

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

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13  
14 **Type of Manuscript:** Registered report – Stage 1 Proposal

15  
16 **Conflict of Interest Statement:**

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

19  
20 **Ethics approval statement:**

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

23  
24 **Data availability:**

25 The authors confirm that the raw data and experimental/analysis code will be made  
26 available to the public.

27  
28 **Funding:**

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

Cross-modal statistical regularities and Visual selection

1 Dear Recommender/Editor, PCI RR

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

11  
12 This registered report proposes to test a question that addresses whether the study participants learn to  
13 utilize task-irrelevant, cross-modal stimulus spatial (Experiment 1) and non-spatial regularities  
14 (Experiment 2) indicating the salient visual distractor’s likely location in search displays to perceptually  
15 suppress them for optimizing task efficiency. It would provide evidence that the visuospatial attentional  
16 priority map can flexibly be modified based on the learning of task-irrelevant, cross-modal stimulus  
17 statistical regularities.

18  
19 We confirm that sufficient funding and facilities are available to complete the proposed study  
20 successfully. The experimental procedures involved in this study are already approved by the  
21 Institutional Ethics Committee (IEC) of the Indian Institute of Technology Gandhinagar, India. We  
22 expect to complete the proposed study within three months of study approval. After completing data  
23 collection, we will analyze the data and write the manuscript within one to two months. We agree that  
24 the raw data and experimental/analysis code will be made available to the public. Following Stage-1 in-  
25 principle acceptance, we agree to register the approved protocol on the Open Science Framework or  
26 any other recognized repository either publicly or under private embargo until Stage-2 manuscript  
27 submission. We also agree that if the paper is retracted for any reason, a summary of the proposed pre-  
28 registered study will be made available to publish if required.

29  
30 Sincerely,  
31 (On behalf of authors)  
32 Kishore Kumar Jagini  
33 Indian Institute of Technology Gandhinagar, India.

1 **Abstract:**

2

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

17

18

19 **Keywords:**

20 attention, attention capture, distractor suppression, cross-modal, statistical regularities

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## 1 **Introduction**

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

18  
19 Frost et al. (2015) defined statistical learning as the “extraction of distributional  
20 properties from sensory input across time and space” (Frost et al., 2015). They suggested that  
21 statistical learning is one of the critical cognitive processes in the perceptual processing of  
22 sensory inputs (Frost et al., 2015). Multiple previous studies indicated that sensory systems  
23 utilize the statistical regularities in the sensory input for efficient perceptual processing (for  
24 review see, (Frost et al., 2019). For instance, targets (task-relevant) that frequently appear at a  
25 particular spatial location in visual search displays are perceptually processed better than targets  
26 at infrequent search locations (Awh et al., 2012; Chun & Jiang, 1998; Geng & Behrmann, 2002,  
27 2005; Jiang et al., 2013). Whereas recent studies suggested that the salient distractors (task-  
28 irrelevant) that frequently appear at a particular spatial location in visual search displays are  
29 perceptually suppressed by showing their reduced interference in visual search task  
30 performance (faster RTs) compared to distractors at infrequent search locations to enhance the  
31 task efficiency (Duncan & Theeuwes, 2020; Failing, Feldmann-Wüstefeld, et al., 2019; Failing,  
32 Wang, et al., 2019; Li & Theeuwes, 2020; Lin et al., 2020; Theeuwes et al., 2018; Wang, Samara,  
33 et al., 2019; Wang & Theeuwes, 2018a, 2018b, 2018c). For example, Wang & Theeuwes  
34 (2018a) adopted a well-established additional singleton visual search paradigm developed

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

19  
20 Further, studies also indicate that the learning of distractor statistical regularities can be  
21 non-spatial and feature specific (Failing, Feldmann-Wüstefeld, et al., 2019; Stilwell et al., 2019).  
22 For example, Stilwell et al. (2019) showed that distractor colours that appear in search displays  
23 more frequently were suppressed efficiently compared with less frequent distractor colours  
24 (Stilwell et al., 2019). Although the mechanisms of such distractor suppression are far from  
25 clear, recent studies suggest that the experience of distractor statistical regularities induce  
26 anticipatory or pro-active modulations in the first feedforward sweep of information processing  
27 that de-prioritize the most probable distractor locations (Huang et al., 2021; Wang, Driel, et al.,  
28 2019). Overall, there seems to be enough evidence to support the notion that our brain learns  
29 and utilize statistical regularities of both task-relevant and task-irrelevant sensory stimuli for  
30 optimizing behaviour.

