Do task-irrelevant cross-modal statistical regularities induce distractor suppression in visual search?

Kishore Kumar Jagini[1*] and Meera Mary Sunny[1]

[1]Indian Institute of Technology Gandhinagar, Gandhinagar, India

[*]Corresponding Author:
Kishore Kumar Jagini,
AB5/316, Indian Institute of Technology Gandhinagar
Gandhinagar – 382355Gujarat, India
Email: kishore.jagini@iitgn.ac.in

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The authors declare that the proposed study is without any commercial or other conflicts of interest.

Ethics approval statement:
The experimental procedures have been approved by the Institutional Ethics Committee (IEC) of Indian Institute of Technology Gandhinagar, Gandhinagar, India

Data availability:
The authors confirm that the raw data and experimental/analysis code will be made available to the public.

Funding:
The authors confirm that facilities and resources are available to complete the proposed study.

Dear Recommender/Editor, PCI RR

We wish to propose a stage-1 registered report titled: "**Do task-irrelevant cross-modal statistical regularities induce distractor suppression in visual search?**". Recently, the research community has shown substantial interest in understanding how people learn and utilize distractor regularities in visual search tasks to optimize search behaviour. For example, a recent seminal study by Wang & Theeuwes (2018) showed that salient visual distractors are perceptually suppressed when they frequently appear at a particular spatial location in visual search displays to facilitate the visual search task performance. This evidence indicates that participants, based on distractor spatial statistical regularities, can anticipate the likely location of distractors in visual search and perceptually suppress them for task efficiency.

This registered report proposes to test a question that addresses whether the study participants learn to utilize task-irrelevant, cross-modal stimulus spatial (Experiment 1) and non-spatial regularities (Experiment 2) indicating the salient visual distractor's likely location in search displays to perceptually suppress them for optimizing task efficiency. It would provide evidence that the visuospatial attentional priority map can flexibly be modified based on the learning of task-irrelevant, cross-modal stimulus statistical regularities.

We confirm that sufficient funding and facilities are available to complete the proposed study successfully. The experimental procedures involved in this study are already approved by the Institutional Ethics Committee (IEC) of the Indian Institute of Technology Gandhinagar, India. We expect to complete the proposed study within three months of study approval. After completing data collection, we will analyze the data and write the manuscript within one to two months. We agree that the raw data and experimental/analysis code will be made available to the public. Following Stage-1 in-principle acceptance, we agree to register the approved protocol on the Open Science Framework or any other recognized repository either publicly or under private embargo until Stage-2 manuscript submission. We also agree that if the paper is retracted for any reason, a summary of the proposed pre-registered study will be made available to publish if required.

Sincerely,

(On behalf of authors)

Kishore Kumar Jagini

Indian Institute of Technology Gandhinagar, India.

Abstract:

We are constantly bombarded with a vast number of multisensory stimuli in our daily lives. Our sensory systems are known to extract and utilize statistical regularities in the sensory inputs across space and time to optimize the attentional orienting in the multisensory environment. This registered report proposes to test a question that addresses whether participants learn to utilize task-irrelevant, cross-modal stimulus spatial (Experiment 1) and non-spatial regularities (Experiment 2) indicating the salient visual distractor's likely location (color singleton distractor) in search displays to perceptually suppress them for optimizing task efficiency. Critically, the spatial location of a colour singleton distractor in each trial could be either predicted or unpredicted based on the task-irrelevant auditory statistical regularities simultaneously presented across search displays. If the auditory statistical regularities induce visual distractor location suppression, it would provide evidence that the visuospatial attentional priority map can flexibly be modified based on the learning of task-irrelevant, cross-modal stimulus statistical regularities. We also test participants' awareness about the statistical regularities to determine whether the learning is implicit or not.

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 ignore 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 that can neither be categorized into top-down goals nor bottom-up processes that 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 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) in colour singleton present trials compared to colour singleton absent trials is considered evidence for selective attentional priority of colour singleton distractor (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 statical 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 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 distractor colours that appear in search displays more frequently were suppressed efficiently compared with less frequent distractor colours (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 in cross-modal contexts (Chen et al., 2020, 2021; Kawahara, 2007; Nabeta et al., 2002). For example, 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 participant's 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 used to improve 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 will investigate whether and how task-irrelevant, cross-modal stimulus statistical regularities 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 target or distractor in a visual search task.

