to compare the mean RTs of HpValD and HpInValD. The Bayesian analysis used to obtain the relative strength of null and alternative hypothesis, and degree to which either hypothesis supported by the data (Dienes, 2019). The Bayesian analysis results supported the null hypothesis of no difference between mean RTs of HpValD and HpInValD more likely than the alternate hypothesis ($BF_{01} = 8.2885$). The Bayesian analysis performed using JASP software with a default Cauchy prior of 0.707.

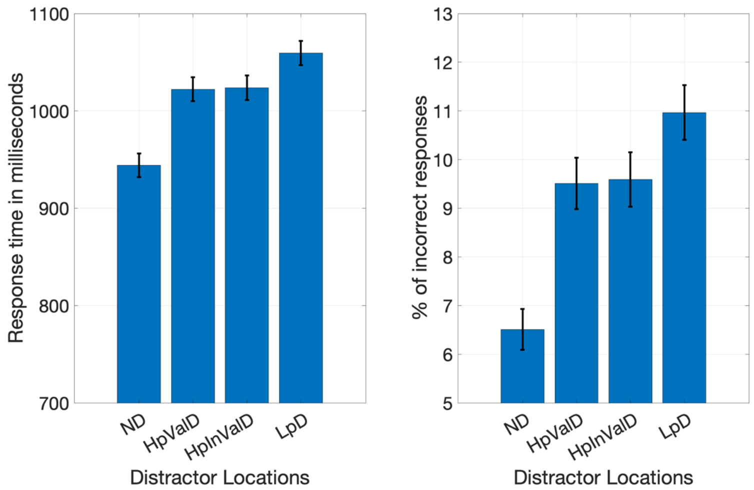

Figure 3. Mean response times (left panel) and percent of incorrect responses (right panel) for experiment 1. ND = No distractor trials; HpValD = Trials with the distractor appeared in one of the two high probability locations with auditory stimulus location match; HpInValD = Trials with the distractor appeared in one of the two high probability locations with auditory stimulus location mis-match; LpD = Trials with the distractor appeared in low probability locations. Error bars indicate ± SEM.

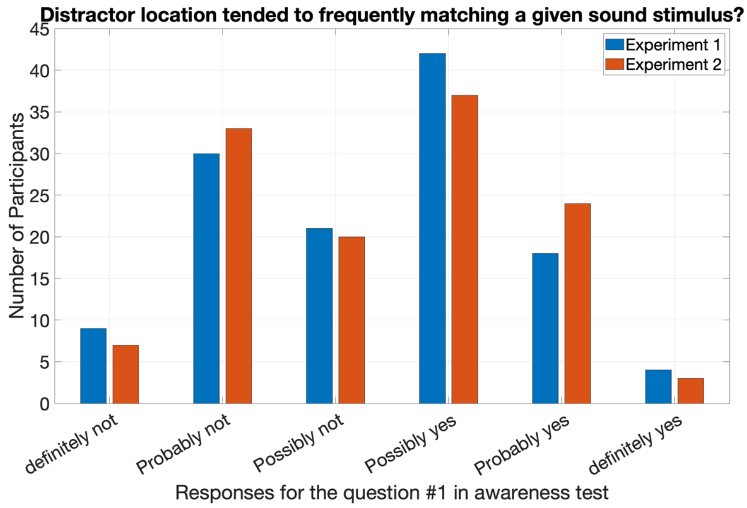

Figure 4. Summary of responses received by participants for Question #1 in the awareness test.

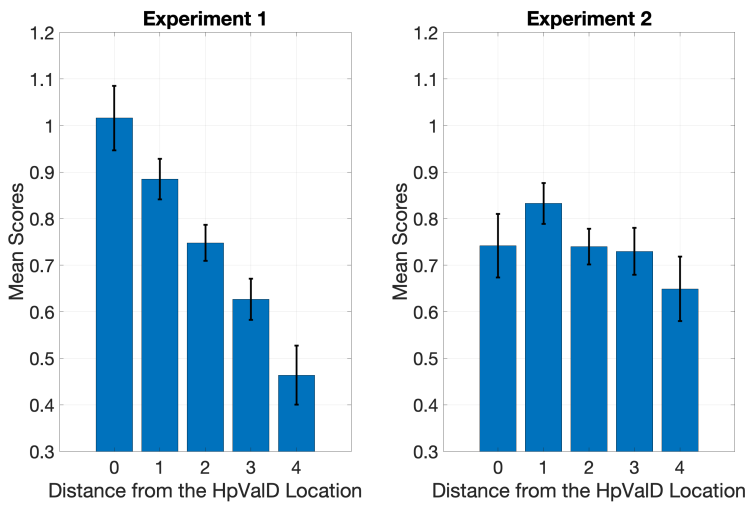

Figure 5. Summary of responses received by participants for Questions 2 & 3 in the awareness test. Left panel for Experiment #1; Right panel for Experiment #2. Error bars indicative of SEM.