31  
32 While investigations of most previous research focused on understanding how statistical  
33 learning of visual objects influences selective attention, fewer studies have investigated in  
34 cross-modal contexts (Chen et al., 2020, 2021; Kawahara, 2007; Nabet et al., 2002). For

1 example, Chen et al. (2020) required their participants to search for a visual target in a task-  
2 irrelevant tactile stimulus context. The spatial location of the visual search target in each trial  
3 was either predictable or unpredictable based on statistical regularities of tactile stimuli  
4 (stimulated on participant's fingertips) embedded in the experimental trials. The search RTs for  
5 the visual target were faster in predictive compared to the un-predictive tactile context in their  
6 experiment 2. This finding suggests that task-irrelevant, cross-modal stimulus context can be  
7 processed and used to improve performance in a visual search task. Critically, the experimental  
8 investigations in previous studies focussed on whether and how task-irrelevant, cross-modal  
9 stimulus statistical regularities that are indicative of visual search target location influence task  
10 performance. The current study will investigate whether and how task-irrelevant, cross-modal  
11 stimulus statistical regularities indicative of salient visual distractor location influence task  
12 performance. If so, it would imply that the attentional system can be flexibly modified based  
13 on the task-irrelevant, cross-modal stimulus regularities irrespective of whether they indicate  
14 target or distractor in a visual search task.

15

16 We have proposed two experiments in this study. The first experiment is designed to test  
17 whether the study participants learn to utilize the task-irrelevant auditory spatial regularities,  
18 simultaneously presented across search displays, indicating salient visual distractor's likely  
19 location influence visual search task performance. The second study is designed to test whether  
20 the task-irrelevant auditory non-spatial and frequency-based regularities, simultaneously  
21 presented across search displays, indicating salient visual distractor's likely location influence  
22 visual search task performance. We adopt the additional singleton visual search paradigm  
23 developed initially by Theeuwes (1991, 1992) with few modifications. In the proposed  
24 experiments, we manipulate statistical regularities of colour singleton distractor locations along  
25 with auditory stimulus spatial (experiment 1) and non-spatial, frequency-based (experiment 2)  
26 regularities synchronously presented across search displays (see methods section for more  
27 details). Critically, the spatial location of a colour singleton distractor in each trial could be  
28 either predicted or unpredicted based on the task-irrelevant auditory statistical regularities. For  
29 testing awareness about the relationship between auditory and visual distractor location  
30 regularities, we will use the confidence rating scale and ranking method, adapted with slight  
31 modifications from the study by Vadillo et al. (2020). The confidence rating scale and ranking  
32 methods are, arguably, more sensitive measures for testing awareness than dichotomous "Yes"  
33 or "No" responses and/or indicating a particular location where participants believe that the  
34 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 such locations 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.

**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

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Alternatively, if the study participants cannot learn to utilize auditory stimulus statistical regularities to anticipate the likely location of a salient visual distractor (color singleton distractor) in search displays, no suppression effects can be observed for valid distractor trials compared to the invalid distractor trials. The response times (RTs) are expected to be the same for HpValD and the HpInValD trials.

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Moved up [1]: Alternatively, if the study participants cannot learn to utilize auditory stimulus statistical regularities to anticipate the likely location of a salient visual distractor (color singleton distractor) in search displays, no suppression effects can be observed for valid distractor trials compared to the invalid distractor trials. The response times (RTs) are expected to be the same for HpValD and the HpInValD trials.

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1 HpValD and HpInValD conditions. While the later condition associated with the appearance  
 2 of the salient visual distractor in infrequent search locations having uninformative sound  
 3 stimulus — should produce slower search RTs compared to HpValD and HpInValD conditions.