We have proposed two experiments in this study. The first experiment is designed to test whether the study participants learn to utilize the task-irrelevant auditory spatial regularities, simultaneously presented across search displays, indicating salient visual distractor's likely location influence visual search task performance. The second study is designed to test whether the task-irrelevant auditory non-spatial and frequency-based regularities, simultaneously presented across search displays, indicating salient visual distractor's likely location influence visual search task performance. We adopt the additional singleton visual search paradigm developed initially by Theeuwes (1991, 1992) with few modifications. In the proposed experiments, we manipulate 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 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 statistical regularities. For testing awareness about the relationship between auditory and visual distractor location regularities, we will use 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 et al., 2020). First, at the end of the experiment, each participant will have to indicate whether they have 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 will be 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 will be given a score of 3, 2, 1, respectively, and for other locations, the score will be zero. We will assign 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 "high-probability valid distractor location (HpValD)". For each participant, we will then combine the data of two sound stimulus conditions to calculate the mean scores obtained by locations according to the five categories mentioned above (0-4). We will then analyse the linear relationship between scores received by each location from its distance from the actual HpValD location to test the awareness of audio-visual statistical regularities.

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Hypothesis:

We propose to test 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 hypotheses is presented in Figure 1. We also test participants' awareness about the the relationship between auditory and visual distractor location regularities for experiment 1 and 2.

Hypothesis #1: We hypothesize that if the study participants can 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) are 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 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.

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 later 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.

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 76 participants (who meets the participant selection criteria) from the Indian Institute of Technology. **Sample Size Justification:** 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-bound limit of the effect size by following the advice of Perugini et al. (2014). By taking account of the limited time and resources that the authors have and able collect the maximum sample size of 80±5 for each proposed experiment, we chose 60% lower-confidence interval limit of the effect size as the smallest effect size of interest. The 60% confidence interval implies a 20% risk that the true effect size might be lower than the lower-confidence interval limit (Perugini et al., 2014). The determined effect size of interest is 0.424 (estimated using Shiny R web app: https://designingexperiments.shinyapps.io/ci_smd/). Conducting an a priori power analysis with effect size d = 0.424, given alpha = 0.02 and power ≥ 90, yields a minimum of 76 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.

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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 81 participants. **Sample Size Justification:** 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 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 [95% CI: 0.41, 0.74] 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-bound limit of the effect size by following the advice of Perugini et al. (2014). The reported lower limit of the 95% confidence interval of the effect size in Vadillo et al. (2020) study is 0.41. The effect size of d = 0.41 requires a minimum of 81 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.
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about the the relationship between auditory (non-spatial and frequency based) and visual distractor location regularities? (Experiment 2)				

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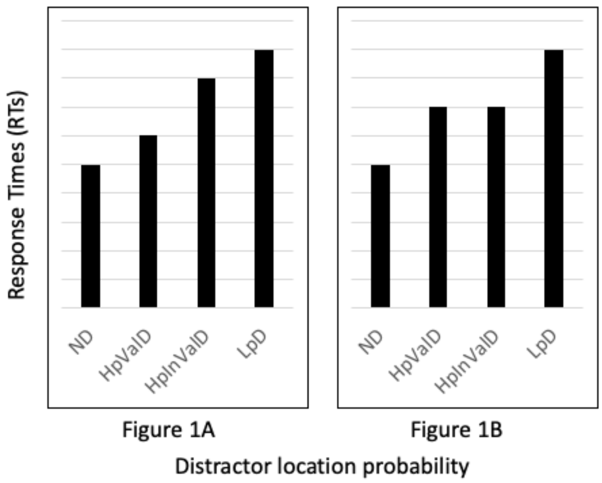

Figure 1. *Possible Experimental Outcomes. (1A) If the auditory statistical regularities induce suppression of the high probability valid distractor location processing, shorter RTs expected in HpValD compared to the HpInValD condition. (1B) If the auditory regularities did not affect the visual search 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 in-valid distractor location")= high probability distractor location not-indicated by auditory regularities. LpD ("Low probability distractor locations") = Low probability distractor locations with uninformative sound.*

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Number of Participants:

Justification for the sample size to test the hypothesis #1: The sample size is 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 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). Therefore, to guard against the underpowered study, we determined the smallest effect size of interest as the lower-bound limit of the effect size by following the advice of Perugini et al. (2014). By taking account of the limited time and resources that the authors have and able collect the maximum sample size of 80±5 for each proposed experiment, we chose 60% lower-confidence interval limit of the effect size as the smallest effect size of interest. The 60% confidence interval implies a 20% risk that the true effect size might be lower than the lower-confidence interval limit (Perugini et al., 2014).

