Load-dependent processing of prediction violations in task-irrelevant space

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Attentive and predictive mechanisms crucially shape perception, but the interplay between these fundamental processes remains poorly understood. Studies on interactions between attention and prediction have yielded discrepant results, potentially because of differences in task demands. The present study examined whether the perceptual load (i.e., task difficulty) affects predictive processing in task-relevant and task-irrelevant hemifields. To this end, we developed a novel delayed match-to-reference task that orthogonally manipulated task-relevance, prediction, and perceptual load. We hypothesized that a low-load

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condition should facilitate the processing of prediction violations (oddball effects) in task-irrelevant space because of the availability of spare processing resources. We analyzed accuracy and response time (RT) data from 28 healthy young participants with separate repeated measures analyses of variance. The results confirmed the effectiveness of the load manipulation because a high perceptual load significantly increased RTs and decreased accuracy. Notably, the accuracy analysis yielded a significant three-way interaction between task-relevance, prediction, and load. Post-hoc tests revealed that load modulated the processing of prediction violations in the task-irrelevant hemifield. Importantly, the prediction violation, induced by a low-frequency and task-irrelevant feature (orientation), reduced accuracy in the low-load but not in the high-load condition. This finding suggests that predictive processing in task-irrelevant space is contingent on the availability of processing resources, with high perceptual load inhibiting the processing of unexpected events in task-irrelevant regions. The present study shows that load is a crucial factor in the interaction between task-relevance and prediction.

Introduction

Attention and prediction are two fundamental mechanisms involved in perception. Attention involves selecting and prioritizing information to allocate the limited processing resources of the neural apparatus to relevant stimuli and to suppress irrelevant information from further processing (Carrasco, 2011; James, 1913; Summerfield & Egner, 2009). Attention can be allocated to different types of information such as spatial locations (Posner, 1980), objects (Duncan, 1984) or visual features such as color or orientation (Müller, Heller, & Ziegler, 1995). Broadly, attentional control can be subdivided into two main categories: endogenous (top-down/goal-driven) and exogenous (bottom-up/stimulus-driven) attention. These two types of attentional control involve distinct but interacting neural systems, i.e., the dorsal and ventral attention networks (Corbetta, Patel, & Shulman, 2008; Corbetta & Shulman, 2002; Vossel, Geng, & Fink, 2014). Prediction refers to generating internal models regarding the likelihood of sensory signals and their external causes based on prior information (Friston, 2010; Friston, 2012), allowing an efficient and adaptive response to the environment. Predictive coding schemes offer plausible theoretical frameworks to integrate the relationship between attention and prediction (Friston, 2010; Mirza, Adams, Friston, & Parr, 2019; Schröger, Marzecová, & SanMiguel, 2015). They postulate a cascade of recurrent neuronal processes at different levels of cortical hierarchies that enables a bidirectional exchange of "top-down" (feedback) predictions and "bottom-up" (feedforward) prediction errors to update the internal models based on sensory evidence (Clark, 2013; Friston, 2005; Lee & Mumford, 2003; Rao & Ballard, 1999). Attention could modulate the amplitude or synaptic gain of prediction errors, thereby affecting the precision (i.e., the relative influence) of bottom-up predictions (Friston, 2010).

Indeed, predictions can govern the deployment of attention, and unexpected events inducing prediction errors may capture attention (e.g., Denison, 2024; Vossel et al., 2015; for a comprehensive review of the effects of prediction on endogenous and exogenous attention—and the two attentional cortical networks, respectively—see Macaluso & Doricchi, 2013). The two mechanisms are often conflated in the literature, especially in paradigms with probabilistic cues that direct attention, but at the same time alter predictions (Chica, Martín-Arévalo, Botta, & Lupiáñez, 2014; Posner, Snyder, & Davidson, 1980).