Results and Discussion of Experiment 2:

Pre-registered analysis:

In accordance with the participant selection criteria, a total of 127 participants who were able to discriminate the sound frequency (low and high) with a minimum of 75% accuracy were recruited for the Experiment 2 (Mean % accuracy ± SEM: 90.5906 ± 0.6996). Out of these, we excluded the data of 3 participants who failed to achieve a minimum of 75% overall accuracy in the search task (pre-registered criteria). The remaining data from 124 participants were included for further analysis. Although we pre-registered to have a minimum sample of N = 121 for Experiment 2 , our total sample that included for the statistical analysis was N=124 after counter-balancing the two High-probability Distractor Locations in the search displays across participants. We performed statistical tests after we collected the data of 124 participants who achieved a minimum of 75% overall accuracy in the search task.

Mean correct RTs were used for the statistical testing after removing the incorrect responses (including timed-out trials, 9.6%) and response times shorter than 200ms (0.2%). All the statistical analyses were performed using JASP software (Team, 2022). In cases where the sphericity assumption was violated for tests of repeated measures of ANOVA, the reported p-values were Greenhouse-Geisser corrected. Similarly, In cases where the assumption of normality was violated (Shapiro-Wilk test) for paired t-tests, the reported p-values were obtained by Wilcoxon signed-rank tests. In accordance with the pre-registered analysis plan, a statistical significance threshold of 0.02 was used to interpret the results.

RT analysis:

According to the pre-registered protocol, comparison between mean RTs of experimental conditions HpValD and HpInValD with paired samples t-test revealed a non-significant difference between them (HpValD: 1031.683ms ± 10.900 SEM; HpInValD: 1028.521ms ± 11.179 SEM; $t(123) = 1.138$, $p = 0.305$, $r_b = 0.106$). These results indicate that the valid distractor locations (distractor appears in one of the two high probability locations with auditory stimulus feature match) were not perceptually suppressed relative to the invalid distractor locations (distractor appears in one of the two high probability locations with auditory stimulus feature mismatch). Figure 6 shows the mean RTs and percent of incorrect responses for all experimental conditions in Experiment #2.

Awareness Test:

Figure 4 provides the responses received by participants for Question #1 in the awareness tests. When participants were asked whether they had noticed if a given sound pitch (high pitch or low pitch) frequently matched with a distractor location in search displays, the modal response was “probably yes”. The average response (± SD) on a scale of 1 to 6 is 3.371 ± 0.1146 SEM. Overall, participants were low confident in their responses in both directions.

Following the pre-registered protocol, we calculated the mean scores obtained by each location based on five categories (0-4) for each participant. Figure 5 (Right panel) summarizes mean scores for each of the five categories (0-4). A linear mixed effects model with random intercepts for participants indicated that the mean scores for each location were not significantly decreased linearly as a function of its distance from the HpValD location ($b= -0.03$, $t(618)= -1.646$, $p = 0.100$). These results suggest that the participants do not have awareness of the relationship between auditory stimulus features and visual distractor location regularities in Experiment #2.

Non-Pre-registered analysis:

Similar to Experiment #1, we explored whether colour singleton distractors interfere with the search task performance when the distractor is present in low and high-probability distractor locations (regardless of sound stimulus manipulations in the experiment) relative to the distractor absent trials. Mean RTs were submitted to a one-way repeated-measures of ANOVA with the experimental condition of interest (ND vs. LpD vs. HpD) as a factor. The analysis indicated a significant main effect of condition, $F(2, 246) = 686.784$, $p < 0.001$, partial $\eta^2 = 0.848$. Relative to RTs on no-distractor trials (956.955ms ± 11.161 SEM), RTs were significantly slower in HpD condition (1031.087ms ± 10.904 SEM, $p < 0.001$, $t(123) = 22.704$, Cohen’s $d = 2.039$), and LpD condition (1064.347ms ± 11.047 SEM, $p < 0.001$, $t(123) = 30.890$, Cohen’s $d = 2.774$). Moreover, RTs in the LpD condition were significantly slower than RTs in the HpD condition ($p < 0.001$, $t(123) = 17.393$, Cohen’s $d = 1.562$). A similar analysis was conducted on the percentage of incorrect responses in each condition of interest. The one-way repeated measures of ANOVA indicated a significant main effect of condition,

