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Is perceptual learning always better at task-relevant locations? It depends on the distractors

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Abstract

The role of attention in task-irrelevant perceptual learning has been contested. Attention has been studied in the past using distractor-type manipulations. Hence, during an initial exposure phase, we manipulated distractor similarity within a set of six gratings, to study its effects on perceptual learning at task-relevant and task-irrelevant locations. Of these six gratings, one was at a task-relevant location, one at a task-irrelvant location, which shared the orientation with the task-relevant grating, and the rest (four) were distractor gratings. The orientations of the distractor gratings were all either the same (homogeneous) or different from each other (heterogeneity). We hypothesized that learning at the task-irrelevant location would be worse than learning at the task-relevant location when distractors are heterogeneous and vice versa when the distractors are homogeneous. Participants were initially exposed to a grating set; they reported contrast changes at only one prespecified task-relevant location. This grating was grouped based on orientation with a task-irrelevant grating presented at the furthermost distractor location and presented alongside four control-distractors (homogeneous or heterogeneous). In the testing phase, orientation discrimination performance was measured at task-relevant, task-irrelevant (grouped), and control-distractor locations. Participants were exposed and tested sequentially, each day for 5 days. Participants learned and performed better at the task-irrelevant location compared to the task-relevant location with homogenous distractors and vice versa with heterogenous distractors. The poorer learning at the task-relevant location compared to the task-irrelevant location challenges current models of perceptual learning. Selection mechanisms driven by the nature of distractors influence perceptual learning at both task-relevant and task-irrelevant locations.

Keywords Perceptual learning · Task-irrelevant perceptual learning · Task-relevant learning · Distractor homogeneity · Salience · Distractor interference

Introduction

"Practice makes perfect" is an age-old adage. The adage presumably arises from the knowledge that individuals can reach phenomenal levels of expertise, with practice and training. Whether it is a conductor finding an offbeat note in an orchestra or a connoisseur appraising wine, their abilities are due to learning. This kind of improvement has been shown in auditory, visual, gustatory, and tactile modalities (Fahle & Poggio, 2002). In a recent review (Sagi, 2011), perceptual learning was defined as the improvement and honing of perceptual skills over time and with repeated trials.

A key aspect missing from this definition is attention and salience. Even though attention and improvement in perception have long been thought to be linked (Ahissar, 1999; Ahissar & Hochstein, 1993, 2000, 2004; James, 1890), attention is not used explicitly in definitions of perceptual learning (although see Byers & Serences, 2012). Various aspects or mechanisms of attention have been shown to influence perceptual learning, such as external noise reduction and stimulus enhancement (Dosher & Lu, 1998, 1999, 2000), orienting of attention (Mukai et al., 2011; Szpiro & Carrasco, 2015), failure to suppress sub-threshold stimuli (Tsushima et al., 2008), object-based attention (Mastropasqua & Turatto, 2013), selection in binocular rivalry (Xu et al., 2012), and feature similarity-based learning (Gutnisky et al., 2009).

In contrast, it has been argued that attention is not necessary for perceptual learning, since participants can learn to discriminate stimuli that are presented below perceptual thresholds

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even when they are engaged in performing a secondary suprathreshold task, a phenomenon called "task-irrelevant perceptual learning" (TIPL) (Seitz & Watanabe, 2003; Watanabe et al., 2001). TIPL is explained as occurring due to rewards for identifying the target also reinforcing task-irrelevant stimuli, which here are not inhibited by selective attention as they are below perceptual threshold (Tsushima et al., 2008; Sasaki et al., 2010).

However, over time a role for attention has been proposed in explaining TIPL (Byers & Serences, 2012; Dosher et al., 2013; Dosher & Lu, 2017). Herein, Dosher and Lu (2017) propose that attention refines feature representations (orientation, tilt, motion, etc.) specifically at locations where attention is directed, but also in a feature space where irrespective of location, feature representations are fine tuned. This fine tuning has been argued to be achieved through the same mechanisms employed in their perceptual template model, i.e., via excluding external noise and reducing internal additive noise. However, it remains contentious to purport that attention and perceptual learning involve the same mechanisms (as described above) and similar brain regions (Byers & Serences, 2012).

Current study

Several key features of selective attention like attentional zoom (Eriksen & James, 1986), perceptual load (Lavie, 1995, 2005), and dilution of attention (Tsal & Benoni, 2010) remain understudied in the context of perceptual learning. Even though conceptualizations of selective attention are still debated (Cave & Chen, 2016; Chen & Cave, 2013), a commonality that is shared among many studies is the attempt to understand distractor interference and non-target processing in the context of selective attention. Herein, attentional selection of the target is influenced by distractor load (high vs. low), proximity, similarity, task relevance, and response competition. In the context of perceptual learning, changes in distractor sets that influence selection of task-relevant stimuli and the spilling over of attention to task-irrelevant stimuli is one way in which the role of attention in task-irrelevant perceptual learning could be investigated.

Manipulations to understand the role of distractor processing can orthogonally employ changes in target-distractor similarity and distractor-distractor similarity. Roper et al. (2013) report evidence of slower visual search times when distractors are similar to each other only when target and distractors are also similar. Salience of stimuli including that of distractors influences attentional selection (Eltiti et al., 2005).

A couple of studies have shown TIPL when a task-irrelevant stimulus is made similar in terms of shared features with a task relevant stimulus (Gutnisky et al., 2009) or "grouped" with it (Mastropasqua & Turatto, 2013). In one of the studies (Gutnisky et al., 2009), participants were asked to report contrast changes of a grating at one location, and ignore contrast changes in two other peripheral gratings. Unbeknownst to the participants, this grating (what they call "attended") and another peripheral grating (what they call "unattended") had the same orientation. The third grating (what they called "control") while placed closer to the "attended," did not have the same orientation. After the contrast change detection task, participants performed an orientation discrimination task at the same three locations. In the orientation discrimination task, a sample grating was followed by a comparator grating and participants were asked to report whether the sample and comparator gratings had different or same orientations. Crucially, the sample grating always has the same orientation as the grating on which participants performed the contrast change detection task. Already being exposed to these orientations increased tuning to that particular orientation and helped in the subsequent orientation discrimination task. The performance over days was best at the "attended" (task-relevant) location. However, performance at the "unattended" location (task-irrelevant) was better than that at the control location. They argued that repeated exposure of the feature (orientation) similarity between these two locations boosts performance at the task-irrelevant location as well. They argued that perceptual learning need not be specific to locations but can be driven by feature-based plasticity (orientation tuning).