The determined effect size of interest is 0.424 (estimated using Shiny R web app: https://designingexperiments.shinyapps.io/ci_smd/). Conducting an a priori power analysis with effect size d = 0.424, given alpha = 0.02 and power ≥ 90%, yields a minimum of 76 participants required to test the hypothesis #1 for each proposed experiment with 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)).

Justification for the sample size to test the hypothesis #2: The sample size is 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

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target/distractor appeared most frequently to test awareness about 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 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 [95% CI: 0.41, 0.74] for their meta-analysis of experiment 1 and 2. However, choosing the effect size from the 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-bound limit of the effect size by following the advice of Perugini et al. (2014). By taking account of the limited time and resources that the authors have and able collect the maximum sample size of 80±5 for each proposed experiment, we chose 95% lower-confidence interval limit of the effect size as the smallest effect size of interest. The 95% confidence interval implies a 5% risk that the true effect size might be lower than the lower-confidence interval limit (Perugini et al., 2014).

The reported lower limit of the 95% confidence interval of the effect size in Vadillo et al. (2020) study is 0.41. Conducting an a priori power analysis with effect size of d = 0.41, given alpha = 0.02 and power ≥ 90%, yields a minimum of 81 participants required to test the hypothesis #2 for each proposed experiment in a two-tailed matched-sample t-test (calculated using G*Power 3.1).

The experimental procedures have been approved by the Institutional Ethics Committee (IEC) of the Indian Institute of Technology Gandhinagar, Gandhinagar, India. We will conduct the experiment after obtaining written informed consent from the participants.

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Participant selection criteria:

Selected participants must report normal hearing and colour vision and normal or corrected to normal visual acuity with an age range from 18 to 35 years. Additionally, we will test whether the participants can discriminate the spatial location of sound (left and right) in experiment 1. In experiment 2, we will test whether participants can discriminate between two different sound frequencies (500Hz & 1000Hz). A short two-alternative forced choice, 20 auditory-only trials will be 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 show a minimum of 75% accuracy will be selected for participation in the experiment. Selected participants must provide informed consent before they participate in the study. The experimental procedures have been approved by the Institutional Ethics Committee (IEC) of the Indian Institute of Technology Gandhinagar, India.

Materials:

The experiments will be conducted in a dim-lit room. All the experimental stimuli will be created and presented using MATLAB with Psychophysics Toolbox extensions (Brainard, 1997). The visual stimuli will be shown on an LCD monitor screen 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 display will be 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 will be in green or vice versa (50% probability). The auditory stimulus in experiment 1 will be 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 500 Hz or 1000 Hz frequency presented via headphones. The sound level will be adjusted for each participant according to their comfort at the beginning of the experiment and will be kept constant throughout the experiment.

Experiment 1:

The experiment 1 is aimed to test whether the study participants learn to utilize the task-irrelevant auditory spatial regularities, simultaneously presented across search displays, indicating salient visual distractor's likely location influence visual search task performance. We hypothesize that if the study participants can 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 starts with a fixation cross presented until the trial ends. 500ms after the fixation cross onset, the visual search display is presented for 2000ms or until the participant makes a response (<2000ms). The participants will be instructed to search for a shape singleton in the displays. For example, participants will be asked to search for a diamond shape among circles or vice versa and respond to the line segment's orientation embedded in the target. If the orientation of the line segment is horizontal, the participant is required to press the "Z" key, and if the line segment is vertical, the participant is required to press the "M" key as soon as possible. Participants will be asked to press the response key quickly and accurately. The target (shape singleton) will be present in all the trials, and the target can be either circle or diamond with equal probability. A blank display with intertrial interval (ITI) will be randomly determined between 500ms to 750ms. The timed-out responses will be considered incorrect responses. In cases of incorrect responses and timed-out responses, feedback will be provided to the participants with white text "Incorrect response" or "Timed-out", respectively at the center of the LCD screen for 1000ms. No feedback will be provided for the correct responses. Two critical design factors are important in the experiment regarding the experimental manipulations of the additional (color) singleton distractor and the auditory stimulus across the trials.