$F(2, 246) = 202.362$, $p < 0.001$, partial $\eta^2 = 0.622$. Relative to the parentage of incorrect responses on no-distractor trials (6.368% ± 0.429 SEM), incorrect responses were significantly higher in HpD condition (9.892% ± 0.517 SEM, $p < 0.001$, $r_b = 0.944$), and LpD condition (11.508% ± 0.560 SEM, $p < 0.001$, $t(123) = 17.413$, Cohen's $d = 1.564$). Moreover, the mean percentage of incorrect responses was significantly higher in the LpD condition than in the HpD condition ($p < 0.001$, $r_b = 0.681$). These patterns of results indicate that the response time differences in conditions were not due to the speed-accuracy trade-off. Overall, results provide evidence that singleton distractors indeed capture attention and interfere with search tasks indicated by slower RTs in search displays when the distractor is present compared to when it is absent. Further, this effect was partially ameliorated when the distractor was present in high-probability locations compared to low-probability locations, which indicates the suppression of distractors at high-probability locations compared to low-probability locations.

We then conducted paired t-test on the mean percent of incorrect responses between HpValD and HpInValD conditions to check if the observed non-significant difference in mean response times of HpValD and HpInValD were not due to speed-accuracy trade-off. We found a non-significant difference between the mean percentage of incorrect responses of HpValD condition (9.716% ± 0.489 SEM) and HpInValD condition (9.966% ± 0.510 SEM, $p = 0.371$, $t(123) = 0.898$, Cohen's $d = 0.081$), which shows that mean RT differences were not due to speed-accuracy trade-off.

Next, we conducted a one-way repeated measures of ANOVA on mean RTs with all experimental conditions (ND vs. HpValD vs. HpInValD vs. LpD). This analysis was intended to test whether the data passed the pre-registered outcome-neutral criteria (i.e., absence of floor and ceiling effects). There was a main effect of experimental condition, $F(3, 369) = 438.309$, $p < 0.001$, partial $\eta^2 = 0.781$. Bonferroni corrected post-hoc test revealed that the mean RTs were significantly faster in ND compared to all other conditions (all $p < 0.001$), and RTs were significantly slower in LpD compared to all other conditions (all $p < 0.001$). Similarly, the mean percentage of incorrect responses was significantly lower in ND compared to all other conditions (all $p < 0.001$), and the percentage of incorrect responses were significantly higher in LpD compared to all other conditions (all $p < 0.001$), which assures that RT differences were not a consequence of speed-accuracy trade-off. These results indicate that the data passed the pre-registered outcome-neutral criteria (i.e., absence of floor and ceiling effects) and ensured that the results of Experiment #2 could test the stated hypothesis proposed in the pre-registered protocol.

Next, similar to Experiment 1, RT performance analysed in terms of epochs rather than taking mean performance per experimental condition. Figure 7 (right panel) in shows the mean RTs as a function of epochs, separately for valid and invalid distractor trial conditions. We submitted mean RTs to repeated measures of ANOVA with factors Validity (Valid vs. Invalid distractor trials) and Epochs (1 to 6). The results revealed a significant main effect of Epoch, $F (5, 615) = 347.076$, $p < .001$, $r_b = 0.738$. However, there was no significant main effect of Validity ($p = 0.273$) or Validity × Epoch interaction ($p = 0.134$) on the mean RTs. These results indicate that RT performance did not significantly differ between the valid and invalid distractor location trials across Epochs, corroborating the lack of evidence supporting distractor suppression effects by statistical regularities of cross-modal stimuli.

Finally, we conducted Bayesian paired samples t-test to compare the mean RTs of HpValD and HpInValD. The Bayesian analysis results supported the null hypothesis of no difference between mean RTs of HpValD and HpInValD more likely than the alternate hypothesis ($BF_{01} = 5.338$). The Bayesian analysis performed using JASP software with a default Cauchy prior of 0.707.