In the current study (Experiment 1), we investigated how the nature of information in the control-distractor locations as a distractor set would influence the pairing of the stimuli at the task-relevant and irrelevant locations, and subsequently influence learning at these locations. That is, we investigated whether distractor homogeneity as a manipulation of attention would influence the exposure-based perceptual learning as seen in the exposure phase (Part 1) of the experiment in Gutnisky et al. (2009). If the learning at the task-irrelevant location was not being influenced by attention, then distractor set type (heterogenous/homogenous) during the exposure phase would not change the learning outcomes at the task-irrelevant location. However, if attention had a role to play in TIPL, then we expected that the learning at the task-irrelevant location would be diminished with heterogenous distractor sets. This prediction was drawn from prior work in attention literature manipulating distractor sets in visual search and learning studies (Eltiti et al., 2005; Lavie, 1995, 2005; Roper et al., 2013; Scalf et al., 2013; Tsal & Benoni, 2010).

To this end, we modified the design used in Gutnisky et al. (2009) – we had six gratings (unlike three gratings in their study). One of the six was a task-relevant grating and another was a task-irrelvant grating, which shared the orientation with the task-relevant grating. The remaining four were control-distractor gratings, unlike only one in earlier studies

(Gutnisky et al., 2009). Participants in part one of the experiment performed training on only one of these gratings. The use of multiple control-distractor gratings allowed us to manipulate the orientation similarity between them. One set of participants trained with homogenous distractors, i.e., the four control-distractors, had the same orientation (different from gratings at the task-relevant and task-irrelevant locations). The other group of participants trained with heterogeneous distractors, i.e., the four control-distractors all had different orientations (still different gratings at the task-relevant and task-irrelevant locations). From the perspective of participants, there was one task-relevant grating and five irrelevant gratings. From the experimenter's perspective, there was one task-relevant grating, four control-distractor gratings, and one grouped task-irrelevant grating. We also performed an additional experiment to evaluate the differences in perceptual processing at task-relevant location as a function of distractor homogeneity, given our results from Experiment 1.

Experiment 1

We hypothesized that the grouped task-irrelevant grating would have different salience based on the distractor set to which it belongs, as it would influence how much the grouped grating "stands out" within the set of distractors. This hypothesis was based on the relative salience difference of the task-irrelevant grouped grating in the homogenous and heterogeneous distractor conditions. Our hypothesis stated that overall the grouped grating would stand out more when the control-distractor gratings are homogeneous compared to when the control-gratings are heterogeneous. Learning at the task-relevant and task-irrelevant locations would be affected by the relative salience of the grouped grating. Previous work (Eltiti et al., 2005; Lavie, 1995, 2005; Roper et al., 2013; Scalf et al., 2013; Tsal & Benoni, 2010) allowed us to predict that more efficient attentional selection with heterogeneous distractors would limit learning at a task-irrelevant location. More importantly, we predicted that distractor homogeneity would result in better learning at the task-irrelevant location since attention would spill over to the task-irrelevant location under low perceptual load of homogeneous distractor sets. However, since the distractor manipulation would affect the exposure-based learning at the task-irrelevant location, we expected this effect would not be present on the first day itself and would start appearing in later days with more practice. In addition, we wanted to see whether distractor homogeneity would influence learning at the task-relevant location given that it can potentially affect processing at the task-irrelevant location.

Method

Participants

Twenty-two volunteers (nine females, age = 20–30 years) with normal or corrected-to-normal vision from the University of Allahabad provided informed consent and participated in the experiment. Sample size was calculated using GPower 3.1 for a two-variable interaction between location and distractor homogeneity (effect size $f = 0.3$, $\eta_p^2 = .082$, $\alpha = 0.05$, power = 0.85). Participants were randomly assigned to either homogeneous or heterogeneous distractor conditions. Data from two participants was excluded due to excessive eye movements and or overall poor performance. Participants were compensated for their time with a total of Rs. 250 (Rs. 50 per session). The study was approved by the Institutional Ethics Review Board of the University of Allahabad.

Stimuli and apparatus

To ensure fixation of participants' eyes during the experiment, a SMI-Eye tracker (1,250 Hz monocular setup) was used. In a trial if participants moved their eyes away from the fixation cross (more than 1°), the trial was removed from analysis offline. Overall, less than 3% of trials (maximum trials removed from one participant was 52 out of 1,800) were excluded due to eye movements. Participants sat at a distance of 57cm from a 17-in. LCD monitor with a resolution of 1,024 × 768 and refresh rate of 100 Hz, with their chins placed on a fixed headrest. Their eye movements were calibrated with the eye tracker twice, once before each part of the experiment with a 13-point calibration setup. The stimuli were presented using E-Prime 2.0 developed by Psychology Software Tools.

Sinusoidal gratings were used as stimuli; they had a sharp circular edge envelope and were displayed on a gray background. The gratings had alternating colors of black and white. The frequency of the gratings was 0.1 cycles/pixel, i.e. they had ten black stripes and nine white stripes. The size of the grating was 1.8° in radius and were presented approximately 5.5° (visual angle) from the fixation cross. The dimmed gratings were 50% less bright than the usual gratings during part one. For the orientation discrimination experiment, the gratings were rotated anti-clockwise.

Procedure

All participants completed five consecutive sessions of the experiment, one session per day. Each session had two parts and lasted for approximately 25 min (3 min for part 1 and 22 min for part 2). The sessions were strictly performed on consecutive days. Participants sat in a closed dark room and came to the lab at almost the same time on each day to minimize confounding variables.

