

1 **No reliable effect of task-irrelevant cross-modal statistical**
2 **regularities on distractor suppression,**

Deleted: Do ask-irrelevant cross-modal statistical regularities induce distractor suppression in visual search?...

3
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6 Gandhinagar, India

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13 **Type of Manuscript:** Registered report – Stage-2, manuscript,

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16 **URL to the pre-registered Stage-1 protocol:** <https://osf.io/qjbmg>

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19 **Conflict of Interest Statement:**

20 The authors declare that the study was conducted, without any commercial or other
21 conflicts of interest.

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Ethics approval statement: ¶

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

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Funding: ¶

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

Cross-modal statistical regularities and Visual selection

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2 Dear Recommender/Editor, PCI RR

3
4 We ~~wish to submit the stage-2 manuscript for the~~ registered report (IPA approved) titled: “Do
5 task-irrelevant cross-modal statistical regularities induce distractor suppression in visual
6 search?”. ~~URL to the pre-registered stage-1 protocol: https://osf.io/qjbmj~~

7
8 We confirm that ~~we have followed the study procedures proposed in the pre-registered protocol~~
9 ~~to successfully complete the study. In the stage-2 report we have included a few unregistered~~
10 ~~analyses of data with justifications mentioned for the same. The study materials (data for~~
11 ~~experiment 1 and experiment 2, experimental codes, and other supplementary material) are~~
12 ~~made publicly available at the Open Science Framework repository:~~
13 ~~https://doi.org/10.17605/OSF.IO/9M35P~~

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16 Sincerely,
17 (On behalf of authors)
18 Kishore Kumar Jagini
19 Indian Institute of Technology Gandhinagar, India.

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Deleted: 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.

Deleted: sufficient funding and facilities are available

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Deleted: 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.

Cross-modal statistical regularities and Visual selection

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 unpredictable (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 when auditory stimulus regularities were spatial in nature. 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

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Deleted: 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.

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Deleted: 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.

1 Introduction

2

3 Our senses are bombarded with a vast number of sensory stimuli, at any given moment,
 4 from the external world and our body. In order to efficiently manage metabolic resources, our
 5 brain prioritizes the task or goal-relevant sensory information and ignores the task-irrelevant
 6 information. The set of processes involved in this optimization is referred to as selective
 7 attention. Prominent theories of selective attention have proposed that the selection of
 8 information in the environment is mainly dependent on two types of processes: top-down (aka
 9 goal-dependent) and bottom-up (aka stimulus-dependent) processes (Egeth & Yantis, 1997;
 10 Theeuwes, 2010a). Recently, numerous empirical studies have indicated various cognitive
 11 factors which can neither be categorized into top-down goals nor bottom-up processes to
 12 determine attentional selectivity (Awh et al., 2012; Theeuwes & Failing, 2020). Many of these
 13 cognitive factors are collectively referred to as “history-driven” influences on selective
 14 attention (Theeuwes & Failing, 2020). They hypothesized that top-down, bottom-up, and
 15 history-driven signals are projected onto a feature map representing selection priority to
 16 determine the selective behaviour of organisms (Theeuwes & Failing, 2020). Pertinent to this
 17 paper, we focus on the role of statistical learning, a history-driven cognitive mechanism, in
 18 attentional selection (Awh et al., 2012; Theeuwes & Failing, 2020; Wang & Theeuwes, 2018b).
 19

20 Frost et al. (2015) defined statistical learning as the “extraction of distributional
 21 properties from sensory input across time and space” (Frost et al., 2015). They suggested that
 22 statistical learning is one of the critical cognitive processes in the perceptual processing of
 23 sensory inputs (Frost et al., 2015). Multiple previous studies indicated that sensory systems
 24 utilize the statistical regularities in the sensory input for efficient perceptual processing (for
 25 review see, (Frost et al., 2019). For instance, targets (task-relevant) that frequently appear at a
 26 particular spatial location in visual search displays are perceptually processed better than targets
 27 at infrequent search locations (Awh et al., 2012; Chun & Jiang, 1998; Geng & Behrmann, 2002,
 28 2005; Jiang et al., 2013). Whereas recent studies also suggested that the salient distractors (task-
 29 irrelevant) that frequently appear at a particular spatial location in visual search displays are
 30 perceptually suppressed by showing their reduced interference in visual search task
 31 performance (faster RTs) compared to distractors at infrequent search locations to enhance the
 32 task efficiency (Duncan & Theeuwes, 2020; Failing, Feldmann-Wüstefeld, et al., 2019; Failing,
 33 Wang, et al., 2019; Li & Theeuwes, 2020; Lin et al., 2020; Theeuwes et al., 2018; Wang,
 34 Samara, et al., 2019; Wang & Theeuwes, 2018a, 2018b, 2018c). For example, Wang &

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1 Theeuwes (2018a) adopted a well-established additional singleton visual search paradigm
2 developed initially by (Theeuwes, 1991, 1992) with few modifications in their study. In the
3 classic additional singleton visual search task, participants are asked to search for a shape
4 singleton (a diamond among circles or vice versa) while ignoring a colour singleton distractor.
5 Typically, a reduced visual search task performance (slower RTs) is observed in colour
6 singleton present trials compared to colour singleton absent. This RT cost trials is considered
7 evidence for selective attentional priority of colour singleton distractors (Luck et al., 2020;
8 Theeuwes, 1992, 2010b). In their study, Wang & Theeuwes (2018a) have shown that if the
9 salient colour-singleton distractor more frequently appears at a particular spatial location in
10 visual search displays, its interference in visual search task performance is reduced (faster RTs)
11 compared to distractors at infrequent search locations. Thus, learning statistical regularities of
12 distractor locations modulates attentional processes to enhance task efficiency. Moreover, such
13 distractor statistical regularities improved search performance without the participants'
14 awareness, suggesting that learning distractor regularities is implicit and influences perception
15 independent of top-down control (Duncan & Theeuwes, 2020; Wang & Theeuwes, 2018b,
16 2018c). However, in recent studies utilizing similar probabilistic tasks, testing the awareness of
17 statistical regularities with more sensitive measures indicated the evidence of explicit
18 knowledge of awareness (Giménez-Fernández et al., 2020; Vadillo et al., 2020). These studies
19 cast doubts on the implicit nature of learning distractor statistical regularities in additional
20 singleton tasks.

21
22 Further, studies also indicate that the learning of distractor statistical regularities can be
23 non-spatial and feature-specific (Failing, Feldmann-Wüstefeld, et al., 2019; Stilwell et al.,
24 2019). For example, Stilwell et al. (2019) showed that a distractor colour that appears in search
25 displays more frequently was suppressed efficiently compared with a less frequent distractor
26 colour (Stilwell et al., 2019). Although the mechanisms of such distractor suppression are far
27 from clear, recent studies suggest that the experience of distractor statistical regularities induce
28 anticipatory or pro-active modulations in the first feedforward sweep of information processing
29 that de-prioritize the most probable distractor locations (Huang et al., 2021; Wang, Driel, et al.,
30 2019). Overall, there seems to be enough evidence to support the notion that our brain learns
31 and utilize statistical regularities of both task-relevant and task-irrelevant sensory stimuli for
32 optimizing behaviour.