5 **Study Design Table:**

6

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 68 participants (who meets the participant selection criteria) from the Indian Institute of Technology.  <u>Sample Size Justification:</u> <u>Given an effect size of <math>d = 0.602</math> in a similar study by Failing et al. (2019), which was obtained by taking a difference between colour-match and colour-mismatch trials at two high probability distractor locations, a minimum of 39 participants required for power <math>\geq 90\%</math> with alpha set to 0.02 (calculated using G*Power 3.1). However, we do not have evidence to expect a similar effect in the context of auditory stimulus induced effect between two high probability distractor location trials. We believe that the effect size in the current experimental context is smaller than the effect size found in the study by Failing et al. (2019), and thus we are attempting to detect a smaller effect size of <math>d = 0.45</math>. The effect size <math>d = 0.45</math> requires a minimum of 68 participants for each proposed experiment to get power <math>\geq 90\%</math> with alpha set to 0.02 (calculated using G*Power 3.1) in a two-tailed matched-sample t-test. 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 &amp; Theeuwes, 2018a, 2018b, 2018c)).</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”) 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. <u>Otherwise, we will claim that the auditory spatial statistical regularities do not have influence on the distractor suppression in visual search tasks.</u>

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The response times (RTs) are expected to be the same for HpValD and the HpInValD trials.

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Deleted: To test the strength of no-difference between HpValD and HpInValD the conditions, we will use Bayesian t-test for the same comparison in JASP software (JASPTeam, 2021) with default Cauchy distribution (scale = 0.707) as the prior. Bayes Factor (BF)  $> 6$  will be considered to support the evidence of no difference. between the conditions.

Deleted: Based on a previous study by Failing et al. (2019), our sample size would be appropriate to detect a minimum effect size of  $d = 0.6$ , power  $> 90\%$  with alpha set to 0.02 (calculated using G\*Power 3.1).

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Cross-modal statistical regularities and Visual selection

<p>Do task-irrelevant cross-modal (auditory) non-spatial, frequency-based regularities induce distractor suppression in visual search? (Experiment 2)</p>	<p>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.</p>	<p>As above</p>	<p>As above</p>	<p>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.</p>
<p>Do participants have awareness about the relationship between auditory (spatial) and visual distractor location regularities? (Experiment 1)</p>	<p>We hypothesise 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.</p>	<p>Minimum of 68 participants. <b>Sample Size Justification:</b> 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 <math>h = 0.52</math> in their experiment 1. However, we do not have evidence to expect a similar effect size, utilising these sensitive measures of awareness, in studies identical to the proposed experimental context. Assuming that the effect size in the current experimental context might be small, we are attempting to detect a smaller effect size of <math>d = 0.45</math>. The effect size of <math>d = 0.45</math> requires a minimum of 68 participants for each proposed experiment to get power <math>\geq 90\%</math> with alpha set to 0.02 (calculated using G*Power 3.1) in a two-tailed matched-sample t-test.</p>	<p>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.</p>	<p>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.</p>
<p>Do participants have awareness about the relationship</p>	<p>As above</p>	<p>As above</p>	<p>As above</p>	<p>As above</p>

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**Deleted:** We aim to recruit a minimum of 39 participants (who meets the participant selection criteria) from the Indian Institute of Technology. Based on a previous study by Failing et al. (2019), our sample size would be appropriate to detect a minimum effect size of  $d = 0.6$ , power  $> 90\%$  with alpha set to 0.02 (calculated using G\*Power 3.1).

**Deleted:** 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  $> 0.90$ .

**Deleted:** To test the strength of no-difference between HpValD and HpInValD the conditions, we will use Bayesian t-test for the same comparison in JASP software (JASPTeam, 2021) with default Cauchy distribution (scale = 0.707) as the prior. Bayes Factor (BF)  $> 6$  will be considered to support the evidence of no difference between the conditions.

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The response times (RTs) are expected to be the same for HpValD and the HpInValD trials.

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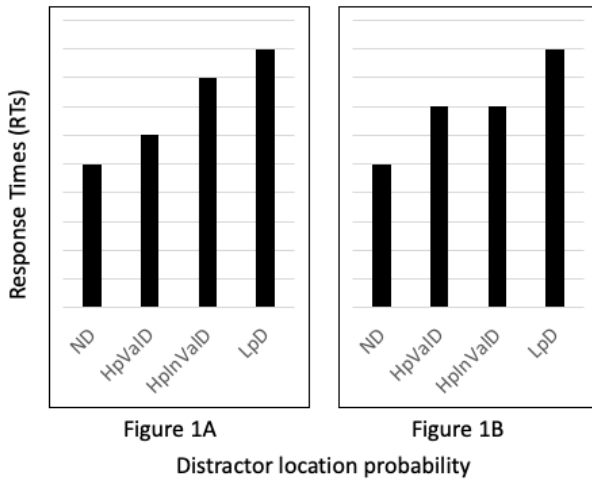
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Cross-modal statistical regularities and Visual selection

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.