Part 1

Part 1 was the exposure or the priming phase, similar to Gutnisky et al. (2009). Participants were presented with six sinusoidal gratings on the screen at a time. The gratings were placed on hexagonal vertex points in order to be equidistant from the central fixation cross (see Fig. 1). Participants were instructed to maintain their gaze at a fixation cross throughout the experiment. On each trial, one of the gratings appeared "dim" (50% lower contrast). Participants were asked to report the contrast only at one pre-specified location (task-relevant) without making an eye movement. They had to press one key when the contrast of the grating at their assigned location looked "normal" and press another key when it appeared "dim." They were asked to ignore changes at any other location. This was done to ensure that participants focus at one location and orientation. The task-relevant location was counterbalanced with the task-irrelevant location between participants (see Fig. 1), but the grating always had the same orientation (60°). The orientation of the grating at the task-relevant and task-irrelevant location was kept the same throughout the exposure phase.

The distractor similarity was manipulated in this phase. Participants were assigned randomly to a group (homogeneous or heterogeneous distractor condition) and remained in the same group for all five sessions. In the homogeneous distractor condition, all the four gratings had the same orientation in each trial and the possible orientations were 110°, 100°, 50°, or 40°. In the heterogeneous distractor condition, all the four gratings in the distractor set had different orientations (100°, 110°, 40°, and 50°) every trial (see Fig. 1). The orientations of the control-distractor gratings were never the same as that of the task-relevant grating.

Each trial began with a fixation cross for 500 ms, followed by a grating set displayed for 200 ms. The experiment proceeded to the next trial only after the participant made a response. Part 1 had a total of 50 trials, where 15 trials had dim gratings appearing at the task-relevant location. In the rest of the trials the dim grating appeared five times at each of the distractor locations and 15 times at the task-irrelevant location. Participants' accuracy for each session was required to be greater than 85% during part 1 for inclusion in the study. No participant was excluded based on this criterion.

Part 2

Part 2 began immediately after part 1 on all five days. Part 2 consisted of an orientation discrimination task performed at the same six locations as part 1. Each trial in part 2 began with a fixation cross, at which participants were again asked to maintain their gaze. After 400 ms, a sample grating appeared at one of the six locations for 200 ms and disappeared; 200 ms after the sample grating went away, another grating appeared in the same location for 200 ms (see Fig. 2). The task was to indicate by a key press whether the two

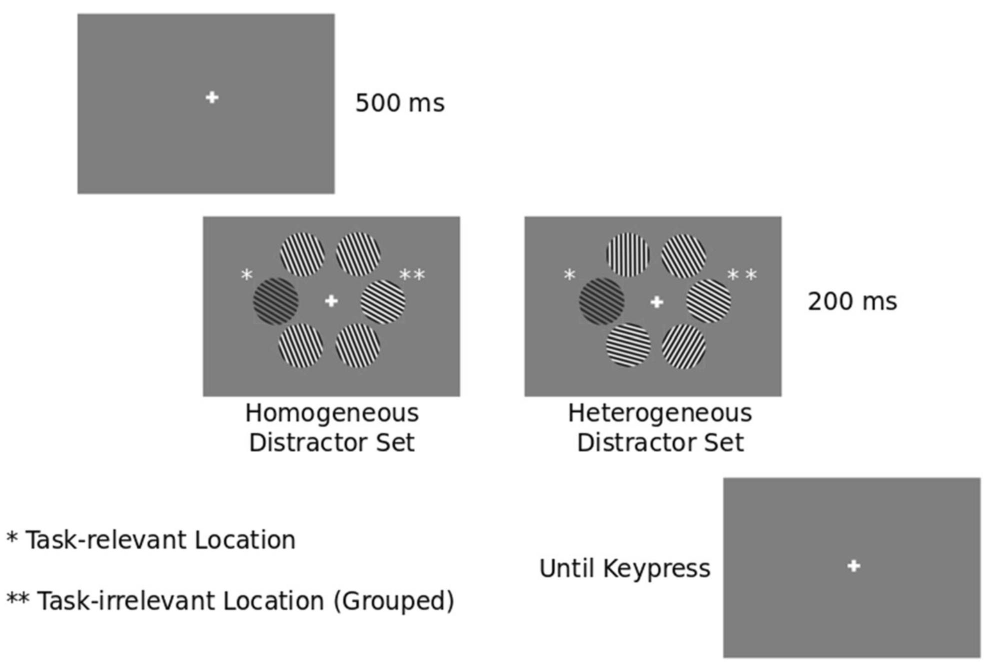

Fig. 1 Procedure of part 1 of the experiment (exposure phase). Each trial began with a fixation cross. Participants were told to report contrast changes only at the task-relevant location. The four gratings, two above and two below, were either similar or dissimilar. The two gratings on the horizontal vertex (axis) were grouped by always having the same orientation; one of them was task-relevant and the other was task-irrelevant. The task-relevant nature of the locations in the horizontal vertex (axis) was counterbalanced across participants