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

19
20 We **conducted** two experiments in this study. The first experiment **was** designed to test
21 whether the study participants learn to utilize **task-irrelevant** auditory spatial regularities,
22 simultaneously presented across search displays, indicating **the** salient visual distractor's likely
23 location influence visual search task performance. The second study **was** designed to test
24 whether the task-irrelevant auditory non-spatial and frequency-based regularities,
25 simultaneously presented across search displays, indicating **the** salient visual distractor's likely
26 location influence visual search task performance. We adopted **the** additional singleton **visual**
27 search paradigm developed initially by Theeuwes (1991, 1992) with few modifications. **We**
28 manipulated statistical regularities of colour singleton distractor locations along with auditory
29 stimulus spatial (**Experiment 1**) and non-spatial, frequency-based (**Experiment 2**) regularities
30 **synchronously** presented across search displays (see **the** methods section for more details).
31 Critically, the spatial location of a colour singleton distractor in each trial could be either
32 predicted or unpredicted based on the task-irrelevant auditory **stimulus** statistical regularities.
33 For testing awareness about the relationship between auditory and visual distractor location
34 regularities, we **used** the confidence rating scale and ranking method, adapted with slight

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1 modifications from the study by Vadillo et al. (2020). The confidence rating scale and ranking
 2 methods are, arguably, more sensitive measures for testing awareness than dichotomous “Yes”
 3 or “No” responses and/or indicating a particular location where participants believe that the
 4 target/distractor appeared most frequently (Giménez-Fernández et al., 2020; Vadillo et al.,
 5 2020). First, at the end of the experiment, each participant had to indicate whether they noticed
 6 the relationship between auditory and visual distractor location regularities on a scale of 1 to 6
 7 (1= “Definitely not”; 6= “Definitely yes”). Second, participants were asked to rank three
 8 locations on the search display to indicate the high probability visual distractor for each sound
 9 stimulus separately (See the methods section for more details). The first, second, and third-
 10 ranked locations were given a score of 3, 2, and 1, respectively, and for all other locations, the
 11 score was zero. We assigned these locations into five categories (0-4) depending on their
 12 distance from the corresponding auditory stimuli that match the likely location of a salient
 13 visual distractor that is a “high-probability valid distractor location (HpValD)”. For each
 14 participant, we then combined the data of two sound stimulus conditions to calculate the mean
 15 scores obtained by location, according to the five categories mentioned above (0-4). We then
 16 analysed the linear relationship between mean scores received by each location from its
 17 distance from the actual HpValD location to test the awareness of audio-visual statistical
 18 regularities.

19
 20 **Hypothesis:**

21 This study tests the hypothesis regarding whether and how task-irrelevant, cross-modal
 22 stimulus statistical regularities indicating the salient visual distractor’s likely location in search
 23 displays influence search task performance in terms of response times (RTs). The graphical
 24 representation of the hypotheses is presented in Figure 1. We also tested participants’ awareness
 25 of the relationship between auditory and visual distractor location regularities for Experiments
 26 1 and 2.

27
 28 **Hypothesis #1:** We hypothesized that if participants learn to utilize auditory stimulus statistical
 29 regularities to anticipate the likely location of a salient visual distractor (colour singleton
 30 distractor) in search displays, the distractor locations indicated by the auditory stimuli (valid
 31 distractor location trials) are perceptually suppressed by pro-active modulations in the first
 32 sweep of information processing to optimize the search efficiency (Huang et al., 2021; Wang,
 33 Driel, et al., 2019). The response times (RTs) were expected to be shorter for conditions where
 34 auditory stimuli match the likely location of a salient visual distractor that is “high-probability

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1 valid distractor location (HpValD)” compared to the condition where auditory stimuli do not
2 match the likely location of a salient visual distractor that is “high-probability invalid distractor
3 location (HpInValD)” condition.

4

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

8

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

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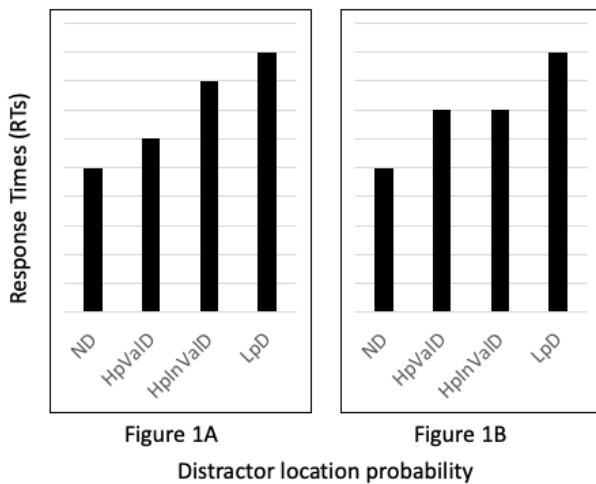
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Question

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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 (“High 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.

11

Sampling plan:

13

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

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1 size of interest as the lower limit of an 80% confidence interval for the effect size, by following
 2 the advice of Perugini et al. (2014).

3
 4 The determined effect size of interest was 0.332, estimated using the Shiny R web app
 5 (Maxwell et al., 2018). Conducting an a priori power analysis with effect size $d = 0.332$, given
 6 $\alpha = 0.02$ and power $\geq 90\%$, in a two-tailed matched-sample t-test, yields a minimum of 121
 7 participants required to test hypothesis #1 for each proposed experiment (calculated using
 8 G*Power 3.1). This sample size is considerably larger than the typical experiments conducted
 9 using the additional singleton tasks (an average of around 26 participants in (Failing,
 10 Feldmann-Wüstefeld, et al., 2019; Wang & Theeuwes, 2018a, 2018b, 2018c)).

11
 12 **Justification for the sample size to test hypothesis #2:** The sample size was determined based
 13 on an a priori power analysis. Most previous studies utilized dichotomous “Yes” or “No”
 14 responses and/or indicating a particular location where participants believe that the
 15 target/distractor appeared most frequently to test awareness of statistical regularities and
 16 concluded that the statistical learning is unconscious (e.g., in studies by (Failing, Feldmann-
 17 Wüstefeld, et al., 2019; Wang & Theeuwes, 2018b)). However, recent studies indicated that
 18 using a confidence rating scale and ranking methods are, arguably, more sensitive measures
 19 for testing awareness (Giménez-Fernández et al., 2020; Vadillo et al., 2020). Utilizing these
 20 sensitive measures to test awareness of statistical regularities in probabilistic cuing search
 21 tasks, the Vadillo et al. (2020) study indicated that participants are not unaware of the statistical
 22 regularities. Their study reported an effect size of Cohen's $h = 0.57$ for their meta-analysis of
 23 Experiments 1 and 2. However, choosing the effect size from the previous study at face value
 24 for an a priori power analysis is not recommended, as this leads to underpowered studies
 25 (Dienes, 2021; Perugini et al., 2014). To guard against the underpowered study, we determined
 26 the smallest effect size of interest as the lower limit of an 80% confidence interval for the effect
 27 size, by following the advice of Perugini et al. (2014).

28
 29 The determined effect size of interest was 0.426, estimated using Shiny R web app
 30 (Maxwell et al., 2018). Conducting an a priori power analysis with effect size of $d = 0.426$,
 31 given $\alpha = 0.02$ and power $\geq 90\%$, in a two-tailed matched-sample t-test yields a minimum
 32 of 75 participants required to test hypothesis #2 for each proposed experiment (calculated using
 33 G*Power 3.1).