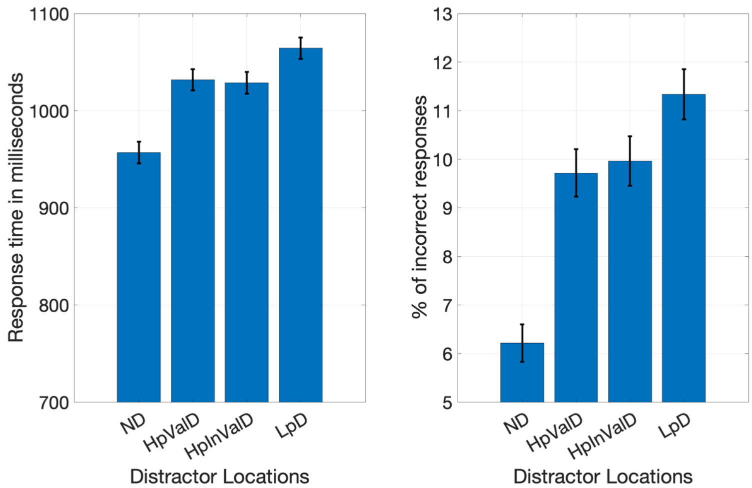

Figure 6. Mean response times (left panel) and percent of incorrect responses (right panel) for experiment 2. ND = No distractor trials; HpValD = Trials with the distractor appeared in one of the two high probability locations with auditory stimulus feature match; HpInValD = Trials with the distractor appeared in one of the two high probability locations with auditory stimulus feature mis-match; LpD = Trials with the distractor appeared in low probability locations. Error bars indicate ± SEM.

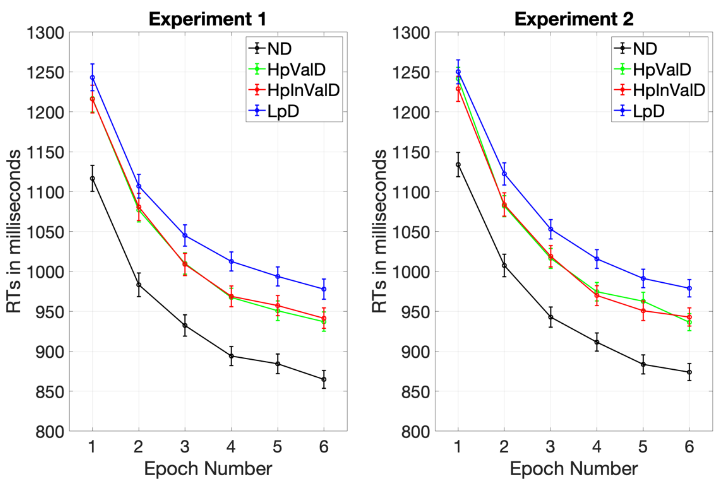

Figure 7. Mean RTs as a function of epochs, separately for No distractor (ND), valid (HpValD) and invalid distractor (HpInValD), and Low probability distractor location (LpD) trial conditions. Left panel: Experiment 1, Right panel: Experiment 2. Error bars represent SEM.

General Discussion:

In this study, we conducted two pre-registered experiments to test the hypothesis that participants utilize statistical regularities of task-irrelevant auditory stimuli (cross-modal) in order to suppress salient visual distractor locations during visual search . Further, we tested participants' awareness of the statistical regularities between distractor locations and auditory stimuli for each experiment. We used an additional singleton visual search task with two high-probability colour singleton distractor locations. Critically, the spatial location of the high-probability distractor was either predictive (valid distractor location) or unpredictive (invalid distractor location) based on the statistical regularities of auditory stimulus. The statistical regularities of auditory stimuli were "spatial" in Experiment 1, whereas they were "non-spatial frequency-based" in Experiment 2.

We hypothesised that the statistical regularities of cross-modal stimuli would induce distractor suppression at valid distractor locations relative to invalid distractor locations via pro-active changes within the attentional priority map (Huang et al., 2021; Wang, Driel, et al., 2019). The results replicated earlier findings of visual distractor suppression that shows faster RTs for trials that contain distractors at high-probability locations compared to low-probability locations (Duncan & Theeuwes, 2020; Failing, Feldmann-Wüstefeld, et al., 2019; Failing, Wang, et al., 2019; Li & Theeuwes, 2020; Lin et al., 2020; Theeuwes et al., 2018; Wang, Samara, et al., 2019; Wang & Theeuwes, 2018a, 2018b, 2018c). Contrary to our hypothesis , however, results did not show RT advantage for valid distractor location trials as compared with invalid distractor location trials in both Experiments 1 and 2. This absence of RT advantage for valid distractor trials indicates that neither predictive nor un-predictive auditory stimuli modulate the distractor suppression effect. This outcome was observed irrespective of whether the auditory stimulus statistical regularities were spatial or not. Moreover, these results suggest that, at least under the conditions of Experiments 1 and 2, the participants are unable to learn associations between the location of the visual distractor and the auditory stimulus. Our findings support the null effect that statistical regularities of cross-modal stimuli do not modify distractor suppression in additional singleton search tasks (See Results and Discussion Sections).