Additional singleton distractor and search target manipulations: All search elements will be red or green with equal probability in one-sixth of the trials ("distractor absent trials"). In the remaining trials, one of the distractors will have the same shape as other distractors but with a unique color (red among green distractors or vice versa with equal probability). These trials are labelled as additional singleton distractor present trials or simply "distractor present trials". The red or green additional singleton distractor could be present at any of the eight search locations in distractor present trials. However, the additional singleton distractors are 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 are 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 are 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 is randomly determined such that it does not coincide with the color singleton distractor location.

Auditory stimulus manipulations: No auditory stimulus will be presented to the participants for the distractor absent trials. However, for the distractor present trials, an auditory stimulus will be presented simultaneously with the search display. There are 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 will be more likely (80 %) to be presented at the spatially congruent side of the distractor location (left or right hemifield) and less likely (20 %) to be presented at the spatially incongruent side. Second, when the additional singleton distractor appears at one of the low probability distractor locations, the auditory stimulus is 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 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 will start 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 will be presented randomly with equal probability in each experimental block. A 30-second break will be given to participants after completing each experimental block.

Testing participants' awareness of statistical regularities: To determine whether participants are aware of the relationship between auditory and visual distractor location regularities, all participants will be asked to answer forced-choice questions at the end of the experiment (See supplementary materials section). First, participants will be asked to indicate whether they had noticed regularities in the sound location such that the sound stimulus location was most frequently matching the color distractor location in display on a rating scale from 1 to 6. Second, we will inform the participants that each sound stimulus location (Left or Right) was most frequently matched with a specific color distractor location in display and 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).

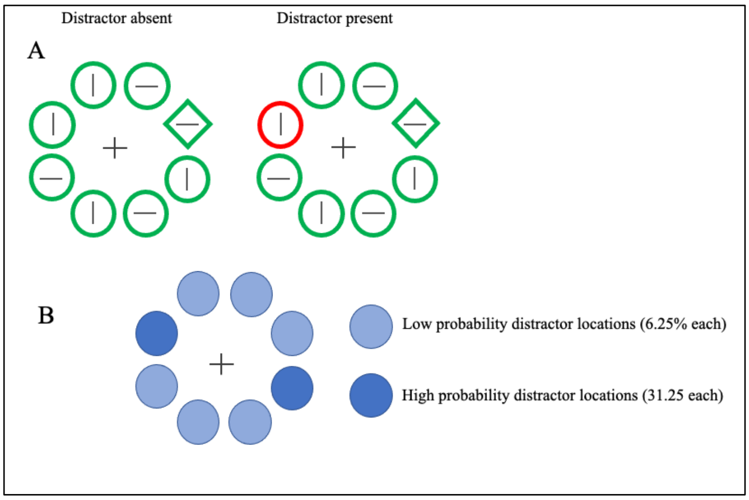

Figure 2. *(A) Schematic illustration of search displays. Examples of the search display. The participant's task is to search for shape singleton. In distractor present trials, participants will be instructed to ignore the colour-singleton distractor. (B) Schematic illustration of spatial regularities 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:

The experiment 2 is 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 hypothesize 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).

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Procedure and Design for experiment 2:

The experimental procedure and design will be the same as experiment 1, except 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 will be presented to the participants for the distractor absent trials. However, for the distractor present trials, an auditory stimulus will be presented simultaneously with the search display. There are 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 will be more likely (80%) presented with one of the two pure tones (e.g., 500Hz frequency tone) and less likely (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 will be 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 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 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.

Participant and data replacement:

Any of the following criteria will be used to replace a given participant in both the 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 who voluntarily choose not to perform the task at any time before completing the experiment.

Data analysis plan:

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

Analysis on Response times (RTs): As mentioned in Figure 1, the relevant comparison is to test whether the auditory regularities influence distractor suppression. For this comparison, we will use paired t-test to compare experimental conditions of “high-probability valid distractor location” with “high-probability invalid distractor location”.