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

4
 5 **Participant selection criteria:**

6
 7 Selected participants reported normal hearing and colour vision and normal or corrected
 8 to normal visual acuity with an age range from 18 to 35 years. Additionally, we tested whether
 9 the participants could discriminate the spatial location of sound (left and right) in experiment
 10 1. In Experiment 2, we tested whether participants could discriminate between two different
 11 sound frequencies (500Hz & 1000Hz). A short two-alternative forced choice, 20 auditory-only
 12 trials were presented to the participants to judge the sound location (e.g., Left or Right) or
 13 sound frequency (e.g., Low or High). Those participants who showed a minimum of 75%
 14 accuracy were selected for participation in the experiment. Selected participants provided
 15 informed consent before they participated in the study. The experimental procedures were
 16 approved by the Institutional Ethics Committee (IEC) of the Indian Institute of Technology
 17 Gandhinagar, India.

18
 19 **Materials:**

20
 21 The experiments were conducted in a dim-lit room. All the experimental stimuli were
 22 created and presented using MATLAB with Psychophysics Toolbox extensions (Brainard,
 23 1997). The visual stimuli were shown on an LCD monitor with a black background. Figure 2
 24 shows the schematic of a visual search display consisting of eight shapes (e.g., one diamond
 25 and seven circles) presented on an imaginary circle with a radius of 4 degrees centred at the
 26 white fixation cross (1x1 degree). Each unfilled shape (circle subtended with 1-degree radius,
 27 diamond subtended with 2 x 2 degrees) contains an embedded grey line (0.3 x 1.5 degrees,
 28 RGB:127/127/127) oriented either horizontally or vertically. The colour of the shapes in the
 29 search displays were red (RGB: 255/0/0) and green (RGB: 0/255/0). For example, the displays
 30 contain one circle in red, and the remaining all shapes will be in green or vice versa (50%
 31 probability). The auditory stimulus in Experiment 1 was a burst of white noise (50ms duration)
 32 presented via speakers placed on the left and right sides of the LCD screen. In experiment 2,
 33 auditory stimuli consist of two pure tones (50ms duration) with 500Hz or 1000Hz frequency

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1 presented via headphones. The sound level was adjusted for each participant according to their
2 comfort at the beginning of the experiment and was kept constant throughout the experiment.

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7 Experiment 1:

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

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18 Procedure and design for Experiment 1:

20 Each trial starts with a fixation cross presented until the trial ends. 500ms after the
21 fixation cross onset, the visual search display is presented for 2000ms or until the participant
22 makes a response (<2000ms). The participants were instructed to search for a shape singleton
23 in displays. For example, participants are asked to search for a diamond shape among circles or
24 vice versa and respond to the line segment's orientation embedded in the target. If the
25 orientation of the line segment is horizontal, the participant was required to press the "Z" key,
26 and if the line segment is vertical, the participant was required to press the "M" key as soon as
27 possible. Participants were asked to press the response key quickly and accurately. The target
28 (shape singleton) was present in all the trials, and the target can be either circle or diamond with
29 equal probability. A blank display with intertrial interval (ITI) will be randomly determined
30 between 500ms to 750ms. The timed-out responses were considered as incorrect responses. In
31 cases of incorrect responses and timed-out responses, feedback was provided to the participants
32 with white text "Incorrect response" or "Timed-out", respectively, at the center of the LCD
33 screen for 1000ms. Feedback was not provided for the correct responses. Two critical design

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1 factors are important in the experiment regarding the experimental manipulations of the
2 additional (color) singleton distractor and the auditory stimulus across the trials.

3

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

21

22 Auditory stimulus manipulations: No auditory stimulus was presented to the participants
23 for the distractor-absent trials. However, for the distractor-present trials, an auditory stimulus
24 was presented simultaneously with the search display. There were two critical manipulations in
25 the auditory stimulus presentations. First, when the additional singleton distractor appears in
26 one of the two high-probability search locations, the auditory stimulus will be more likely (80
27 %) to be presented at the spatially congruent side of the distractor location (left or right
28 hemifield) and less likely (20 %) to be presented at the spatially incongruent side. Second,
29 when the additional singleton distractor appears at one of the low-probability distractor
30 locations, the auditory stimulus is presented by both left and right-sided speakers. Thus, the
31 auditory stimulus is virtually perceived to be coming from the center of the search display. This
32 makes the auditory stimulus uninformative about the distractor location in the search display.

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Cross-modal statistical regularities and Visual selection

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

- 3 a) No distractor trials with no auditory stimulus (“no-distractor” condition)
- 4 b) Distractor appears in one of the two high probability locations with auditory stimulus
5 location match (“high-probability valid distractor location”)
- 6 c) Distractor appears in one of the two **high-probability** locations with auditory stimulus
7 location mismatch (“high-probability invalid distractor location”)
- 8 d) Distractor appears in one of the **low-probability** locations with the **uninformative**
9 auditory stimulus (“low-probability distractor location”)

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

15
16 Testing participants’ awareness of statistical regularities: To determine whether participants
17 are aware of the relationship between auditory and visual distractor location regularities, all
18 participants **had** to answer forced-choice questions at the end of the experiment (See
19 supplementary materials section). First, participants **were** asked to indicate whether they had
20 noticed regularities in the sound location such that the sound stimulus location **most** frequently
21 **matched** the color distractor location in display on a rating scale from 1 to 6. Second,
22 participants **were informed** that each sound stimulus location (Left or Right) was most
23 frequently matched with a specific color distractor location in display and asked to rank three
24 such locations for each sound stimulus location separately. The rating scale and ranking
25 methods are, arguably, more sensitive measures for testing awareness than dichotomous “Yes”
26 or “No” responses and/or indicating a location where participant believes that the
27 target/distractor appeared most frequently (Giménez-Fernández et al., 2020; Vadillo et al.,
28 2020).

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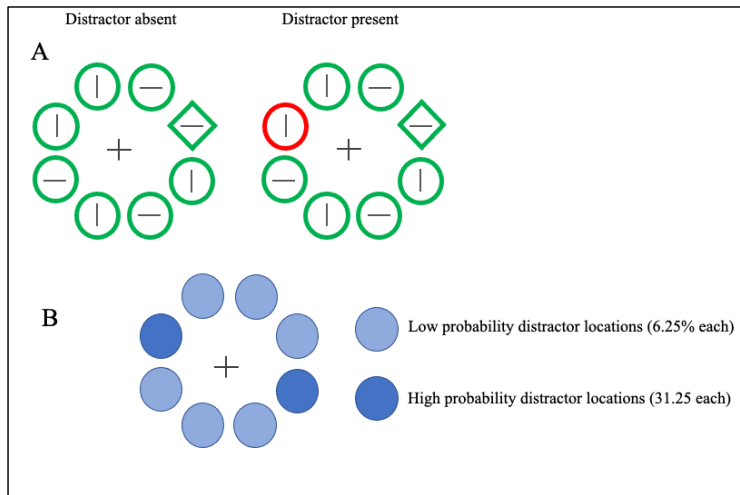


Figure 2. (A) Schematic illustration of search displays. The participant's task is to search for a shape singleton. In distractor present trials, participants will be instructed to ignore the colour-singleton distractor. (B) Schematic illustration of spatial regularities of distractors. Low-probability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

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Cross-modal statistical regularities and Visual selection

1 distractor-present trials, an auditory stimulus was presented simultaneously with the search
2 display. There were two critical manipulations in the auditory stimulus presentations. First,
3 when the additional singleton distractor appears in one of the two high-probability search
4 locations, the auditory stimulus was more likely to be (80%) presented with one of the two pure
5 tones (e.g., 500Hz frequency tone) and less likely to be (20%) presented with the other pure
6 tone (e.g., 1000Hz frequency tone) and vice versa. Second, when the additional singleton
7 distractor appears at one of the low probability distractor locations, the auditory stimulus was a
8 noise burst with a 50ms duration.