Therefore the mutual interactions between attention and prediction are still poorly understood, and it remains unclear whether or under which circumstances predictive processes need attention. The two processes can be differentiated experimentally (Vossel, Weidner, Thiel, & Fink, 2009; Schröger, Kotz, & SanMiguel, 2015; Schröger, et al., 2015), but studies investigating whether prediction depends on attention have provided mixed results. Here, it should be noted that the use of the terms "prediction" and "attention" as independent entities may be oversimplified, because prediction may affect attention and vice versa. However, a careful experimental design can enable a further dissection of the processes related to a specific set of predictions and a modulation of these predictions by attention/task-relevance (that may itself be accompanied by other types of predictions). Some of these studies suggested that sequential regularities can be encoded automatically, as reflected in the mismatch negativity (MMN) event-related potential component (Garrido, Teng, Taylor, Rowe, & Mattingley, 2016; Näätänen, Paavilainen, Titinen, Jiang, & Alho, 1993; Näätänen, Tervaniemi, Sussman, Paavilainen, & Winkler, 2001). Similarly, a prediction-related sharpening of representations in the visual cortex has been observed independently from task-relevance (Kok, Jehee, & de Lange, 2012). Furthermore, visual statistical learning can occur independently from explicit top-down attention (Duncan & Theeuwes, 2020; Gao & Theeuwes, 2020). In contrast, other studies highlighted a modulatory role of attention during predictive processing (Alain & Woods, 1997; Guo & Koelsch, 2015; Hisagi, Shafer, Strange, & Sussman, 2015; Sulykos, Kecskés-Kovács, & Czigler, 2015; Woldorff, Hillyard, Gallen, Hampson, & Bloom, 1998) or even demonstrated that attention can be necessary for predictions and statistical learning (Duncan, Van Moorselaar, & Theeuwes, 2024; Richter & De Lange, 2019).

These discrepant findings may be explained by differences in the characteristics and demands of tasks used in the different studies (e.g., stimulus complexity, presentation modalities, or the type of attention and prediction manipulation). One critical factor could be load, since perceptual and cognitive load crucially affect the efficiency of attentional selection (Lavie & Tsal, 1994). The perceptual load theory proposes that when task demands exceed the perceptual capacity, early selection processes prevent task-irrelevant items from being processed. Conversely, when the task requires low perceptual capacity, resources remain available to be allocated to task-irrelevant items (Lavie, 1995; Lavie, Hirst, De Fockert, & Viding, 2004; Murphy, Groeger, & Greene, 2016). These load-dependent mechanisms may be highly relevant for attention-prediction interactions. If the task-relevant perceptual task involves low perceptual resources (i.e., low-load), task-irrelevant predictions may be generated and prediction violations may drive attention automatically, causing distraction. However, if the task-relevant perceptual task involves high perceptual resources (i.e., high-load), task-irrelevant predictions may not be established, or prediction violations may not be processed because of early filtering.

One study (Garrido et al., 2016) directly tested the modulatory role of working memory (i.e., cognitive) load on the electroencephalography (EEG) response to deviant tones. It showed that the MMN component was unaffected by this load manipulation. However, working memory load effects might not be comparable with perceptual load effects. Therefore the current behavioral study aimed to introduce a perceptual (as opposed to cognitive) load manipulation as a factor, which has so far not been considered in previous studies on the interplay between attention and prediction. Moreover, in contrast to Garrido et al. (2016), the present study presented all stimuli in the same (visual) modality to engage the same processing resources. To disentangle attention and prediction, we combined a delayed match-to-reference task (in which participants discriminated the spatial frequency of pairs of gratings) with an oddball-like manipulation of a task-irrelevant stimulus feature (orientation) in the task-relevant or task-irrelevant hemifield. At the beginning of each trial, participants were presented with a central reference grating and a spatial cue indicating the side of the to-be-attended (task-relevant) target grating. The spatial cue served as an endogenous attentional cue to orient attention to the task-relevant hemifield. Subsequently, two peripheral gratings were presented, and participants were asked to compare the spatial frequency of the previously presented reference and the cued target grating. Infrequent changes of grating orientation (a task-irrelevant feature in this study) at the task-relevant grating, the task-irrelevant grating, or at both gratings probed the effect of prediction violations. Additionally, we manipulated the spatial frequency difference between the reference and test stimuli to create two different perceptual load conditions. This manipulation has been shown to influence visual search performance inducing the expected perceptual load-dependent modulation of flanker effects (Roper, Cosman, & Vecera, 2013). Assuming a capacity-limited perceptual system, we presumed that perceptual load critically governs attentional allocation, so that high perceptual load allocates more processing resources to the task-relevant location and fewer processing resources remain for the task-irrelevant location.