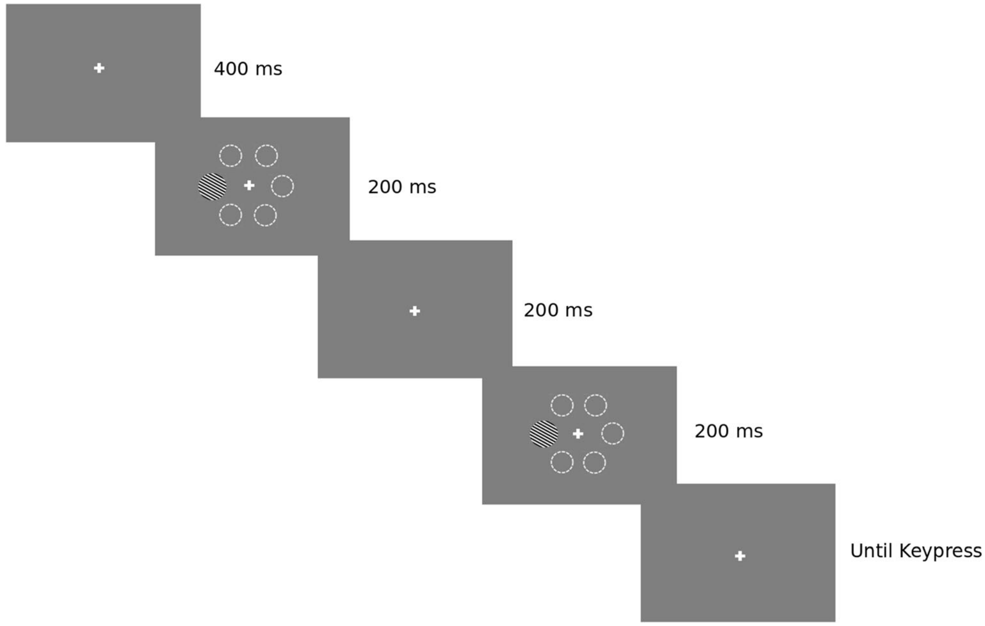

Fig. 2 Procedure in part 2 of the experiment (testing phase). Each trial began with a fixation cross for 400 ms. A sample grating was followed by a comparator grating in the same location; the participant had to report whether the two gratings had the same or different orientations. In a particular trial, the sample and comparator grating always appeared in the same location. Over trials they were presented in all six locations, i.e., participants were tested in the orientation discrimination task at all six locations

gratings had the same or a different orientation. Trials where the participant moved their eyes beyond 1° of fixation were eliminated from analysis offline. The sample grating orientation was always 60°, the second grating could have any orientation randomly picked from 60°, 62°, 64°, 66°, 68°, 70°, or 72°. An increase in small steps (2°) of orientation was chosen to increase task difficulty. Half the trials had a 60° sample grating followed by a 60° comparator grating ("same" trials); the other half of the trials had a 60° sample grating followed by a randomly picked comparator grating with orientation between 62° and 72° (ten trials each). The exposure phase from part 1 was done to boost fine-tuning for 60° at the task-relevant location, since participants reported contrast changes for gratings at the same location and same orientation. Previous studies have shown this benefit is not constrained by location (Gutnisky et al., 2009). Here, we investigated whether this exposure-based tuning from part 1 would influence learning in part 2 of the experiment under different distractor types (homogeneous vs. heterogenous); that is, whether the benefit of repeated exposure to an orientation unrelated to a task would be affected by the nature of the distractors present during the task.

In part 2, the task-relevant and the task-irrelevant ("grouped") locations had 120 such trials each. The other four locations (control-distractor locations) collectively had 120 trials (4 × 30). Thus, total trials for part 2 were 360 trials in a day and 1,800 trials over 5 days (360 × 5). Participants from both conditions performed the same orientation discrimination experiment.

The experiment was designed to be somewhat difficult to minimize ceiling effects and allow for learning to occur over the five sessions. Ensuring fixation allowed us to selectively train specific locations fixed at the proximal retinal level to specific orientations. We counterbalanced the position of the task-relevant (attended) location with the task-irrelevant (grouped location). The counterbalancing was done for only these two locations, i.e., either the left-most or the right-most location was assigned as task-relevant to a participant. This was done to maintain maximum Euclidean distance between the task-relevant and -irrelevant locations. The control-distractor locations were above and below the horizontal axis.

Participants were not given any feedback regarding their performance to eliminate the possibility of task-irrelevant learning due to feedback or reward. Moreover, participants were only compensated for their time and not their performance, which was explicitly laid out to the participants to minimize the possibility of the compensation as a motivator for their performance.

Results

First, we calculated simple accuracy (percent correct) for each participant's performance at each location over the five sessions (averaged over all the different orientations). We performed a mixed ANOVA with one between-group variable (distractor type) and two within-group variables (location and time) on accuracy scores. Assumptions of normality and homogeneity of variance were checked using Shapiro-Wilk and Levene tests, respectively. The assumptions were not violated (see Online Supplementary Material (OSM)). All the t-tests reported are two-sided tests and corrected for multiple comparisons (Holm method). All statistical analysis were done in JASP (0.13.1.0). Additional material not mentioned in the main text is provided in the OSM.

The mixed ANOVA showed a significant main effect of time, $F(4, 72) = 19.1$, $p < .001$, $\eta_p^2 = .52$, with performance getting better over time (days). Post hoc analysis revealed that participants performed better over different sessions (see section 2 of the OSM). There was no significant main effect of location, $F(2, 36) = 1.6$, $p = .22$, $\eta_p^2 = .08$ or distractor type, $F(1, 18) = 0.03$, $p = .86$, $\eta_p^2 = .002$. The interactions between distractor type and time, $F(4, 72) = 1.16$, $p = .33$, $\eta_p^2 = .06$, location and time, $F(8, 144) = 1.7$, $p = .1$, $\eta_p^2 = .08$, and distractor type, location, and time, $F(4.6, 48.3) = 2.25$, $p = .06$, $\eta_p^2 = .11$, were not significant.

The interaction between location of learning and distractor type was significant, $F(2, 36) = 6.86$, $p = .003$, $\eta_p^2 = .277$ (Cohen's $f = 0.62$). Post hoc analysis was performed for distractor type and location interaction. In the heterogeneous distractor condition, performance at the task-relevant location was significantly better than that at the task-irrelevant grouped location (see Figs. 3 and 4 and Table 1). Surprisingly, these results reverse in the homogeneous distractor condition (see Figs. 3 and 4) in which task-irrelevant grouped location performance was significantly better than that at the task-relevant location (see Table 2).