9
10 Like Experiment 1, the combination of the additional singleton distractor and auditory
11 stimulus manipulations in the trials generate the following four different experimental
12 conditions:

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

20
21 Testing participants’ awareness of statistical regularities: The questionnaire for the experiment
22 is similar to Experiment 1 mentioned above, except that we used text sound pitch, either high
23 or low, instead of the text mentioning the right or left sound locations.

24 Participant and data replacement:

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

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

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1 **Data analysis plan:**

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

8

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

13

14 Analysis of participants’ awareness of regularities: We planned to calculate the mean
 15 rating for Question #1 in the questionnaire for the awareness test (see the supplementary
 16 materials). As mentioned in the methods above, all participants will be asked to rank three
 17 locations for each sound stimulus condition separately (Question #2 & Question #3). The first,
 18 second, and third-ranked locations will be given scores of 3, 2, and 1, respectively. For the
 19 remaining locations, the scores will be zero. We assign these locations into five categories (0-
 20 4) depending on their distance from the corresponding HpValD location. For example, 0
 21 corresponds to the HpValD location, 1 corresponds to two locations immediately next to the
 22 HpValD location, and so on. For each participant, we then combine the data from Question #2
 23 & Question #3 to calculate the mean scores obtained by location, according to the five
 24 categories mentioned above (0-4). To analyse the data, we planned to use a linear mixed-effects
 25 model with a random intercept for participants to determine a linear relationship between scores
 26 obtained by each location and their distance from the HpValD location (0-4).

27

28 **Predicted Outcomes:**

29 The experimental question is whether the task-irrelevant auditory regularities indicative
 30 of the additional singleton location in the visual search display modulates the search efficiency.
 31 Suppose the auditory regularities indeed generate the predictions for the likely distractor
 32 location. In that case, these distractor locations (in “high-probability valid distractor location”)
 33 are perceptually suppressed, and the RTs in those trials are shorter than invalid distractor
 34 locations (in “high-probability invalid distractor location” trials). Likewise, in Experiment 2,

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1 RTs are expected to be shorter for high-probability valid distractor location trials (indicated by
2 sound feature) than for high-probability invalid distractor location trials. A graphical
3 representation of experimental predictions is presented in Figure 1.

4 **Results and Discussion of Experiment 1:**

5 Pre-registered analysis:

6 In accordance with participant selection criteria, a total of 132 participants were
7 recruited for the Experiment 1. Out of these, we excluded the data of 8 participants who failed
8 to achieve a minimum of 75% overall accuracy in the search task (pre-registered criteria). The
9 remaining data from 124 participants were included for further analysis.

10 Mean correct RTs were used for the statistical testing by removing the incorrect
11 responses (including timed-out trials) (9.47% removed) and response times shorter than 200ms
12 (0.4% removed). All the statistical analyses were performed using JASP, an open-source
13 statistical software (Team, 2022). In cases where the sphericity assumption was violated for
14 tests of repeated measures of ANOVA, the reported p-values are Greenhouse-Geisser
15 corrected. Similarly, in cases where the assumption of normality was violated (Shapiro-Wilk
16 test) for paired t-tests, the reported p-values were obtained by Wilcoxon signed-rank tests. In
17 accordance with the pre-registered analysis plan, a statistical significance threshold of 0.02 was
18 used to interpret the results.

19 RT analysis:

20
21 The paired samples T-test between mean RTs of experimental conditions HpValD and
22 HpInValD revealed a non-significant difference between them (HpValD: 1022.227ms ±
23 137.409; HpInValD = 1023.794ms ± 140.716; $p > 0.02$, $r_b = 0.041$). These results indicate that
24 the valid distractor locations (distractor appears in one of the two high probability locations
25 with auditory stimulus location match) were not perceptually suppressed relative to the invalid
26 distractor locations (distractor appears in one of the two high probability locations with auditory
27 stimulus location mismatch). Figure 3 shows the mean RTs and percent of incorrect responses
28 for all experimental conditions in Experiment #1.

29

30 Awareness test:

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1 Figure 4 provides the responses received by participants for Question #1 in the
2 Questionnaire for testing awareness of statistical regularities. When participants were asked
3 whether they had noticed that a given sound location frequently matched with a distractor
4 location in search displays, the modal response was “probably yes”. The average response (\pm
5 SD) on a scale of 1 to 6 is 3.298 ± 1.275 . Overall, participants were less confident in their
6 responses in both directions.

7 Following the pre-registered protocol, we calculated the mean scores obtained by each
8 location based on five categories (0-4) for each participant. Figure 5 (Left panel) summarizes
9 mean scores for each of the five categories (0-4). A linear mixed effects model with random
10 intercepts for participants indicated that the mean scores for each location were significantly
11 decreased linearly as a function of its distance from the HpValD location ($b = -0.136$, $t(618) =$
12 -8.113 , $p < 0.001$). These results suggest that the participants are aware of the relationship
13 between auditory stimulus location and visual distractor location regularities in Experiment #1.

14 Non-Pre-registered analysis:

15 We explored whether colour singleton distractors interfere with search task when the
16 distractor is present in low and high-probability distractor locations (regardless of sound
17 stimulus manipulations in the experiment) relative to the distractor-absent trials. This
18 exploratory analysis was intended to see whether the data replicated the distractor suppression
19 effects typically observed in prior studies (e.g., Wang & Theeuwes, 2018). For each
20 participant, we calculated mean search RTs for distractor absent trials (ND), distractor-present
21 trials in low probability locations (LpD), and distractor-present trials in high probability
22 locations (HpD; combined HpValD and HpinValD trials). Mean RTs were submitted to a one-
23 way repeated-measures of ANOVA with the experimental condition of interest (ND vs. LpD
24 vs. HpD) as a factor. The analysis indicated a significant main effect of condition, $F(2, 246) =$
25 664.12 , $p < 0.001$, partial $\eta^2 = 0.844$. Relative to RTs on no-distractor trials ($944.1\text{ms} \pm$
26 134.93), RTs were significantly slower in the HpD condition ($1022.55\text{ms} \pm 137.606$, $p < 0.001$,
27 $r_b = 0.981$), and LpD condition ($1059.461\text{ms} \pm 138.19$, $p < 0.001$, $r_b = 0.999$). Moreover, RTs in
28 the LpD condition were significantly slower than RTs in the HpD condition ($p < 0.001$, $t(123)$
29 $= 16.197$, Cohens' $d = 1.455$). A similar analysis was conducted on the percentage of incorrect
30 responses in each condition of interest. The one-way repeated measures of ANOVA indicated
31