We hypothesized that a higher similarity of the spatial frequency of reference and test gratings (i.e., higher perceptual load) would generally increase response times (RTs) and decrease accuracy. For *task-relevant* gratings, we anticipated distraction effects (as reflected in increased RTs and/or reduced accuracy when responding to spatial frequency) by unexpected orientation changes despite orientation being task-irrelevant (oddballs, see, e.g., Wiesing, Fink, Weidner, & Vossel, 2020) for both load conditions. If more attentional resources are allocated to the task-relevant hemifield, the distraction effects there could potentially be enhanced in the high-load condition. For *task-irrelevant gratings*, we hypothesized a load-dependent modulation of distraction effects. Importantly, if the effect of task-relevance on prediction depends on load, we expected to observe stronger performance decrements (higher RTs or lower accuracy) in response to unexpected orientation changes (i.e., the task-irrelevant feature) at the uncued/*task-irrelevant* grating in the low-load than in the high-load condition. Conversely, if the prediction is independent of task-relevance and load, distraction effects by the infrequent oddball orientation of the task-irrelevant grating should equally be observed in both load conditions.

Methods

Participants

Thirty-four participants were recruited for this study. Two participants were excluded because they did not complete the entire experiment, and four participants were excluded due to poor performance during the task ($\leq$50% accuracy in either the high-load or low-load condition). Thus the final sample consisted of 28 participants (18 female, mean age = 26.9, SD = 4 years, age range = 19–40 years). All participants were right-handed, had normal or corrected-to-normal