Analysis of participants’ awareness of regularities: We will calculate 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 will be asked to rank three locations for each sound stimulus condition separately (Question #2 & Question #3). The first, second, and third-ranked locations will be given scores of 3, 2, and 1, respectively. For the remaining locations, the scores will be zero. We will assign 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 will then combine the data of Question #2 & Question #3 to calculate the mean scores obtained by locations according to the five categories mentioned above (0-4). These data will be analyzed using 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 is 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 generate the predictions for the likely distractor location. In that case, these distractor locations (in “high-probability valid distractor location”) are perceptually suppressed, and the RTs in those trials are shorter than invalid distractor locations (in “high-probability invalid distractor location” trials). Likewise, in experiment 2, RTs expected to be shorter for high-probability valid distractor location (indicated by sound feature) than high-probability invalid distractor location. A graphical representation of experimental predictions is presented in Figure 1.

Supplementary Materials

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 pilot study indicated that the high probability color singleton distractor location (HpSD) condition is suppressed and facilitated the visual search efficiency by indicating faster RTs than the low probability color singleton distractor locations (LpSD) condition. Figure 3 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

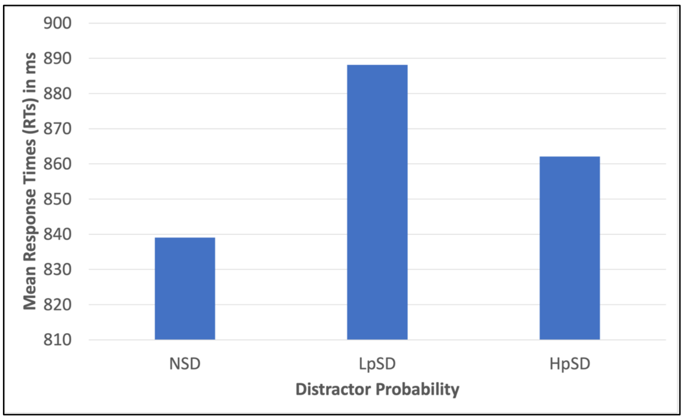


Figure 3: *Pilot conceptual* replication of the study design done by Wang and Theeuwes, 2018. The pilot study indicated that the high probability color singleton distractor location (HpSD) is suppressed and facilitated the visual search task efficiency by indicating faster RTs than the low probability color singleton distractor locations (LpSD).

Questionnaire for testing awareness of statistical regularities:

For experiment 1:

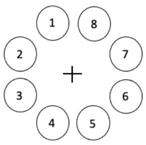
Question #1: You might have noticed that, in most of the displays, one of the visual items in display appeared in a different color than the rest (e.g., red color visual item among green items or vice versa). Do you think that a given sound location (e.g., the sound coming from the Left or Right side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

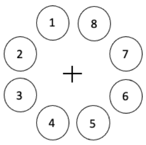
* Definitely not (Press 1)
* Probably not (Press 2)
* Possibly not (Press 3)
* Possibly yes (Press 4)
* Probably yes (Press 5)
* Definitely yes (Press 6)

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.

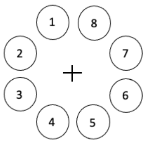
* Now, if you had to choose a particular location where the differently colored visual item frequently appeared along with the sound coming from the left side of the display, which one that would be, in your opinion? Please indicate such location by pressing corresponding numbered spatial locations shown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

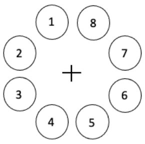


* Finally, ignoring your previous response, if you had to choose the next location where the differently colored visual item frequently appeared along with the sound coming from the left side of the display, which one that would be, in your opinion? Please indicate such location by pressing corresponding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

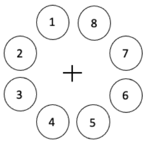


Question #3: In the experiment, in most of the trials, the sound coming from the right side of the display was most frequently matched with a particular location of the differently colored visual item in the display.

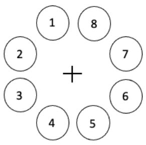
* Now, if you had to choose a particular location where the differently colored visual item frequently appeared along with the sound coming from the Right side of the display, which one that would be, in your opinion? Please indicate such location by pressing corresponding numbered spatial locations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

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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.

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