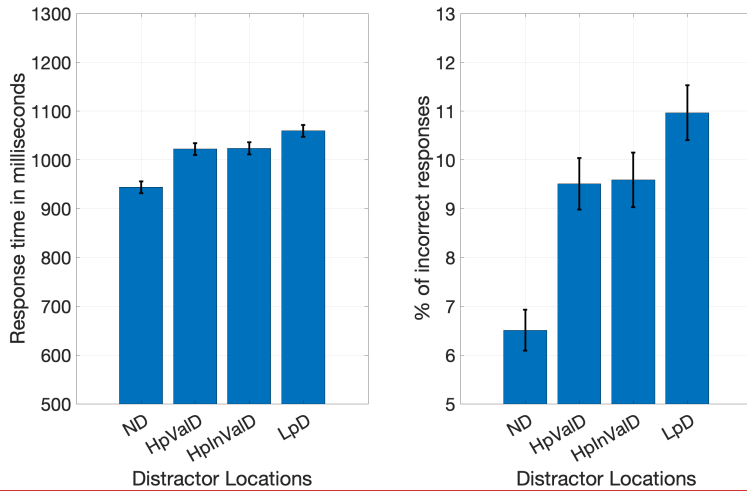
Cross-modal statistical regularities and Visual selection

1 a significant main effect of condition, $F(2, 246) = 166.53$, $p < 0.001$, partial $\eta^2 = 0.574$.
2 Relative to the percentage of incorrect responses on no-distractor trials ($6.746\% \pm 5.371$),
3 incorrect responses were significantly higher in the HpD condition ($9.761\% \pm 6.396$, $p < 0.001$,
4 $r_b = 0.910$), and LpD condition ($11.136\% \pm 6.686$, $p < 0.001$, $r_b = 0.967$). Moreover, the
5 percentage of incorrect responses were significantly higher in the LpD condition than in the
6 HpD condition ($p < 0.001$, $t(123) = 7.278$, Cohens' $d = 0.654$). This pattern of results indicates
7 that the response time differences among conditions were not due to the speed-accuracy trade-
8 off. Overall, results indicate that the singleton distractors indeed capture attention and interfere
9 with search tasks indicated by slower RTs in search displays when the distractor was present
10 compared to when it was absent. Further, this effect was improved when distractors were
11 present in high-probability locations compared to low-probability locations which indicates the
12 better suppression of distractors at high-probability locations compared to low-probability
13 locations.

14 We conducted paired t-test on the mean percent of incorrect responses between HpValD
15 and HpInValD conditions to check if the observed non-significant difference in mean RTs of
16 HpValD and HpInValD were due to speed-accuracy trade-off. We found a non-significant
17 difference in the mean percent of incorrect responses between HpValD condition ($9.511\% \pm$
18 5.884) and the HpInValD condition ($9.590\% \pm 6.223$, $p > 0.02$, $t(123) = 0.313$, Cohens' $d =$
19 0.028). These results indicate that the non-significant difference in mean response times
20 between HpValD and HpInValD was not a consequence of the speed-accuracy trade-off.

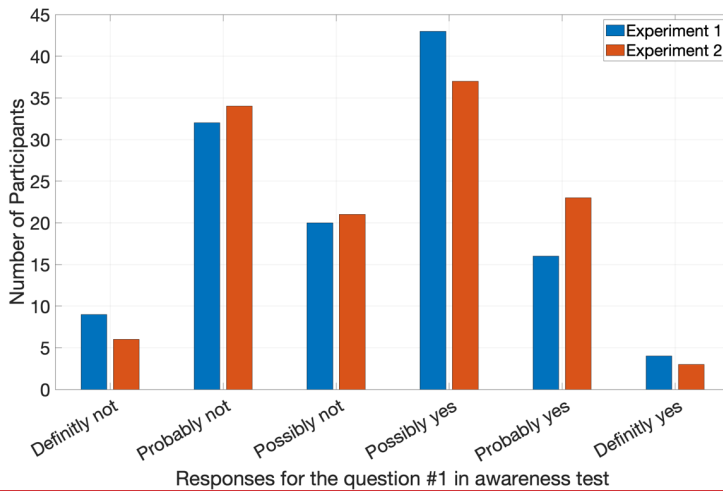
21 Next, we conducted one-way repeated measures of ANOVA on mean RTs in all
22 experimental conditions (ND vs. HpValD vs. HpInValD vs. LpD). This analysis was intended
23 to test whether the data passed the pre-registered outcome-neutral criteria (i.e., absence of floor
24 and ceiling effects). There was a main effect of experimental condition, $F(3, 369) = 436.441$,
25 $p < 0.001$, partial $\eta^2 = 0.780$. Bonferroni corrected post-hoc test revealed that RTs were
26 significantly faster in ND compared to all other conditions (all $p < 0.001$), and RTs were
27 significantly slower in LpD compared to all other conditions (all $p < 0.001$). Similarly, the
28 mean percentage of incorrect responses was significantly lower in ND compared to all other
29 conditions (all $p < 0.001$), and the percentage of incorrect responses were significantly higher
30 in LpD compared to all other conditions (all $p < 0.001$). These results indicate that data passed
31 the pre-registered outcome-neutral criteria and ensure that the experimental results can test the
32 stated hypothesis proposed in the pre-registered protocol.

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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.



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

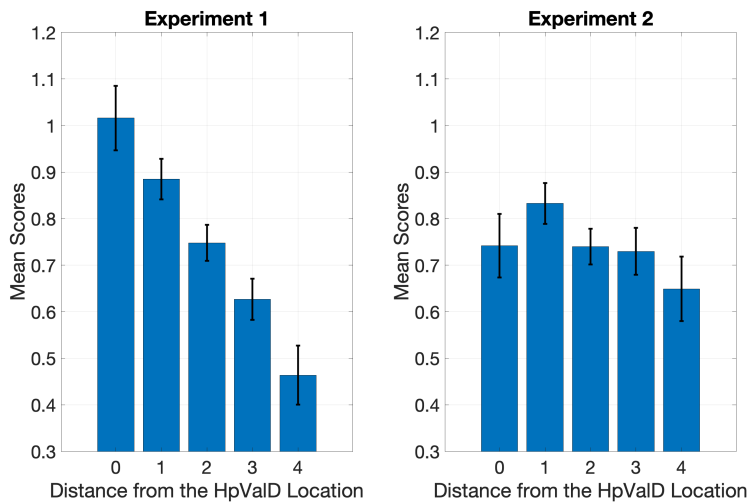


Figure 5. Summary of responses received by participants for Questions 2 & 3 in the awareness test. Left panel for Experiment #1; Right panel for Experiment #2. Error bars indicative of SEM.

Results and Discussion of Experiment 2:

Pre-registered analysis:

In accordance with the participant selection criteria, a total of 127 participants were recruited for Experiment 2. 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.

Mean correct RTs were used for the statistical testing by removing the incorrect responses (including timed-out trials) (9.6% removed) and response times shorter than 200ms (0.2% removed). 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-

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1 values were obtained by Wilcoxon signed-rank tests. In accordance with the pre-registered
2 analysis plan, a statistical significance threshold of 0.02 was used to interpret the results.

3 RT analysis:

4 According to the pre-registered protocol, comparison between mean RTs of
5 experimental conditions HpValD and HpInValD with paired samples t-test revealed a non-
6 significant difference between them (HpValD: 1031.683ms \pm 121.377; HpInValD:
7 1028.521ms \pm 124.485; $p > 0.02$, $r_b = 0.106$). These results indicate that the valid distractor
8 locations (distractor appears in one of the two high probability locations with auditory stimulus
9 feature match) were not perceptually suppressed relative to the invalid distractor locations
10 (distractor appears in one of the two high probability locations with auditory stimulus feature
11 mismatch). Figure 6 shows the mean RTs and percent of incorrect responses for all
12 experimental conditions in Experiment #2.