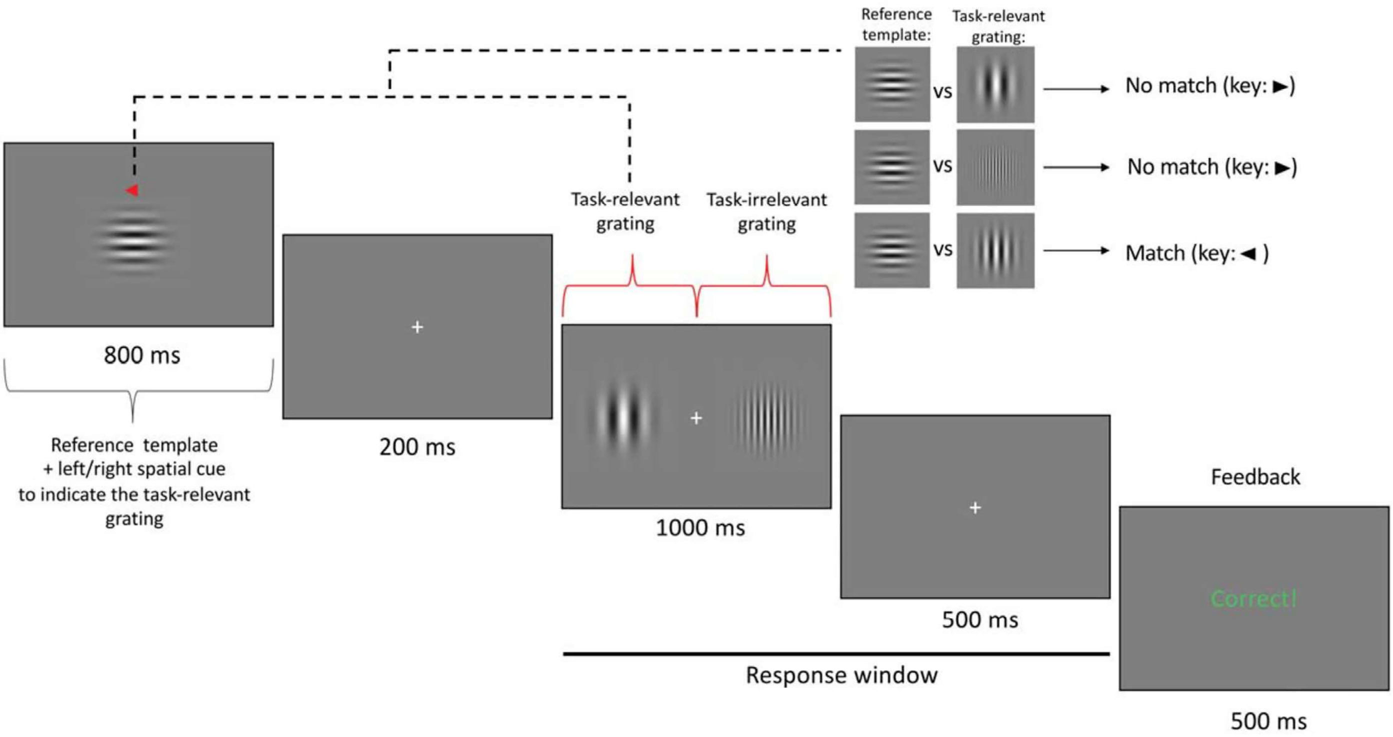

Figure 1. Illustration of the delayed match-to-reference task with a manipulation of task-relevance. Participants were asked to compare the spatial frequency of reference and task-relevant (cued) target grating and to indicate matches and non-matches by button presses. A schematic representation of spatial frequencies, which were calibrated per participant before the experiment, is shown. Unexpected changes in grating orientation (not shown) were introduced at the task-relevant, task-irrelevant or both gratings.

vision, and had no history of neurological or psychiatric diseases. Written informed consent was obtained before the experiment, following the Declaration of Helsinki. The study was approved by Ethics Commission of the German Society for Psychology, and participants were remunerated for their time.

Apparatus

The stimuli were presented on a 47.53″ OLED display (Gigabyte, Aorus F048U). The spatial resolution was 1920 × 1080 pixels with a refresh rate of 120 Hz. The distance from the screen was 70 cm. A chin and forehead rest was used to keep the distance from the screen constant. Stimuli presentation and response recordings were controlled using PsychoPy psychology software for Python, version 2021.2.3 (Peirce, 2007; Peirce, 2008).

Stimuli and task

Participants performed a delayed match-to-reference task with reference and test grating stimuli (see Figure 1). The gratings were sine-wave gratings (7.7° × 7.7°) windowed by a two-dimensional Gaussian envelope with a standard deviation of 1.29° on a gray background.

Each trial started with the presentation of a reference grating at the center of the screen for 800 ms. Together with the reference grating, a spatial cue (red arrow) pointing with equal probability towards the left or right hemifield was presented (size = 1.94° × 1.30°, position [x,y] = [0°, 7.8°]) for 800 ms. With 100% validity, this cue indicated the side of the relevant target grating that participants had to attend covertly while ignoring the opposite hemifield and keeping the gaze fixated at the center of the screen during the entire trial. After a 200 ms inter-stimulus interval, two horizontally aligned gratings were shown simultaneously for 1000 ms, with 6.9° eccentricity left and right from fixation. Participants were asked to indicate by button press with the index and middle finger of their right hand whether the spatial frequency of the task-relevant (cued) grating matched the spatial frequency of the reference grating, regardless of grating orientation. The participants were instructed to respond as accurately and fast as possible. Responses could be given within a 1500 ms time window. At the end of each trial, a feedback screen (“correct/incorrect”) was shown to the participants for 500 ms. All participants performed a short practice session before performing the task.

The reference grating always had a spatial frequency of 1.30 c/° and a horizontal orientation. The different (horizontal) orientation was selected to prevent priming of, or interference with, the standard or oddball orientation. The spatial frequency of the subsequent target grating was adjusted according to the load conditions described below. The spatial frequency of the task-irrelevant grating was kept constant at 1.04 c/°. The list of all the spatial frequencies used in the experiment is provided in the supplementary materials.