## 1 Number of Participants:

2 For each proposed experiment in this study, we aim to recruit a minimum of 68  
 3 participants (who meets the participant selection criteria) from the Indian Institute of  
 4 Technology. Given an effect size of  $d = 0.602$  in a similar study by Failing et al. (2019), which  
 5 was obtained by taking a difference between colour-match and colour-mismatch trials at two  
 6 high probability distractor locations, a minimum of 39 participants required for power  $\geq 90\%$   
 7 with alpha set to 0.02 (calculated using G\*Power 3.1). However, we do not have evidence to  
 8 expect a similar effect in the context of auditory stimulus induced effect between two high  
 9 probability distractor location trials. We believe that the effect size in the current experimental  
 10 context is smaller than the effect size found in the study by Failing et al. (2019), and thus we  
 11 are attempting to detect a smaller effect size of  $d = 0.45$ . The effect size  $d = 0.45$  requires a  
 12 minimum of 68 participants for each proposed experiment to get power  $\geq 90\%$  with alpha set  
 13 to 0.02 (calculated using G\*Power 3.1) in a two-tailed matched-sample t-test. This sample size  
 14 is considerably larger than the typical experiments conducted using the additional singleton  
 15 tasks (an average of around 26 participants in (Failing, Feldmann-Wüstefeld, et al., 2019; Wang  
 16 & Theeuwes, 2018a, 2018b, 2018c)).

17 Justification for the sample size to determine awareness of statistical regularities in the  
 18 proposed experiments: A minimum of 68 participants for each proposed experiment will be  
 19 considered for testing awareness about the relationship between auditory and visual distractor  
 20 location statistical regularities. Most previous studies utilized dichotomous “Yes” or “No”  
 21 responses and/or indicating a particular location where participants believe that the  
 22 target/distractor appeared most frequently to test awareness about statistical regularities and  
 23 concluded that the statistical learning is unconscious (e.g., in studies by (Failing, Feldmann-  
 24 Wüstefeld, et al., 2019; Wang & Theeuwes, 2018b)). However, recent studies indicated that  
 25 using a confidence rating scale and ranking methods are, arguably, more sensitive measures for  
 26 testing awareness (Giménez-Fernández et al., 2020; Vadillo et al., 2020). Utilizing these  
 27 sensitive measures to test awareness of statistical regularities in probabilistic cuing search tasks,  
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 29 regularities. Their study reported an effect size of Cohen's  $h = 0.52$  in their experiment 1.  
 30 However, we do not have evidence to expect a similar effect size, utilising these sensitive  
 31 measures of awareness, in studies identical to the proposed experimental context. Assuming  
 32 that the effect size in the current experimental context might be small, we are attempting to  
 33 detect a smaller effect size of  $d = 0.45$ . The effect size of  $d = 0.45$  requires a minimum of 68

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1 participants for each proposed experiment to get power  $\geq 90\%$  with alpha set to 0.02 (calculated  
 2 using G\*Power 3.1) in a two-tailed matched-sample t-test.

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

8 **Participant selection criteria:**

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

21 **Materials:**

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

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**Deleted:** The experiment will be conducted with the approval of the Institutional Ethics Committee (IEC) of the Indian Institute of Technology Gandhinagar and

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1 experiment 2, auditory stimuli consist of two pure tones (50ms duration) with 500 Hz or 1000  
2 Hz frequency presented via headphones. The sound level will be adjusted for each participant  
3 according to their comfort at the beginning of the experiment and will be kept constant  
4 throughout the experiment.