14 Awareness Test:

15 Figure 4 provides the responses received by participants for Question #1 in the
16 awareness tests. When participants were asked whether they had noticed if a given sound pitch
17 (high pitch or low pitch) frequently matched with a distractor location in search displays, the
18 modal response was “probably yes”. The average response (\pm SD) on a scale of 1 to 6 is 3.371
19 \pm 1.265. Overall, participants were low confident in their responses in both directions.

20 Following the pre-registered protocol, we calculated the mean scores obtained by each
21 location based on five categories (0-4) for each participant. Figure 5 (Right panel) summarizes
22 mean scores for each of the five categories (0-4). A linear mixed effects model with random
23 intercepts for participants indicated that the mean scores for each location were not
24 significantly decreased linearly as a function of its distance from the HpValD location ($b = -$
25 0.03, $t(618) = -1.646$, $p > 0.02$). These results suggest that the participants do not have
26 awareness of the relationship between auditory stimulus features and visual distractor location
27 regularities in Experiment #2.

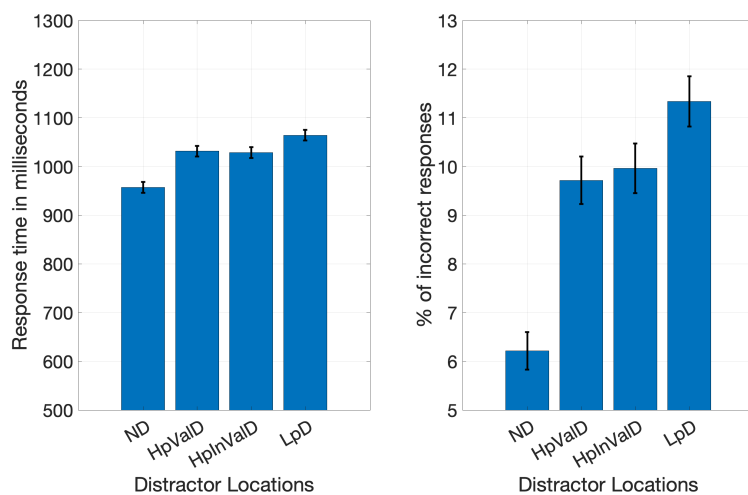
1 Non-Pre-registered analysis:

2 Similar to Experiment #1, we explored whether colour singleton distractors interfere
3 with the search task performance when the distractor is present in low and high-probability
4 distractor locations (regardless of sound stimulus manipulations in the experiment) relative to
5 the distractor absent trials. Mean RTs were submitted to a one-way repeated-measures of
6 ANOVA with the experimental condition of interest (ND vs. LpD vs. HpD) as a factor. The
7 analysis indicated a significant main effect of condition, $F(2, 246) = 686.784$, $p < 0.001$, partial
8 $\eta^2 = 0.848$. Relative to RTs on no-distractor trials ($956.955\text{ms} \pm 124.285$), RTs were
9 significantly slower in HpD condition ($1031.087\text{ms} \pm 121.421$, $p < 0.001$, $t(123) = 22.704$,
10 Cohen's $d = 2.039$), and LpD condition ($1064.347\text{ms} \pm 123.018$, $p < 0.001$, $t(123) = 30.890$,
11 Cohen's $d = 2.774$). Moreover, RTs in the LpD condition were significantly slower than RTs
12 in the HpD condition ($p < 0.001$, $t(123) = 17.393$, Cohen's $d = 1.562$). A similar analysis was
13 conducted on the percentage of incorrect responses in each condition of interest. The one-way
14 repeated measures of ANOVA indicated a significant main effect of condition, $F(2, 246) =$
15 202.362 , $p < 0.001$, partial $\eta^2 = 0.622$. Relative to the parentage of incorrect responses on no-
16 distractor trials ($6.368\% \pm 4.782$), incorrect responses were significantly higher in HpD
17 condition ($9.892\% \pm 5.760$, $p < 0.001$, $r_b = 0.944$), and LpD condition ($11.508\% \pm 6.234$,
18 $p < 0.001$, $t(123) = 17.413$, Cohen's $d = 1.564$). Moreover, the mean percentage of incorrect
19 responses was significantly higher in the LpD condition than in the HpD condition ($p < 0.001$,
20 $r_b = 0.681$). These patterns of results indicate that the response time differences in conditions
21 were not due to the speed-accuracy trade-off. Overall, results provide evidence that singleton
22 distractors indeed capture attention and interfere with search tasks indicated by slower RTs in
23 search displays when the distractor is present compared to when it is absent. Further, this effect
24 was partially ameliorated when the distractor was present in high-probability locations
25 compared to low-probability locations, which indicates the suppression of distractors at high-
26 probability locations compared to low-probability locations.

27 We then conducted paired t-test on the mean percent of incorrect responses between
28 HpValD and HpInValD conditions to check if the observed non-significant difference in mean
29 response times of HpValD and HpInValD were not due to speed-accuracy trade-off. We found
30 a non-significant difference between the mean percentage of incorrect responses of HpValD
31 condition ($9.716\% \pm 5.446$) and HpInValD condition ($9.966\% \pm 5.675$, $p > 0.02$, $t(123) =$

1 0.898, Cohen's $d = 0.05$), which shows that mean RT differences were not due to speed-
 2 accuracy trade-off.

3 Next, we conducted a one-way repeated measures of ANOVA on mean RTs with all
 4 experimental conditions (ND vs. HpValD vs. HpInValD vs. LpD). This analysis was intended
 5 to test whether the data passed the pre-registered outcome-neutral criteria (i.e., absence of floor
 6 and ceiling effects). There was a main effect of experimental condition, $F(3, 369) = 438.309$,
 7 $p < 0.001$, partial $\eta^2 = 0.781$. Bonferroni corrected post-hoc test revealed that the mean RTs
 8 were significantly faster in ND compared to all other conditions (all $p < 0.001$), and RTs were
 9 significantly slower in LpD compared to all other conditions (all $p < 0.001$). Similarly, the
 10 mean percentage of incorrect responses was significantly lower in ND compared to all other
 11 conditions (all $p < 0.001$), and the percentage of incorrect responses were significantly higher
 12 in LpD compared to all other conditions (all $p < 0.001$), which assures that RT differences were
 13 not a consequence of speed-accuracy trade-off. These results indicate that the data passed the
 14 pre-registered outcome-neutral criteria (i.e., absence of floor and ceiling effects) and ensured
 15 that the results of Experiment #2 could test the stated hypothesis proposed in the pre-registered
 16 protocol.



17
 18 Figure 6. Mean response times (left panel) and percent of incorrect responses (right panel) for experiment 2. ND
 19 = No distractor trials; HpValD = Trials with the distractor appeared in one of the two high probability locations
 20 with auditory stimulus feature match; HpInValD = Trials with the distractor appeared in one of the two high

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1 probability locations with auditory stimulus feature mis-match; LpD = Trials with the distractor appeared in low
2 probability locations. Error bars indicate \pm SEM.