To further understand whether the interaction between location and distractor type obtained with accuracy scores is due to differences in sensitivity, we also calculated d' for each participant as a function of location, distractor type, and orientation. Since we had very few trials (ten trials each) to calculate d' for each orientation at each location for every session, we combined the trials across sessions (days) to calculate overall discriminability performance (ten trials × five sessions = 50) for each orientation. We calculated d' values by assigning a correct report of "different" as a "hit," a report of "same" when orientations were different as a "miss," reports of "different" when orientations were the same as a "false alarm" and correct identification of "same" as a "correct rejection." We again performed a similar mixed ANOVA on these sensitivity values, with orientation (six orientations: 62–72) and location as within-subject factors and distractor type as a between-subject factor.

As expected, our analysis showed a main effect of orientation $F(5, 180) = 565.6$, $p < 001$, $\eta_p^2 = .96$. Participants discriminated orientations further away from the standard grating of 62° better than those closer to 62°. We once again found no significant effects of location $F(2, 36) = 3.03$, $p = .08$, $\eta_p^2 = .1$ or distractor type $F(1, 18) = 0.33$, $p = .57$, $\eta_p^2 = .02$.

Importantly, as with the previous analysis, the interaction of location and distractor type was significant $F(2, 36) = 3.54$, $p = .039$, $\eta_p^2 = .16$ (see Fig. 4b and the figure in the OSM). The post hoc tests showed that orientation discrimination was better at the task-relevant compared to the task-irrelevant location for the heterogenous distractor group, $t = 2.82$, $p = .02$, $d = .89$, $CI = [0.02, 0.18]$, and vice versa for the homogenous distractor group, $t = 2.87$, $p = .018$, $d = .91$, $CI = [0.02, 0.19]$. The two-way interactions between location and orientation $F(10, 180) = 1.39$, $p = .19$, $\eta_p^2 = .07$, distractor type and orientation, $F(5, 90) = 0.39$, $p = .86$, $\eta_p^2 = .02$, and the three-way interaction between location, distractor type, and orientation, $F(10, 180) = 0.75$, $p = .67$, $\eta_p^2 = .04$, were not significant (though see OSM section 4 for a three-way interaction when performance on just the first and the last day are considered).

Our results from Experiment 1 show that distractor similarity affects perceptual learning at both task-irrelevant and task-relevant locations. The results show no significant differences in performance at the control-distractor location between the groups. In the heterogeneous distractor condition, we report better learning at the task-relevant location than at the grouped task-irrelevant location. This is consistent with prior findings (Gutnisky et al., 2009), although we did not find better performance at the task-irrelevant grouped location than at control locations. Still, this result can be explained by dilution accounts of attention (Tsal & Benoni, 2010), where the heterogeneity of the distractors limits the resources available for the grouped location. This result is also in agreement with previous reports of the role of distractor salience in selective attention (Eltiti et al., 2005). The homogeneity of the distractors makes the grouped or task-irrelevant location salient and stand out, while the heterogeneity of the distractor reduces the salience of the grouped location.

We expected better performance at the grouped location with a homogenous distractor set, since the "grouping" would become more salient, like in the case of Mastropasqua and Turatto (2013). We had expected that the performance at the task-irrelevant and task-relevant locations would not be

Table 1 Corrected post hoc tests for heterogeneous distractor conditions

Pairwise comparison	*t*	Cohen's *d*	*p*	95% CI	
Task-relevant vs. Grouped task-irrelevant	3.52	0.84	0.012	1.35	16.73
Task-relevant vs. Control-distractor	3.04	0.69	0.04	0.26	15.22
Grouped task-irrelevant vs. Control-distractor	-0.48	-0.14	0.9	-9.1	6.68

Table 2 Corrected post hoc for homogeneous distractors conditions

Pairwise comparison	*T*	Cohen's *d*	*p*	95% CI	
Task-relevant vs. Grouped task-irrelevant	-2.39	-0.76	0.034	-0.23	-8.07
Task-relevant vs. Control-distractor	-1.80	-0.34	0.109	-0.43	0.05
Grouped task-irrelevant vs. Control-distractor	1.06	-0.33	0.319	-0.11	0.31