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#### 8 **Experiment 1:**

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

17

#### 18 **Procedure and design for Experiment 1:**

19 Each trial starts with a fixation cross presented until the trial ends. 500ms after the  
20 fixation cross onset, the visual search display is presented for 2000ms or until the participant  
21 makes a response (<2000ms). The participants will be instructed to search for a shape singleton  
22 in the displays. For example, participants will be asked to search for a diamond shape among  
23 circles or vice versa and respond to the line segment's orientation embedded in the target. If the  
24 orientation of the line segment is horizontal, the participant is required to press the "Z" key, and  
25 if the line segment is vertical, the participant is required to press the "M" key as soon as possible.  
26 Participants will be asked to press the response key quickly and accurately. The target (shape  
27 singleton) will be present in all the trials, and the target can be either circle or diamond with  
28 equal probability. A blank display with intertrial interval (ITI) will be randomly determined  
29 between 500ms to 750ms. The timed-out responses will be considered incorrect responses. In  
30 cases of incorrect responses and timed-out responses, feedback will be provided to the  
31 participants with white text "Incorrect response" or "Timed-out", respectively at the center of  
32 the LCD screen for 1000ms. No feedback will be provided for the correct responses. Two  
33 critical design factors are important in the experiment regarding the experimental manipulations  
34 of the additional (color) singleton distractor and the auditory stimulus across the trials.

1

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

19

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

31

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

34 a) No distractor trials with no auditory stimulus (“no-distractor” condition)

Cross-modal statistical regularities and Visual selection

- 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).

**Deleted:** during the task, participants will be asked to indicate whether they have noticed any spatial regularities in color distractor location (e.g., distractors more frequently appeared in certain search locations and less frequently in other locations). Second, participants will be informed that the color singleton distractors have appeared more frequently in two search locations and asked to indicate such locations (by providing location-based numbers) where they thought distractors were more frequently occurred during the task. Third,

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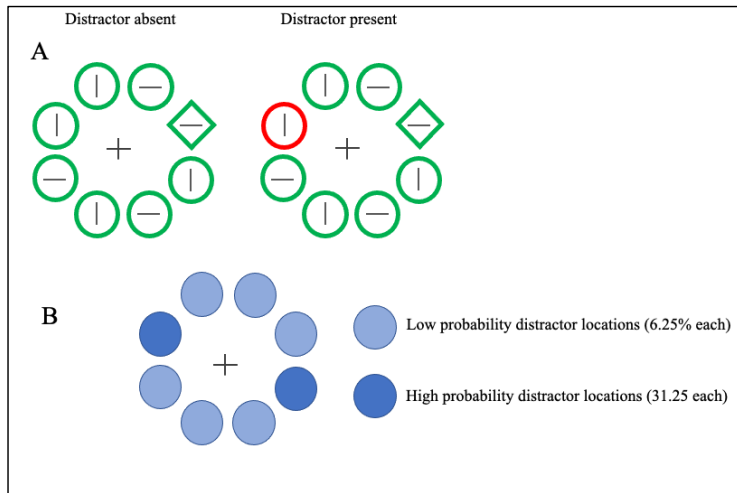
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**Deleted:** indicated a likely distractor location from one of the eight possible search locations during the task. And then, we will ask participants to indicate two distractor locations likely indicated by the sound coming from the left and right speakers, respectively (by providing location-based numbers). Participants are encouraged to use their best guess if they are unsure about the locations.



**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).

### 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



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

7

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

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

17

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

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**Deleted:** Like experiment 1, except that in the third and fourth questions, we will use text “sound pitch (high or low)” instead of the text “sound location”.

21

### 22 **Participant and data replacement:**

23 Any of the following criteria will be used to replace a given participant in both the  
24 experiments:

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

29

### 30 **Data analysis plan:**

31 Identical but separate data analysis will be performed for experiment 1 and 2. The  
32 incorrect responses and response times (RTs) shorter than 200ms will be discarded before  
33 performing statistical analysis on RT data. If the assumptions of normality and sphericity are

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1 violated, appropriate non-parametric tests and sphericity corrections (Greenhouse-Geisser  
2 correction) will be applied to the statistical results.

3  
4 Analysis on Response times (RTs): As mentioned in Figure 1, the relevant comparison  
5 is to test whether the auditory regularities influence distractor suppression. For this comparison,  
6 we will use paired t-test to compare experimental conditions of “high-probability valid  
7 distractor location” with “high-probability invalid distractor location”.