4 **General Discussion:**

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

15 We hypothesised that the statistical regularities of cross-modal stimuli would induce
16 distractor suppression at valid distractor locations relative to invalid distractor locations via
17 pro-active changes within the attentional priority map (Huang et al., 2021; Wang, Driel, et al.,
18 2019). The results replicated earlier findings of visual distractor suppression that shows faster
19 RTs for trials that contain distractors at high-probability locations compared to low-probability
20 locations (Duncan & Theeuwes, 2020; Failing, Feldmann-Wüstefeld, et al., 2019; Failing,
21 Wang, et al., 2019; Li & Theeuwes, 2020; Lin et al., 2020; Theeuwes et al., 2018; Wang,
22 Samara, et al., 2019; Wang & Theeuwes, 2018a, 2018b, 2018c). Contrary to our hypothesis ,
23 however, results did not show RT advantage for valid distractor location trials as compared
24 with invalid distractor location trials in both Experiments 1 and 2. This absence of RT
25 advantage for valid distractor trials indicates that neither predictive nor un-predictive auditory
26 stimuli modulate the distractor suppression effect. This outcome was observed irrespective of
27 whether the auditory stimulus statistical regularities were spatial or not. Moreover, these results
28 suggest that, at least under the conditions of Experiments 1 and 2, the participants are unable
29 to learn associations between the location of the visual distractor and the auditory stimulus.
30 Our findings support the null effect that statistical regularities of cross-modal stimuli do not

1 modify distractor suppression in additional singleton search tasks (See Results and Discussion
2 Sections).

3 Prior research indicates that statistical learning of visual distractors and their
4 suppression effects develop quickly during visual search (Valsecchi & Turatto, 2021).
5 However, we do not have evidence for how fast or slow the learning of cross-modal statistical
6 regularities are as compared with modality specific statistical regularities in the context of
7 auditory stimuli and visual distractors. It is plausible that the time course of learning is slower
8 for the cross-modal statistical regularities due to their complexity. In such cases, it is
9 appropriate that the RT performance be analysed in terms of epochs rather than taking mean
10 performance per experimental condition. The epoch-wise analysis would reveal if there are any
11 significant RT differences between valid and invalid distractor location trials as the duration of
12 Experiment progresses. For each Experiment, mean RT performance was then calculated
13 across six consecutive experimental blocks per condition (valid and invalid distractor trials) for
14 each participant. Figure S2 in the Supplementary Material shows the mean RTs as a function
15 of epochs, separately for valid and invalid distractor trial conditions. We submitted mean RTs
16 to repeated measures of ANOVA with factors Validity (Valid vs. Invalid distractor trials) and
17 Epochs (1 to 6), separately for Experiments 1 and 2. The results indicated a significant main
18 effect of Epoch (with a significant linear decrease in RTs, $p < 0.001$) for both Experiments. The
19 main effect of Epoch is evidence for efficient task performance as a function of the experiment
20 progress, indicating procedural learning (Schneider & Shiffrin, 1977). However, neither the
21 main effect of Validity ($p > 0.05$) nor the interaction between Epoch \times Validity ($p > 0.05$) were
22 significant for both Experiments. This pattern of results shows that RT performance did not
23 significantly differ between the valid and invalid distractor location trials across Epochs,
24 corroborating the lack of evidence supporting distractor suppression effects by statistical
25 regularities of cross-modal stimuli.

26 In general, we find no reliable effect of cross-modal statistical regularities on visual
27 distractor processing during visual search. One possible explanation for this result is related to
28 available attentional resources to process auditory information during visual search. Given that
29 the visual information is task-relevant, participants' attention may have been preferentially
30 allocated to visual information leaving diminished attentional resources for auditory
31 information. This reduced or lack of attentional resources for auditory information might have
32 impaired the learning of statistical regularities between the distractor location and the auditory

1 stimulus. Indeed, prior research suggested that allocating attention to sensory events is required
2 for statistical learning (Failing & Theeuwes, 2020; Turk-Browne et al., 2005) and cross-modal
3 association (Ikumi & Soto-Faraco, 2014). Thus insufficient attentional resources for learning
4 cross-modal statistical regularities might have gated the distractor suppression effects.

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

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

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1 From the observed “low confidence” in the subjective measure of awareness, it is
2 difficult to conclude whether the participants are “aware” or “unaware” of statistical
3 regularities. The reason for this difficulty in categorization is that the “low confidence” in
4 subjective measure could be attributed to either conservative bias in participants’ responses or
5 lack of awareness of regularities (Fleming & Lau, 2014; Tversky & Kahneman, 1974).
6 Therefore, it is rather useful to categorise whether the participants’ are “aware” or “unaware”
7 of regularities based on objective measures only. Hence, in line with the pre-registered
8 protocol, we consider the results of objective measures to support the evidence that the
9 participants are “aware” of statistical regularities in Experiment 1 but not in Experiment 2. The
10 relative contributions of whether the participants’ are “aware” or “unaware” of regularities on
11 distractor suppression is not clear from the previous literature (Theeuwes et al., 2022). It
12 appears that, however, having participants are “aware” of regularities (as observed in
13 Experiment 1) may not be a necessary and sufficient condition for cross-modal influence on
14 the distractor processing.

15 The asymmetry in participants’ objective measures of awareness of statistical
16 regularities between Experiment 1 and Experiment 2 is unclear. We speculate that participants
17 might be biased to rank locations in the region of the screen that is on the same side as the
18 auditory stimulus in Experiment 1. This bias may not have occurred in Experiment 2, where
19 auditory stimulus regularities were non-spatial. According to the two dominant theories of
20 consciousness, such as ‘higher order theories’ and ‘integration theories,’ having objective while
21 lacking strong subjective awareness indicates that the knowledge is unconscious (Dienes &
22 Seth, 2022). In line with these theories of consciousness, the participants’ lack of a strong
23 subjective awareness in both Experiments, corroborate the claim that the participants are
24 “unaware” of the statistical regularities. Future research is required to address the problems in
25 interpreting subjective as well as objective measures of awareness.

26
27 In summary, our experimental results indicate no reliable effect of task-irrelevant cross-
28 modal stimulus regularities on distractor suppression, irrespective of participants’ awareness
29 of the relationship between distractor location and predictive auditory stimulus. Based on our
30 study results and prior studies, we suggest that pro-active distractor suppression might be
31 possible in cases of statistical regularities of within-modality stimulus but not plausible by the
32 cross-modal stimulus. Future studies are required to explore whether statistical regularities of

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- 1 [cross-modal stimuli modulate the distractor processing in various experimental contexts and](#)
- 2 [cross-modal combinations at behavioural and neural levels.](#)
- 3
- 4

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2 We would like to thank the study participants for their time to participate in the experiment.

3 We would also like to thank Ms. Manushi Pandya for her support in data collection process.

4

5 **CRediT Authorship contribution statement:**

6 KKJ: Conceptualization, Investigation, Methodology, Formal analysis, Visualization,

7 Software, Writing - original draft, Writing - review & editing

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

9

10 **Competing interests:**

11 The authors declare no competing interests.

12

13 **Data and Code availability:**

14

15 Anonymised data (includes raw and summary level data, Laboratory record), Experimental

16 codes, Scripts for generating Data figures, Supplementary Material (includes Pre-registered

17 Study Design Table, Questionnaire, Pilot Experiment details), and “Readme.txt” file (explains

18 contents of every file and variable labels within files) are made publicly available at the Open

19 Science Framework repository: <https://doi.org/10.17605/OSF.IO/9M35P>

20

21 Note: We have performed all statistical tests of data using JASP statistical software (Open-

22 source). Therefore, we do not have specific scripts for statistical analysis.