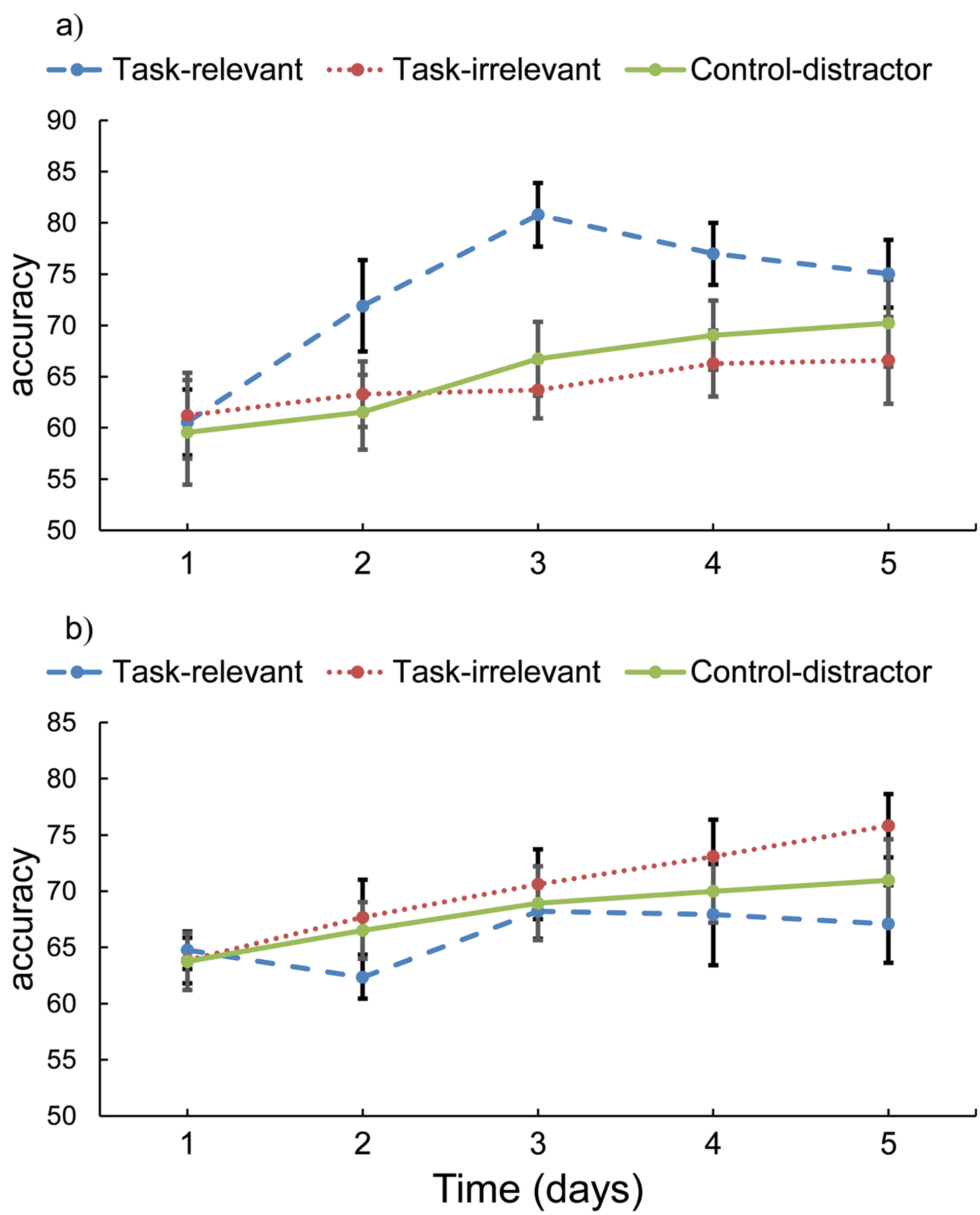

Fig. 3 **a** Performance measured as accuracy (percent correct) plotted for participants in the heterogeneous distractor group over the 5 days and for different locations. Performance at the four control-distractor locations is clubbed together in green. As expected, the performance at the task-irrelevant location (in red; dotted line) was worse than performance at the taskrelevant location (in blue; dashed line). **b** Performance is plotted for participants in the homogenous distractor group over the 5 days and for different locations. The performance at the task-irrelevant location (in red; dotted line) was better than performance at the task-relevant location (in blue; dashed line). Error bars indicate SEM

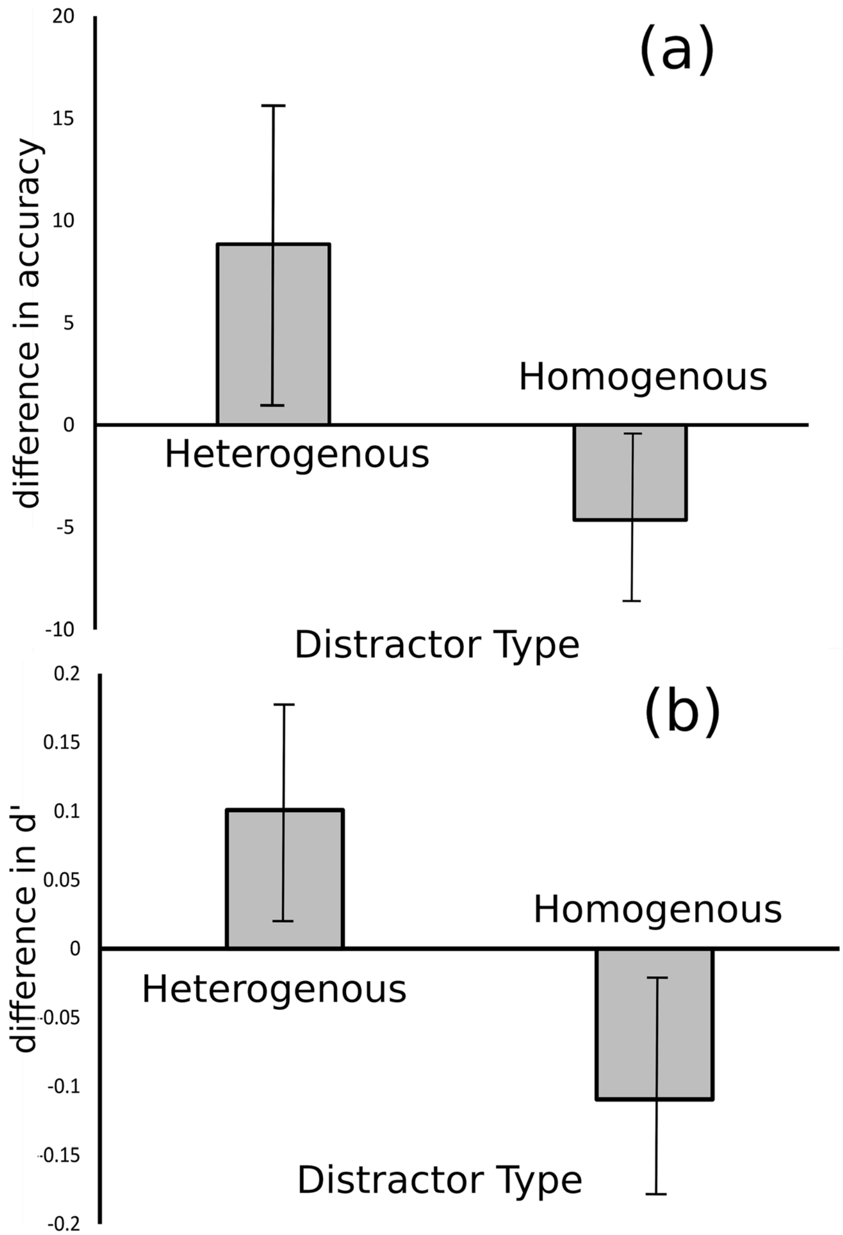

Fig. 4 Difference in (**a**) accuracy and (**b**) *d′* scores obtained by subtracting averaged performance over 5 days of each participant at task-relevant and task-irrelevant locations for homogeneous (bar on right) and heterogeneous (bar on left) distractor conditions. The figure shows better performance for the task-relevant location compared to the task-irrelevant location in heterogeneous distractor group, but poorer performance for task-irrelevant location compared to task-irrelevant location in homogeneous distractor group. The error bars represent 95% confidence intervals

different. However, perhaps the salience of the grouped location interferes with the learning at the task-relevant location. To test for this, we ran another experiment. The aim was to conceptually replicate poorer performance at the task-relevant location under homogenous distractors, but this time with response times (RTs). We wanted to explore whether participants would be slower in responding to contrast changes at the task-relevant location when the distractor set was homogenous. Combined with poorer performance at this location under homogenous distractor conditions in Experiment 1, the follow-up experiment would offer more evidence for interference by task-irrelevant gratings under homogeneous distractor conditions.