8  
9 Analysis of participants’ awareness of regularities: We will calculate the mean rating  
10 for Question #1 in the questionnaire for the awareness test (see the supplementary materials).  
11 As mentioned in the methods above, all participants will be asked to rank three locations for  
12 each sound stimulus condition separately (Question #2 & Question #3). The first, second, and  
13 third-ranked locations will be given scores of 3, 2, and 1, respectively. For the remaining  
14 locations, the scores will be zero. We will assign these locations into five categories (0-4)  
15 depending on their distance from the corresponding HpValD location. For example, 0  
16 corresponds to the HpValD location; 1 corresponds to two locations immediately next to the  
17 HpValD location, and so on. For each participant, we will then combine the data of Question  
18 #2 & Question #3 to calculate the mean scores obtained by locations according to the five  
19 categories mentioned above (0-4). These data will be analyzed using a linear mixed-effects  
20 model with a random intercept for participants to determine a linear relationship between scores  
21 obtained by each location and their distance from the HpValD location (0-4).

22  
23 **Predicted Outcomes:**

24 The experimental question is whether the task-irrelevant auditory regularities indicative  
25 of the additional singleton location in the visual search display modulates the search efficiency.  
26 Suppose the auditory regularities indeed generate the predictions for the likely distractor  
27 location. In that case, these distractor locations (in “high-probability valid distractor location”)  
28 are perceptually suppressed, and the RTs in those trials are shorter than invalid distractor  
29 locations (in “high-probability invalid distractor location” trials). Likewise, in experiment 2,  
30 RTs expected to be shorter for high-probability valid distractor location (indicated by sound  
31 feature) than high-probability invalid distractor location. A graphical representation of  
32 experimental predictions is presented in Figure 1.

**Deleted:** First, in order to test whether statistical regularities of the distractor location (irrespective of auditory regularities), we will perform one way repeated measures of ANOVA on mean RTs across with factors no-distractor × high-probability distractor locations × low-probability distractor locations. Second, as

**Deleted:** To test the strength of no-difference between the conditions, we will use the Bayesian t-test for the same comparison in JASP software (JASP Team, 2021) with default Cauchy distribution (scale = 0.707) as the prior. Bayes Factor (BF) > 6 will be considered to support the evidence of no difference between the conditions.

**Deleted:** Analysis of error rate: Mean percentage of errors will be calculated for each participant in each condition. The statistical tests will be the same as the analysis of Response Times mentioned above.

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**Deleted:** We will calculate the percentage of “yes” responses to the questionnaire’s first and Third questions (see supplementary materials section). For the Second and Fourth questions in the questionnaire, each participant’s awareness score will take the distance between the locations indicated by the participant and the actual locations. The awareness scores will be submitted to the One-Sample t-test to check whether the sample mean significantly different from zero or not. To test the strength of no-difference, we will use the Bayesian equivalent of a one-sample t-test. Bayes Factor (BF) > 6 will be considered to support the evidence of no difference.

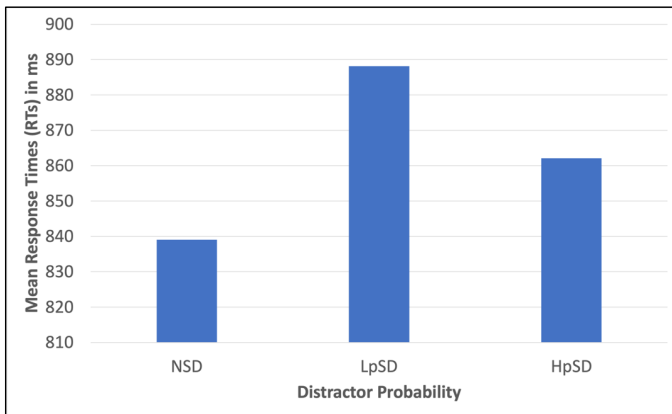
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**Supplementary Materials**

**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](https://osf.io/yba2k/?view_only=ec7ab987de2f4486aa653f24d03936f5)

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**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).