Prior research indicates that statistical learning of visual distractors and their suppression effects develop quickly during visual search (Valsecchi & Turatto, 2021). However, we do not have evidence for how fast or slow the learning of cross-modal statistical regularities are as compared with modality specific statistical regularities in the context of auditory stimuli and visual distractors. It is plausible that the time course of learning is slower for the cross-modal statistical regularities due to their complexity. In such cases, it is appropriate that the RT performance be analysed in terms of epochs rather than taking mean performance per experimental condition. The epoch-wise analysis revealed a significant improvement in the task performance as a function of the experiment progress for both Experiments, indicating procedural learning (Schneider & Shiffrin, 1977). However, RT performance did not significantly differ between the valid and invalid distractor location trials across Epochs for both Experiments. These results corroborating the lack of evidence to support the distractor suppression effects by statistical regularities of cross-modal stimuli.

In general, we find no reliable effect of cross-modal statistical regularities on visual distractor processing during visual search. One possible explanation for this result is related to available attentional resources to process auditory information during visual search. Given that the visual information is task-relevant, participants' attention may have been preferentially allocated to visual information leaving diminished attentional resources for auditory information. This reduced or lack of attentional resources for auditory information might have impaired the learning of statistical regularities between the distractor location and the auditory stimulus. Indeed, prior research suggested that allocating attention to sensory events is required for statistical learning (Failing & Theeuwes, 2020; Turk-Browne et al., 2005; Vadillo, Giménez-Fernández, et al., 2020) and cross-modal association (Ikumi & Soto-Faraco, 2014). Thus insufficient attentional resources for learning cross-modal statistical regularities might have gated the distractor suppression effects.

Deleted: (Schneider & Shiffrin, 1977)

Another possible explanation for the absence of a reliable effect of cross-modal regularities on distractor processing is that participants in the present series of experiments failed to learn associations of auditory stimulus and visual distractor location regularities. Previous research suggested that cross-modal associative learning is relatively strong when the audio and visual stimuli are overlapped in space (Shams & Seitz, 2008). However, in the present series of experiments and each trial, the auditory stimulus was not overlapped in space with the distractor location. This lack of spatial overlap between auditory stimulus and distractor location might have weakened the strength of learning the cross-modal regularities. In any case, it is an interesting idea for future research to address these issues in experimental designs and test the effect, if any, of cross-modal regularities on distractor processing during visual search.

For testing the participants' awareness of the statistical regularities between auditory stimuli and distractor location in visual search displays, each participant was asked to respond to forced-choice questions at the end of the experiment. These questions aimed at measuring subjective (confidence rating) as well as objective (ranking method) awareness of statistical regularities (Giménez-Fernández et al., 2020; Vadillo, Linssen, et al., 2020). For the subjective measures, each participant indicated whether they had noticed regularities between auditory stimulus and location of distractor in display on a confidence rating scale from 1 to 6. For the objective measures, each participant ranked three search locations where they thought the distractor appeared frequently along with a given auditory stimulus. We assigned scores for each distractor location with ranked locations given scores from 3 to 1 (depending on the rank), and zeros for unranked. We hypothesised that if the participants' are "aware" of regularities, the scores would linearly decrease as a function of its distance from the valid distractor location. The results of subjective measures of awareness revealed that the participants had "low confidence" in their awareness of regularities for both Experiments (See Figure 4). However, the objective measures of awareness revealed that participants were "aware" of statistical regularities in Experiment 1 but not in Experiment 2.

From the observed "low confidence" in the subjective measure of awareness in our study, it is difficult to conclude whether the participants were "aware" or "unaware" of statistical regularities. The reason for this difficulty in categorization is that the "low confidence" in subjective measures could be attributed to either conservative bias in participants' responses or lack of awareness of regularities (Fleming & Lau, 2014; Tversky & Kahneman, 1974). Therefore, it is rather useful to categorise whether the participants' were "aware" or "unaware" of regularities based on objective measures. By using objective measures, many previous studies have claimed that the participants learn distractor regularities without their awareness in additional singleton search tasks (Failing, Feldmann-Wüstefeld, et al., 2019; Gao & Theeuwes, 2022; Wang & Theeuwes, 2018b). On contrary, by pointing out methodological shortcomings in previous studies, Vicente-Conesa et al. (2022) with help of better measures of awareness (ranking and estimation methods) claimed that the participants were "aware" of distractor regularities (Vicente-Conesa et al., 2022). In any case, the relative contributions of whether the participants are "aware" or "unaware" of regularities on distractor suppression is not very clear (for review, see Theeuwes et al., 2022). It appears that, however, having participants are “aware” of regularities (as observed in Experiment 1) may not be a necessary and sufficient condition for cross-modal influence on the distractor processing.