Experiment 2

Our results in Experiment 1 did not show a main effect of distractor set type for performance. However, to show that distractor homogeneity influences perceptual processing differently at the task-relevant and task-irrelevant locations, we performed another experiment. This was exactly like part 1 of Experiment 1 (see Fig. 1), except now with the instruction to give speeded responses. Instead of a between-group design like in Experiment 1, distractor homogeneity was a repeated (within-subject) measure in Experiment 2. Distractor homogeneity conditions (homogeneous vs. heterogenous) were blocked and the order was counterbalanced across participants. The rationale of Experiment 2 was to see whether distractor conditions alter the RTs at which participants report contrast changes of the grating at the task-relevant location. Our previous experiment showed poorer discrimination performance at the task-relevant location with homogeneous distractors. Hence, we hypothesized that if distractor sets were influencing the interference by the task-irrelevant grating, participants would be slower in reporting contrast changes at the task-relevant location.

Method

Participants

A total of ten naïve participants (mean age = 24.9 years, five females) from a different subject pool participated in the second experiment. The sample size was calculated using Gpower with the expectation of a large effect size for a paired t-test based on the effect size of the distractor type × location interaction from experiment one (η_p^2 = .348, Cohen's f = 0.62), for a power of 0.85.

Apparatus and stimuli

The apparatus and stimuli were the same as in part 1 of the first experiment.

Procedure

The second experiment was similar to part one of the first experiment except the distractor conditions were now repeated on the same participants in counterbalanced blocks. Participants were also asked to make speeded responses. RTs were measured for participant reports on contrast changes at the task-relevant location.

Results

With this manipulation check experiment, we found that participants were significantly slower to respond to contrast changes at the task-relevant location with homogeneous compared to heterogeneous distractor set, $t(9)$ =2.86 , p =.019, d = .90, CI = [18.84, 161.8], indicating that participants probably paid less attention to the task-relevant location when the control-distractor set was homogenous. This is true even though we asked participants to ignore the other gratings. We conceptually replicated the processing difficulty at the task-relevant location with homogeneous distractors found in the main perceptual learning experiment. In addition to showing that performance in discriminating orientations is poorer at the task-relevant location with a homogeneous distractor set, we also present results that participants are slower in responding to contrast changes at the same location when the distractor set is homogeneous (see Fig. 5).

General discussion

Over two experiments here, we report a novel distractor interference effect in the homogenous distractor condition through influence of the task-irrelevant grating, which is strong enough to impair learning at the task-relevant location. In Experiment 1, we show poorer learning at the task-irrelevant location compared to task-relevant location when participants are exposed to orientations with homogenous distractors; the opposite is true in the heterogenous distractor condition. In Experiment 2, however, we show that participants reporting contrast changes at task-relevant locations are slower when the distractor set is homogenous compared to when it is heterogenous.

Our design uses a setup where we have high distractor-distractor similarity, with high target-distractor similarity and target-grouped gratings being exactly the same (remember the grouped location is a distractor from the participant's perspective). Results from Roper et al. (2013) show similar trends, wherein response to target is slower with high distractor-distractor, and target-distractor similarity. Thus, when the distractors are homogenous, the grating at the grouped location pops out, possibly interfering with task-relevant representations. Evidence of distractors interfering with target (in our case task-relevant grating) have been reported across the attention literature with attentional selection thought to be less efficient, diluted, or zoomed out under high distractor-distractor similarity (Cave & Chen, 2016). In showing a role of attention for task-irrelevant perceptual learning, we postulate that this interference in the exposure phase is carried over into the subsequent testing phase of orientation discrimination, resulting in poorer performance at the task-relevant location. Moreover, in Experiment 2, participants are slower to respond to contrast changes at the task-relevant location, consistent with distractor interference accounts indicating the effect of attentional processes influenced by distractor properties in different locations. Similar effects of stimulus and sensory context have recently been observed in task-irrelevant perceptual learning (Bruns & Watanabe, 2019).

On the other hand, the results we report here in the heterogeneous distractor condition (Experiment 1) also throw light on the role of attention in TIPL. Previous studies (Gutnisky

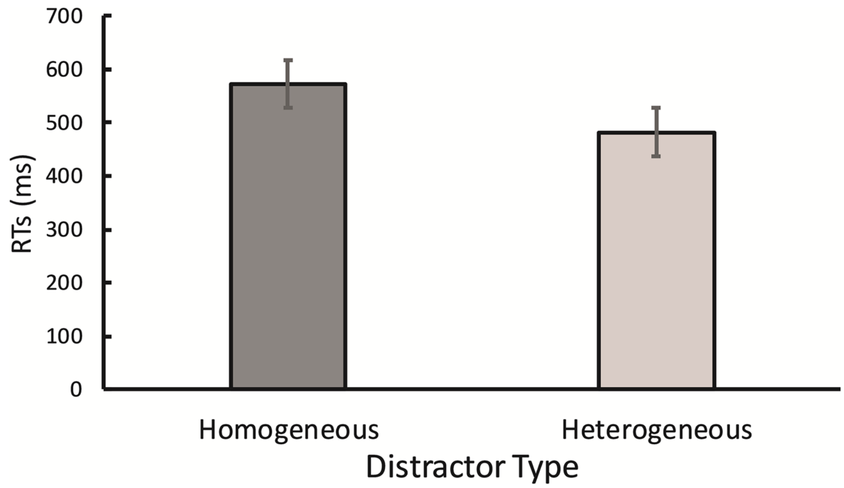

Fig. 5 Response times (RTs) for the speeded version of the exposure phase in Experiment 2 as a function of distractor type. Error bars indicate SEM