1 Questionnaire for testing awareness of statistical regularities:

2 For experiment 1:

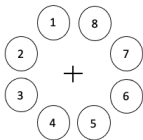
3  
4 Question #1: You might have noticed that, in most of the displays, one of the visual items in display  
5 appeared in a different color than the rest (e.g., red color visual item among green items or vice  
6 versa). Do you think that a given sound location (e.g., the sound coming from the Left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

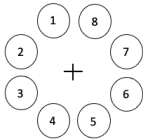
- 10 \* Definitely not (Press 1)
- 11 \* Probably not (Press 2)
- 12 \* Possibly not (Press 3)
- 13 \* Possibly yes (Press 4)
- 14 \* Probably yes (Press 5)
- 15 \* Definitely yes (Press 6)

16  
17  
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  
22 \* Now, if you had to choose a particular location where the differently colored visual item  
23 frequently appeared along with the sound coming from the left side of the display, which one that  
24 would be, in your opinion? Please indicate such location by pressing corresponding numbered spatial  
25 locations shown on the below example display.



26  
27  
28 \* Now, ignoring your previous response, if you had to choose the next location where the  
29 differently colored visual item frequently appeared along with the sound coming from the left side of  
30 the display, which one that would be, in your opinion? Please indicate such location by pressing  
31 corresponding numbered spatial locations shown on the below example display.

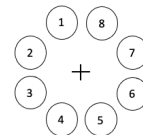


32  
33  
34 \* Finally, ignoring your previous response, if you had to choose the next location where the  
35 differently colored visual item frequently appeared along with the sound coming from the left side of  
36 the display, which one that would be, in your opinion? Please indicate such location by pressing  
37 corresponding numbered spatial locations shown on the below example display.  
38

**Deleted:** During the task, please indicate whether you have noticed any spatial regularities in colored non-target locations in search displays (e.g., colored non-targets more frequently appeared in certain search locations and less frequently in other locations).

Yes (press Y button on the keyboard)  
NO (press N button on the keyboard)

Question #2: In the experiment, colored non-targets appeared more frequently in two search locations and less frequently in other locations. Please indicate the two search locations where colored non-targets more frequently appeared more frequently appeared by pressing corresponding numbered spatial locations shown on the below example search display. If you are unsure about the answer, please indicate your best guess.



Question #3:

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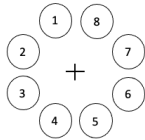
**Deleted:** Please indicate whether you have noticed regularities in the sound location such that the sound location was indicating more likely location of colored non-targets during the task.

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**Deleted:** Yes (press Y button on the keyboard)

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Cross-modal statistical regularities and Visual selection



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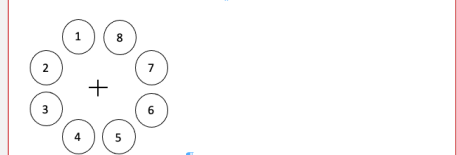
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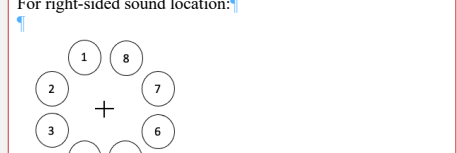
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Question #4: In the experiment, each sound location (left and right-sided) indicated a likely coloured non-target from one of the eight possible search locations during the task. Please indicate such two locations by pressing corresponding numbered spatial locations shown on the below example search display for each sound location. If you are unsure about the answer, please indicate your best guess.

For left-sided sound location:



For right-sided sound location:



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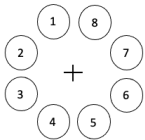
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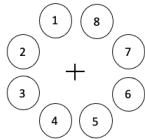
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Question #3: In the experiment, in most of the trials, the sound coming from the right side of the display was most frequently matched with a particular location of the differently colored visual item in the display.

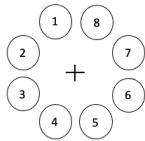
\* Now, if you had to choose a particular location where the differently colored visual item frequently appeared along with the sound coming from the Right side of the display, which one that would be, in your opinion? Please indicate such location by pressing corresponding numbered spatial locations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



\* 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.

1 **Acknowledgements:**

2 We would like to thank, in advance, study participants for their time.

3

4 **CRediT Authorship contribution statement:**

5 KKJ: Conceptualization, Investigation, Methodology, Formal analysis, Visualization, Software,

6 Writing - original draft, Writing - review & editing

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

8

9 **Competing interests:**

10 The authors declare no competing interests.

11

1

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