In our study results, the asymmetry in participants’ objective measures of awareness of statistical regularities between Experiment 1 and Experiment 2 is unclear. We speculated that participants might be biased to rank locations in the region of the screen that is on the same side as the auditory stimulus during the awareness test in Experiment 1. To test this possibility, we restricted the response analysis on same side of auditory stimuli. If the responses were biased to the same side of auditory stimuli, we expected that the scores for each location, within the same hemifield, would be at random and may not linearly decrease as a function of its distance from the valid distractor location. The relevant details of this analysis provided in the supplementary material. The results, however, indicated that the mean scores for each location were not significantly decreased as a function of its distance from the HpValD (for categories: 0, 1, and 2) location for both left and right hemifields. In other words, the participants’ responses were indeed influenced by the inferences made at the awareness test in Experiment 1.

However, according to the two dominant theories of consciousness, such as ‘higher order theories’ and ‘integration theories,’ objective as well as subjective measures of awareness need to be considered to know whether the participants are “aware” or “unaware” of statistical regularities (Dienes & Seth, 2022). In line with these theories of consciousness, the participants’ lack of a strong subjective awareness, in both Experiments, could suggests that the participants were “unaware” of the associations between distractor and auditory stimuli in Experiment 1 as well as in Experiment 2. Future research is required to address the problems in interpreting subjective as well as objective measures of awareness.

In summary, our experimental results indicate no reliable effect of task-irrelevant cross-modal stimulus regularities on distractor suppression, irrespective of participants’ awareness of the relationship between distractor location and predictive auditory stimulus. Based on our study results and prior studies, we suggest that pro-active distractor suppression might be possible in cases of statistical regularities of within-modality stimulus but not plausible by the cross-modal stimulus. Future studies are required to explore whether statistical regularities of cross-modal stimuli modulate the distractor processing in various experimental contexts and cross-modal combinations at behavioural and neural levels.

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CRediT Authorship contribution statement:

KKJ: Conceptualization, Investigation, Methodology, Formal analysis, Visualization, Software, Writing - original draft, Writing - review & editing

MMS: Supervision, Resources, Writing - review & editing,

Competing interests:

The authors declare no competing interests.

Data and Code availability:

Anonymised data (includes raw and summary level data, Laboratory record), Experimental codes, Scripts for generating Data figures, Supplementary Material (includes Pre-registered Study Design Table, Questionnaire, Pilot Experiment details), and "Readme.txt" file (explains contents of every file and variable labels within files) are made publicly available at the Open Science Framework repository: https://doi.org/10.17605/OSF.IO/9M35P

Note: We have performed all statistical tests of data using JASP statistical software (Open-source). Therefore, we do not have specific scripts for statistical analysis.

Authors' statement: "We reported how we determined our sample size, all data exclusions, all inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data analysis, all manipulations, and all measures in the study"

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Supplementary Material

Study Design Table:

Question	Hypothesis	Sampling Plan	Analysis Plan	Interpretation given different outcomes
Do task-irrelevant cross-modal (auditory) spatial regularities induce distractor suppression in visual search? (Experiment 1)	The response times (RTs) are expected to be shorter for HpValD — "high-probability valid distractor location" trials compared to the HpInValD — "high-probability invalid distractor location" trials.	We aim to recruit a minimum of 121 participants (who meets the participant selection criteria) from the Indian Institute of Technology. **<u>Sample Size Justification:</u>** In a previous study that is similar to the current experiments, Failing et al. (2019) reported an effect size of d = 0.602 by taking a difference between colour-match and colour-mismatch trials at two high probability distractor locations. Relying on the effect size from the previous study at the face value for an a priori power analysis is not recommended, as this might lead to underpowered studies (Dienes, 2021; Perugini et al., 2014). To guard against the underpowered study, we determined the smallest effect size of interest as the lower limit of 80% confidence interval for the effect size by following the advice of Perugini et al. (2014). The determined effect size of interest is 0.332 (estimated using Shiny R web app: https://designingexperiments.shinyapps.io/ci_smd/). Conducting an a priori power analysis with effect size d = 0.332, given alpha = 0.02 and power ≥ 90, yields a minimum of 121 participants required for each proposed experiment in a two-tailed matched-sample t-test (calculated using G*Power 3.1). This sample size is considerably larger than the typical experiments conducted using the additional singleton tasks (an average of around 26 participants in (Failing, Feldmann-Wüstefeld, et al., 2019; Wang & Theeuwes, 2018a, 2018b, 2018c)).	We will use paired t-test to compare experimental conditions of *HpValD* ("high-probability valid distractor location") with *HpInValD* "high-probability invalid distractor location") conditions. Significance level – alpha set to 0.02), with power >0.90.	If the RTs are significantly shorter for the HpValD condition than the HpInValD conditions, we claim the hypothesis 1. Otherwise, we will claim that the auditory spatial statistical regularities do not have influence on the distractor suppression in visual search tasks.