The gratings of the test display were presented with different orientations in different proportions of trials to manipulate prediction. The task-relevant and the task-irrelevant grating were presented with either 0° or 45° orientation. One of these orientations (0° or 45°, counterbalanced across participants) was assigned as the standard orientation and was presented in 70% of the trials. The alternative deviant (unexpected) orientation (the oddball) was presented in 30% of the trials. The latter could be further subdivided according to whether the oddball orientation was presented at the task-relevant grating, the task-irrelevant grating, or both gratings: in 10% of all trials (i.e., one third of all trials with an oddball orientation) only the task-relevant grating had an oddball orientation, in 10% (i.e., one third of all trials with an oddball orientation) only the task-irrelevant grating had an oddball orientation, and in 10% (one third of all trials with an oddball orientation) both gratings had an oddball orientation. Note that the participants' task was to respond to the spatial frequency of the stimuli, so that stimulus orientation (and its changes) was always task-irrelevant.

We varied the similarity between the spatial frequencies of the reference grating and the task-relevant test grating to manipulate perceptual load. The spatial frequency of the task-irrelevant grating was kept constant and was always different from the spatial frequency of the reference grating. A higher similarity between the reference and the task-relevant gratings should induce a higher perceptual load (cf., Roper et al., 2013). An individual calibration procedure was used before the actual task to select the specific spatial frequencies for each participant. In this calibration, a series of gratings with different spatial frequencies (5 spatial frequencies above and 5 below the spatial frequency of the reference, each with 5 replicates, linearly spaced at 0.13 c/°) were presented (table provided in the supplementary materials). Participants were instructed to indicate by button press whether the presented grating had a higher or lower spatial frequency than the reference by making button presses. A logistic function was fitted to these responses. For the main experiment, we selected the spatial frequency corresponding to a discrimination probability of 0.01/0.99 for the low-load condition and the spatial frequency corresponding to a discrimination probability of 0.2/0.8 for the high-load condition. These values were chosen to achieve discrimination accuracies of approximately 80% in the main experiment, creating an attention-demanding task whilst maintaining adequate trial numbers for analysis.

A training session comprising two blocks (a low-load block and a high-load block, with counterbalanced order across participants) was performed before the main experiment. Here, 0° and 45° gratings were presented with equal probability. Each training block consisted of 112 trials. After the training, the main task with four blocks (two low-load and two high-load blocks) was performed. Each block consisted of 160 trials, resulting in 320 trials for each load condition (trial numbers per condition are provided in the supplementary material).

Eye-tracking

Eye-tracking (EyeLink 1000; SR Research, Ottawa, ON, Canada) was performed to monitor fixation on every trial. The right eye was recorded with a sampling rate of 1000 Hz. A five-point calibration and validation were used. Participants with more than 10% of trials without eye-tracking data or a general percentage of missing data points greater than 20% were excluded from the analysis. With these criteria, two participants were excluded. Screen dimensions, resolution, and viewing distance were used to convert pixel coordinates into degrees of visual angle. Within each trial, the test grating time window (the time between one to two seconds after reference onset) was selected. We calculated the Euclidean distance from the center to the average eye coordinates during this time window to analyze any deviation from the center. The average distance from the center for each trial for all participants was calculated and analyzed with a 2 × 2 × 2 repeated-measures analysis of variance (ANOVA) with *load* (high, low), *task-relevant (cued) grating orientation* (standard, oddball), and *task-irrelevant (uncued) grating orientation* (standard, oddball) as independent variables.

Statistical analysis of behavioral data

Mean RT and accuracy (% of correct responses) were calculated for each condition and participant. Error trials, trials following errors (to account for post-error slowing) (Laming, 1979), and trials with RTs differing more than two standard deviations from the mean were excluded from the RT analysis.

Statistical analyses were performed using the free software R (R Foundation for Statistical Computing, Vienna, Austria). RTs and accuracy were analyzed with separate 2 × 2 × 2 repeated measures ANOVAs with the factors *load* (high, low), *task-relevant grating orientation* (standard, oddball) and *task-irrelevant grating orientation* (standard, oddball).