23

24 Authors’ statement: “We report how we determined our sample size, all data exclusions, all

25 inclusion/exclusion criteria, whether inclusion/exclusion criteria were established prior to data

26 analysis, all manipulations, and all measures in the study”

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Supplementary Material

Study Design Table:

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<u>Question</u>	<u>Hypothesis</u>	<u>Sampling Plan</u>	<u>Analysis Plan</u>	<u>Interpretation given different outcomes</u>
<p><u>Do task-irrelevant cross-modal (auditory) spatial regularities induce distractor suppression in visual search? (Experiment 1)</u></p>	<p><u>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.</u></p>	<p><u>We aim to recruit a minimum of 121 participants (who meets the participant selection criteria) from the Indian Institute of Technology.</u></p> <p>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).</u></p> <p><u>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)).</u></p>	<p><u>We will use paired t-test to compare experimental conditions of HpValD (“high-probability valid distractor location”) with HpInValD (“high-probability invalid distractor location”). Significance level – α set to 0.02, with power > 0.90.</u></p>	<p><u>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.</u></p>

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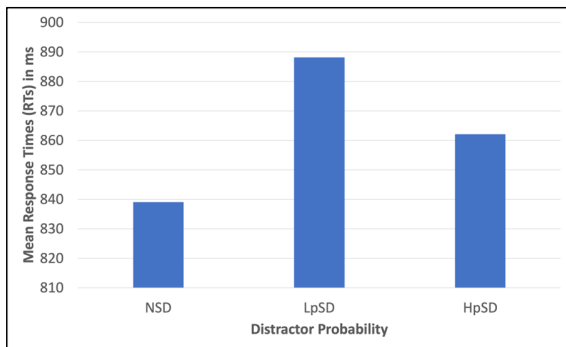
<p><u>Do task-irrelevant cross-modal (auditory) non-spatial, frequency-based regularities induce distractor suppression in visual search? (Experiment 2)</u></p>	<p><u>The response times (RTs) are expected to be shorter for HpValD — “high-probability valid distractor location” trials compared to the HpInValD — “high-probability invalid distractor location” trials.</u></p>	<p><u>As above</u></p>	<p><u>As above</u></p>	<p><u>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.</u></p>
<p><u>Do participants have awareness about the relationship between the auditory (spatial) and visual distractor location regularities? (Experiment 1)</u></p>	<p><u>We hypothesize that if the participants are aware of 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.</u></p>	<p><u>Minimum of 75 participants.</u> <u>Sample Size Justification:</u> <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 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).</u> <u>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 $\geq 90\%$ with alpha set to 0.02 (calculated using G*Power 3.1) in a two-tailed matched-sample t-test.</u></p>	<p><u>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.</u></p>	<p><u>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.</u></p>
<p><u>Do participants have</u></p>	<p><u>As above</u></p>	<p><u>As above</u></p>	<p><u>As above</u></p>	<p><u>As above</u></p>

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



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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).

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

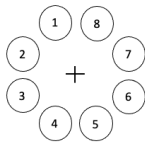
3
4 Question #1: You might have noticed that, in most of the displays, one of the visual items in display
5 appeared in a different color than the rest (e.g., red color visual item among green items or vice
6 versa). Do you think that a given sound location (e.g., the sound coming from the Left or Right side of
7 the display) was most frequently matching a particular location of this visual item in the display?
8

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

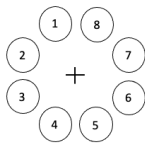
- 10 * Definitely not (Press 1)
- 11 * Probably not (Press 2)
- 12 * Possibly not (Press 3)
- 13 * Possibly yes (Press 4)
- 14 * Probably yes (Press 5)
- 15 * Definitely yes (Press 6)

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

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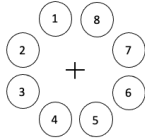


27
28 * Now, ignoring your previous response, if you had to choose the next location where the differently
29 colored visual item frequently appeared along with the sound coming from the left side of the display,
30 which one that would be, in your opinion? Please indicate such location by pressing corresponding
31 numbered spatial locations shown on the below example display.



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34 * Finally, ignoring your previous response, if you had to choose the next location where the
35 differently colored visual item frequently appeared along with the sound coming from the left side of
36 the display, which one that would be, in your opinion? Please indicate such location by pressing
37 corresponding numbered spatial locations shown on the below example display.
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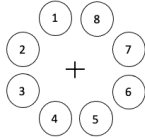
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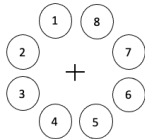
Question #3: In the experiment, in most of the trials, the sound coming from the right side of the display was most frequently matched with a particular location of the differently colored visual item in the display.

* 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



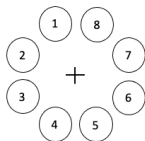
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* Now, ignoring your previous response, if you had to choose the next location where the differently colored visual item frequently appeared along with the sound coming from the Right side of the display, which one that would be, in your opinion? Please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



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* 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.



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For experiment 2:

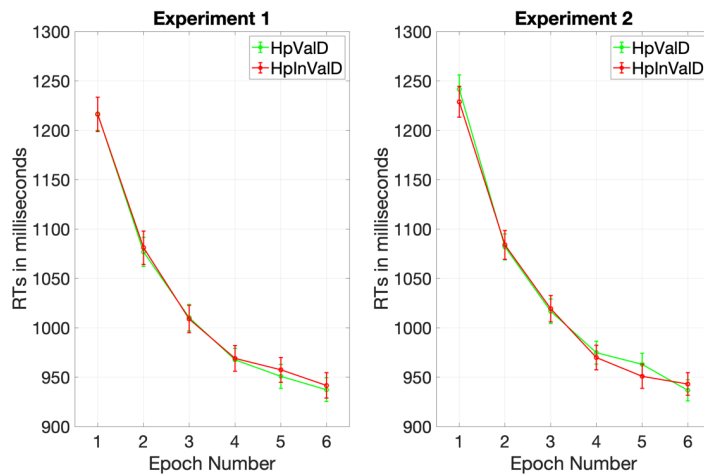
The questionnaire for experiment 2 will be similar to the experiment 1 mentioned above, except that we will use text sound pitch, either high or low, instead of the text mentioning the right or left sound locations.

1 **RT performance analysis in terms of Epochs:**

2 Figure S2 (left panel for Experiment 1; Right panel for Experiment 2) shows the mean
 3 RTs as a function of epochs, separately for valid (HpValD) and invalid distractor (HpInValD)
 4 trial conditions.

5 Results for Experiment 1: A 2 (Validity: HpValD vs. HpInValD) × 6 (Epoch: 1-6)
 6 repeated measures of ANOVA on mean RTs revealed a significant main effect of Epoch, F
 7 (5, 615) = 299.131, $p < .001$, $r_b = 0.709$. The main effect of Validity was not significant
 8 ($p > 0.05$), and a non-significant Validity × Epoch interaction ($p > 0.05$).

9 Results for Experiment 2: A 2 (Validity: HpValD vs. HpInValD) × 6 (Epoch: 1-6)
 10 repeated measures of ANOVA on mean RTs revealed a significant main effect of Epoch, F
 11 (5, 615) = 347.076, $p < .001$, $r_b = 0.738$. The main effect of Validity was not significant
 12 ($p > 0.05$), and a non-significant Validity × Epoch interaction ($p > 0.05$).



13 Figure S2: Mean RTs as a function of epochs, separately for valid (HpValD) and invalid
 14 distractor (HpInValD) trial conditions. Left panel: Experiment 1, Right panel: Experiment 2.
 15 Error bars represent SEM.

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1

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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.

1

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3

4

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