Do task-irrelevant cross-modal (auditory) non-spatial, frequency-based regularities induce distractor suppression in visual search? (Experiment 2)	The response times (RTs) are expected to be shorter for HpValD — "high-probability valid distractor location" trials compared to the HpInValD — "high-probability invalid distractor location" trials.	As above	As above	If the RTs are shorter for the HpValD condition than the HpInValD conditions, we claim the hypothesis 1. Otherwise, we will claim that the auditory non-spatial and frequency based statistical regularities do not have influence on the distractor suppression in visual search tasks.
Do participants have awareness about the the relationship between auditory (spatial) and visual distractor location regularities? (Experiment 1)	We hypothesise that if the participants are aware of the the relationship between auditory and visual distractor location regularities, we expect that the score received by each location linearly decreases from its distance from the actual HpValD location.	Minimum of 75 participants. **<u>Sample Size Justification:</u>** Recent studies indicated that using a confidence rating scale and ranking methods are, arguably, more sensitive measures for testing awareness (Giménez-Fernández et al., 2020; Vadillo, Linssen, et al., 2020). Utilizing these sensitive measures to test awareness of statistical regularities in probabilistic cuing search tasks, the Vadillo et al. (2020) study indicated that participants are not unaware of the statistical regularities. Their study reported an effect size of Cohen's h = 0.57 for their meta-analysis of experiment 1 and 2. However, choosing the effect size from a previous study at the face value for an a priori power analysis is not recommended, as this leads to underpowered studies (Dienes, 2021; Perugini et al., 2014). To guard against the underpowered study, we determined the smallest effect size of interest as the lower limit of 80% confidence interval for the effect size by following the advice of Perugini et al. (2014). The determined effect size of interest is 0.426 (estimated using Shiny R web app: https://designingexperiments.shinyapps.io/ci_smd/).The effect size of d = 0.426 requires a minimum of 75 participants for each proposed experiment to get power ≥ 90% with alpha set to 0.02 (calculated using G*Power 3.1) in a two-tailed matched-sample t-test.	We will use a linear mixed-effects model with random intercept for participants to predict a relationship between the scores received by each location from its distance from the HpValD location.	We will claim that the participants are aware of statistical regularities if the scores received by each location linearly decreases from its distance from the actual HpValD location. Otherwise, we will claim that participants are unaware of statistical regularities.
Do participants have	As above	As above	As above	As above

awareness about the the relationship between auditory (non-spatial and frequency based) and visual distractor location regularities? (Experiment 2)				

Pilot Experiment:

We have conducted a pilot experiment (N=5) to test the feasibility of the study and to test whether color distractors in the search displays can capture attention. The pilot experiment is the conceptual replication of the study design done by Wang and Theeuwes, 2018. The results indicated that the high probability color singleton distractor location (HpSD) is suppressed and facilitated the visual search efficiency by indicating faster RTs than the low probability color singleton distractor locations (LpSD). Figure S1 shows the mean RTs for different distractor conditions on the pilot experiment. The raw data of the pilot study is available at the OSF repository at the following link: https://osf.io/yba2k/?view_only=ec7ab987de2f4486aa653f24d03936f5

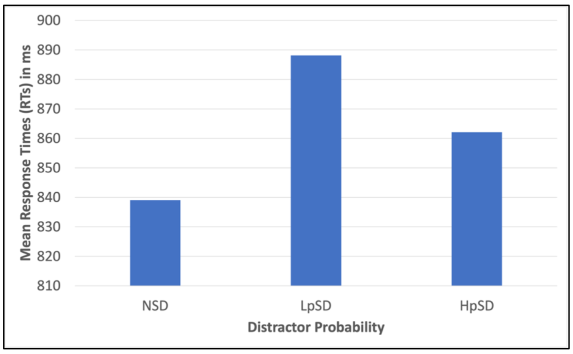


Figure S1: *Pilot conceptual* replication of the study design done by Wang and Theeuwes, 2018. The pilot study indicated that the high probability color singleton distractor location (HpSD) is suppressed and facilitated the visual search task efficiency by indicating faster RTs than the low probability color singleton distractor locations (LpSD).