et al., 2009; Mastropasqua & Turatto, 2013) have shown TIPL at locations that were either matched in orientation or grouped with a task-relevant target. Performance at task-irrelevant locations in these studies was better than at control locations. In our study, we found no difference in performance at task-irrelevant and control locations in the heterogenous distractor (high-load) condition. One way in which our experiment is different from the previous studies is that we have four control locations that together make up a distractor set. When these distractors are heterogeneous, they support more efficient attentional selection, leaving the task-irrelevant grating "zoomed out" of attentional focus. Thus, even though the task-irrelevant grating has the same orientation as the task-relevant grating, it receives no learning boost since it is filtered out efficiently under heterogeneous distractor sets.

It should be noted that there is also a salient difference due to contrast changes of the grating at the task-relevant location (appearing in "dim" or normal contrast, see *Methods* section). Since only one grating appears dim in contrast on any given trial, task-relevant location may have a higher salience than task-irrelevant location when the grating there appears dim (also vice versa to some extent given that orientation is shared between the gratings at the two locations). While one could argue that the contrast salience should benefit the task-relevant location more than the task-irrelevant location, the orientation salience counteracts any putative benefit due to potential contrast salience at the task-irrelevant location. In the homogeneous distractor condition, the stronger grouping of the grating at the task-irrelevant location with the grating at the task-relevant location makes processing more difficult at the task-relevant location. This effect is not only seen in Experiment 1 but is also replicated in Experiment 2 with a speeded task indicating that the task-irrelevant dimension of orientation and its relationship across distractors influence processing at both the task-relevant and task-irrelevant locations.

Models that explain TIPL through reinforcements or internal and external rewards (Sasaki et al., 2010) cannot account for our results, since we do not give any feedback or reinforcement and any internal rewards should be similar between the two participant groups. The dual plasticity model by Watanabe and Sasaki (2015) proposes that both "task-based" learning and "feature-based" learning mechanisms underlie task-relevant learning, whereas only feature-based learning underlies task-irrelevant learning. Our results from the heterogeneous distractor condition and the original results from Gutnisky et al. (2009) are consistent with this postulation (see Watanabe & Sasaki, 2015), where learning at the task-relevant location is better than that at the task-irrelevant location due to both task- and feature-based learning. It is unclear how this model would incorporate our results from the homogenous distractor condition, where performance at the task-relevant location is worse than that at the task-relevant location. A possible revision of the model could include apparent saliency of the task-irrelevant distractor influencing learning at the task-relevant and task-irrelevant location. Here, saliency of the task-irrelevant distractor could be manipulated by changing target-distractor and distractor-distractor similarity, indirectly affecting how singleton task-irrelevant distractors standout (Gaspelin et al., 2017; Roper et al., 2013).

Task-irrelevant perceptual learning has also been explained by models of transfer of perceptual learning (Dosher & Lu, 2017). This model has two components, one for representing features of the stimulus (orientation, contrast, etc.) and another that forms a decision rule based on output from this representation module. The decision rule module explains changes in response to a stimulus based on bias, feedback, and rewards. Since we provide no external feedback and offer no reward for correct responses, the decision rule module most likely cannot explain our results. However, the effects of bias cannot be ruled out in the current study and would require further investigation.

The representation module in this model holds both "location-specific" and "location-invariant" representations of stimulus features (see Fig. 4 in Dosher & Lu, 2017). The location-specific representations of a stimulus feature jointly alter representations of the same stimulus feature (in our case orientations) at the location-invariant module. This is thought to be the role of attention in their model, i.e., changing connection weights between location specific and location invariant representations and fine-tuning feature representations within the module.

Our manipulations were not designed to test this model. However, a possible modification of the "location-invariant" module could enable us to explain the effect of distractor processing during perceptual learning. The nature of processing in the location invariant module (orientation in our case) would not only depend on the orientation of the task-relevant grating but also would depend on the nature of distractors (homogeneity or heterogeneity) and the sensory context modifying the noise in the location-invariant module. Thus, how effectively attention filters out external noise and enhances the attended stimulus (cf. Dosher & Lu, 1998, 1999) would also depend on the context noise (for example, load, distractor similarity, etc.) There is evidence for such an interaction between target and distractor representations from visual search experiments in which distractor-distractor similarity along with target-distractor similarity has been shown to influence target identification (Geng & Witkowski, 2019). This is also confirmed by the slower RTs for contrast change at the task-relevant location when the distractors were homogenous (compared to when they were heterogeneous) in Experiment 2. The homogeneity of distractors possibly influences the attentional feedback, which normally inhibits processing at the task-irrelevant location and facilitates processing at the task-relevant location. The interaction between location-invariant feature processing, location-specific representations, and attentional processes needs to be further investigated as a function of distractor set, salience of stimuli, and other factors that influence selective attention.

In conclusion, the study presents evidence of distractor type influencing both task-relevant and task-irrelevant perceptual learning. While heterogenous distractor sets limit learning at a grouped task-irrelevant location, homogenous distractors allow the task-irrelevant stimulus to "stand out," making it more salient leading to distractor interference and poorer performance at the task-relevant location. This novel finding of poorer performance at the task-relevant location both in sensitivity and RTs has significant implications for models of perceptual learning.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.3758/s13414-022-02450-1.

Declaration of Interests None

Author Contributions NS and IS conceptualized the study and the design. Data collection and analysis was done by IS. Interpretation of the results was done by NS and IS. The article was written and edited by both NS and IS. Both authors approved of the final version of the manuscript for submission.

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