We expected significant main effects of *load*, with higher RTs and lower accuracy in the high-load condition. Moreover, we hypothesized that unexpected orientation deviations at the task-relevant grating would lead to higher RTs or lower accuracy, as reflected in a significant main effect of *task-relevant grating orientation*. If perceptual load indeed modulates predictive processing for task-irrelevant stimuli, the interaction effect of *load* and *task-irrelevant grating orientation* or the three-way interaction effect of *load, task-irrelevant grating orientation,* and *task-relevant grating orientation* should be significant. In case of significant interactions with load, the data were additionally stratified based on load conditions, and separate 2 × 2 ANOVAs (*task-relevant grating orientation* × *task-irrelevant grating orientation*) were conducted for each load condition to reveal the origin of the effect. If the ANOVA revealed a significant interaction, post-hoc tests with Bonferroni-Holm correction were applied.

Results

Eye-tracking

The overall mean fixation distance from the center in the 1sec-time window after the cue and reference onset was 1.49° (95% CI [1.06°, 1.91°]). The 2 × 2 × 2 repeated measures ANOVA with *load* (high, low), *task-relevant grating orientation* (standard, oddball), and *task-irrelevant grating orientation* (standard, oddball) showed no significant main effects for *load* ($F(1, 25) = 1.304$, $p = 0.264$, $\eta_P^2 = 0.050$), *task-relevant grating orientation* ($F(1, 25) = 1.48$, $p = 0.235$, $\eta_P^2 = 0.056$), and *task-irrelevant grating orientation* ($F(1, 25) = 1.424$, $p = 0.244$, $\eta_P^2 = 0.054$) on the distance from the center. Additionally, none of the interaction effects reached significance (all p values > 0.18). These results indicate that our experimental manipulations did not systematically affect fixation performance.

Accuracy

The overall accuracy amounted to 60.95% (± 1.66 *SEM*) in the high-load condition and to 85.20% (± 1.86 *SEM*) in the low-load condition. A 2 × 2 × 2 repeated measures ANOVA with the factors *load* (high, low), *task-relevant grating orientation* (standard, oddball), and *task-irrelevant grating orientation* (standard, oddball) revealed a significant main effect of *load* ($F(1,27) = 205.5$, $p < 0.001$, $\eta_P^2 = 0.883$). The main effects of *task-relevant grating orientation* ($F(1,27) = 0.521$, $p = 0.477$, $\eta_P^2 = 0.019$) and *task-irrelevant grating orientation* ($F(1,27) = 0.827$, $p = 0.371$, $\eta_P^2 = 0.030$) were not significant (figure provided in the supplementary materials). Moreover, the interaction between *load* and *task-relevant grating orientation* was not significant ($F(1,27) = 0.730$, $p = 0.400$, $\eta_P^2 = 0.026$), nor was the interaction between *load* and *task-irrelevant grating orientation* ($F(1,27) = 0.456$, $p = 0.505$, $\eta_P^2 = 0.017$). However, the three-way interaction between *load*, *task-relevant grating orientation* and *task-irrelevant grating orientation* was significant ($F(1,27) = 4.219$, $p = 0.0498$, $\eta_P^2 = 0.135$).