Questionnaire for testing awareness of statistical regularities:
For experiment 1:

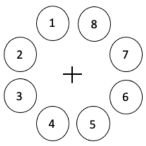
Question #1: You might have noticed that, in most of the displays, one of the visual items in display appeared in a different color than the rest (e.g., red color visual item among green items or vice versa). Do you think that a given sound location (e.g., the sound coming from the Left or Right side of the display) was most frequently matching a particular location of this visual item in the display?

Please respond honestly by choosing one of the options mentioned below:

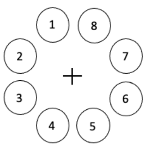
* Definitely not (Press 1)
* Probably not (Press 2)
* Possibly not (Press 3)
* Possibly yes (Press 4)
* Probably yes (Press 5)
* Definitely yes (Press 6)

Question #2: In the experiment, in most of the trials, the sound coming from the left side of the display was most frequently matched with a particular location of the differently colored visual item in the display.

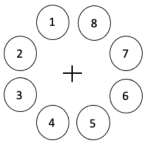
* Now, if you had to choose a particular location where the differently colored visual item frequently appeared along with the sound coming from the left side of the display, which one that would be, in your opinion? Please indicate such location by pressing corresponding numbered spatial locations shown on the below example display.



* Now, ignoring your previous response, if you had to choose the next location where the differently colored visual item frequently appeared along with the sound coming from the left side of the display, which one that would be, in your opinion? Please indicate such location by pressing corresponding numbered spatial locations shown on the below example display.

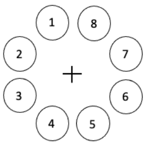


* Finally, ignoring your previous response, if you had to choose the next location where the differently colored visual item frequently appeared along with the sound coming from the left side of the display, which one that would be, in your opinion? Please indicate such location by pressing corresponding numbered spatial locations shown on the below example display.

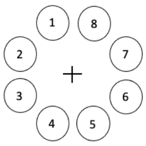


Question #3: In the experiment, in most of the trials, the sound coming from the right side of the display was most frequently matched with a particular location of the differently colored visual item in the display.

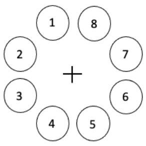
* Now, if you had to choose a particular location where the differently colored visual item frequently appeared along with the sound coming from the Right side of the display, which one that would be, in your opinion? Please indicate such location by pressing corresponding numbered spatial locations shown on the below example display



* Now, ignoring your previous response, if you had to choose the next location where the differently colored visual item frequently appeared along with the sound coming from the Right side of the display, which one that would be, in your opinion? Please indicate such location by pressing corresponding numbered spatial locations shown on the below example display.



* Finally, ignoring your previous response, if you had to choose the next location where the differently colored visual item frequently appeared along with the sound coming from the Right side of the display, which one that would be, in your opinion? Please indicate such location by pressing corresponding numbered spatial locations shown on the below example display.



For experiment 2:

The questionnaire for experiment 2 will be similar to the experiment 1 mentioned above, except that we will use text sound pitch, either high or low, instead of the text mentioning the right or left sound locations.

Awareness test response analyse for Experiment 1 (after restricting the analysis for left and right hemifields, separately)

A linear mixed model with random intercepts for participants indicated that the mean scores for each location were not significantly decreased as a function of its distance from the HpValD location for both left (b = 0.125, t (359.69) = 1.480, p = 0.085) and right hemifields (b= 0.004, t (370) = 0.056, p = 0.955) of Experiment 1. In other words, the responses were indeed influenced by the inferences made at the awareness test in Experiment 1.

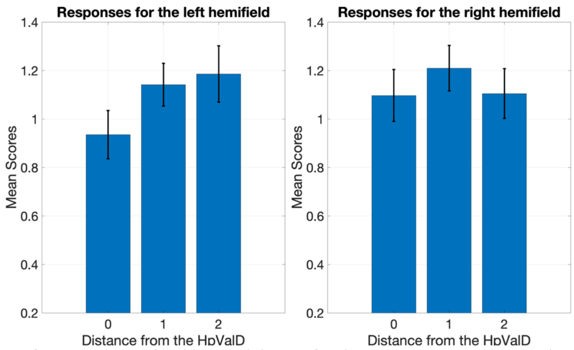


Figure S2: Summary of responses received by participants for the awareness test in Experiment 1. Left panel for the left hemifield; Right panel for the right hemifield. Error bars indicative of SEM. Note: We chose only 3 categories (0, 1, and 2) on the x-axis when restricting the response analyses for left and right hemifields, separately. We have not included the category 3 for the analysis. This is because when restricting the response analysis for each hemifield separately, the category 3 values can be obtained only for two out of four valid distractor locations on each hemifield (indexes: 1, 4, 5, and 8, please see the example displays with index numbers shown in the questionnaires)