To explore the origin of this three-way interaction, separate 2 × 2 (*task-relevant grating orientation* x *task-irrelevant grating orientation*) repeated measures ANOVAs were performed for the two load conditions. The ANOVA in the low-load condition (see Figure 2A) did not reveal any significant main effects (*task-relevant grating orientation*: ($F(1,27) = 1.994$, $p = 0.169$, $\eta_P^2 = 0.069$; *task-irrelevant grating orientation*: $F(1,27) = 0.078$, $p = 0.782$, $\eta_P^2 = 0.003$), but it yielded a significant interaction between both variables ($F(1,27) = 14.97$, $p < 0.001$, $\eta_P^2 = 0.357$). This interaction reflects a mutual impact of the prediction violation (oddball orientation) at the task-relevant and task-irrelevant stimuli, or—in other words—a modulation of the oddball effect at the task-relevant grating, depending on whether there is an oddball effect at the task-irrelevant grating. Post-hoc paired *t*-tests (Holm-Bonferroni corrected) for the effect of the task-irrelevant oddball indicated that there was a significant oddball effect of the task-irrelevant grating when the task-relevant stimulus orientation was standard ($t(27) = 3.196$, $p_{holm} = 0.014$, $\eta_P^2 = 0.275$; cf., Figure 2A). In contrast, no effect of the oddball orientation (nominally even a reversed trend, i.e., higher accuracies for oddball as compared to standard stimuli) was observed for task-relevant oddball stimuli ($t(27) = -2.085$, $p_{holm} = 0.093$, $\eta_P^2 = 0.139$).

Whereas the difference between the standard and the oddball orientation at the task-relevant grating was significant when the task-irrelevant grating orientation was the standard orientation (solid blue line in Figure 2A, $t(27) = 3.066$, $p_{holm} = 0.0147$, $\eta_P^2 = 0.258$), this was not the case when the task-irrelevant grating orientation was the oddball orientation (dashed blue line in Figure 2A, $t(27) = -0.987$, $p_{holm} = 0.332$, $\eta_P^2 = 0.035$).

As in the low-load condition, the ANOVA for the high-load condition revealed no significant main effects (*task-relevant grating orientation*: $F(1,27) = 0.005$, $p = 0.945$, $\eta_P^2 < 0.001$; *task-irrelevant grating orientation*: $F(1,27) = 0.776$, $p = 0.386$, $\eta_P^2 = 0.028$). In contrast to the low-load condition, no significant interaction

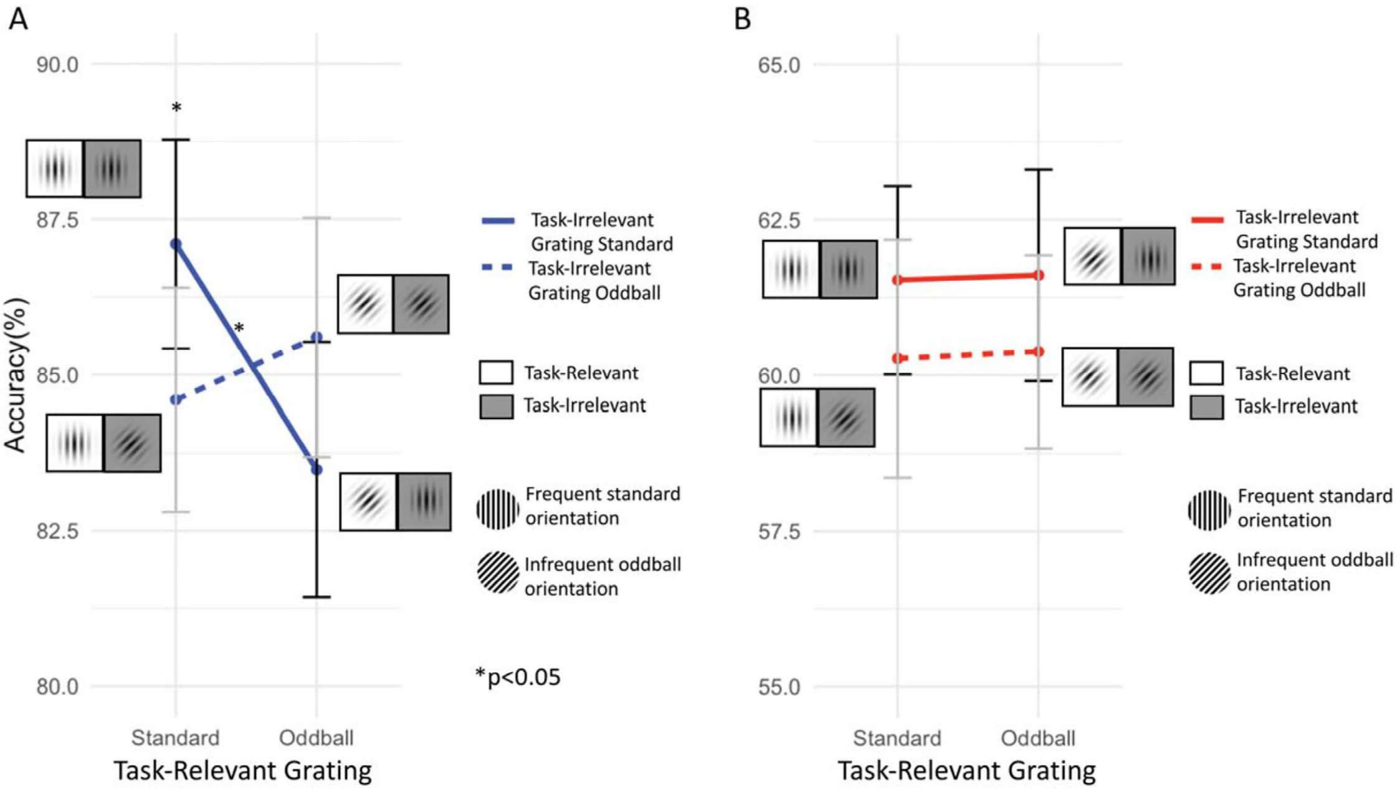

Figure 2. Accuracy in the low-load condition (**A**) and the high-load condition (**B**): note different vertical axes. The standard orientation is depicted as 0° and the oddball orientation as 45° for illustrative purposes (note that the allocation of both orientations to standard and oddball orientation was counterbalanced across participants). The left panel (white) schematically represents the task-relevant grating, and the right panel (gray) represents the task-irrelevant grating for illustrative purposes (note that standard and oddball orientations were presented on the left and right side with equal probability). Error bars depict standard error of the mean.

between both variables was observed ($F(1,27) = 0$, $p = 0.989$, $\eta_P^2 < 0.001$; see Figure 2B). Hence, there were no significant effects of the oddball orientation on accuracy (neither at the task-relevant nor the task-irrelevant grating) in the high-load condition.

Response time

The overall RT amounted to 644.43 ms (17.36 ± *SEM*) in the high-load condition and to 617.30 ms (15.74 ± *SEM*) in the low-load condition. The 2 × 2 × 2 repeated measures ANOVA on RT revealed a significant main effect of *load* ($F(1,27) = 5.742$, $p = 0.0238$, $\eta_P^2 = 0.176$). The main effect of *task-relevant grating orientation* was significant ($F(1,27) = 11.07$, $p = 0.0025$, $\eta_P^2 = 0.291$), with higher RTs for oddball than standard orientations of the task-relevant grating, irrespective of load (see Figure 3, panel A). The main effect of *task-irrelevant grating orientation* was not significant ($F(1,27) = 0.719$, $p = 0.404$, $\eta_P^2 = 0.0260$). Both two-way interactions of *load* × *task-relevant grating orientation* ($F(1,27) = 0.018$, $p = 0.894$, $\eta_P^2 < 0.001$) and *load* × *task-irrelevant grating orientation* ($F(1,27) = 0.587$, $p = 0.45$, $\eta_P^2 = 0.021$) were not significant, nor was the three-way interaction of all factors ($F(1,27) = 2.198$, $p = 0.15$, $\eta_P^2 = 0.075$). Therefore no subsequent stratified analysis per load was performed. However, to compare the RT with the accuracy results, conditions-specific RTs are shown separately for the two load conditions in Figures 3B and 3C.

Discussion

In this study, we orthogonally manipulated task-relevance and prediction. We introduced different levels of perceptual load to investigate its modulatory role on processing prediction violations (oddball effects) in task-irrelevant space on perceptual performance (i.e., frequency judgments) for a task-relevant grating. As predicted, higher load was associated with overall lower accuracies and higher RTs. Furthermore, violations of orientation predictions led to altered RTs in the task-relevant hemifield, irrespective of load. Specifically, RTs were slower for unexpected orientations of the

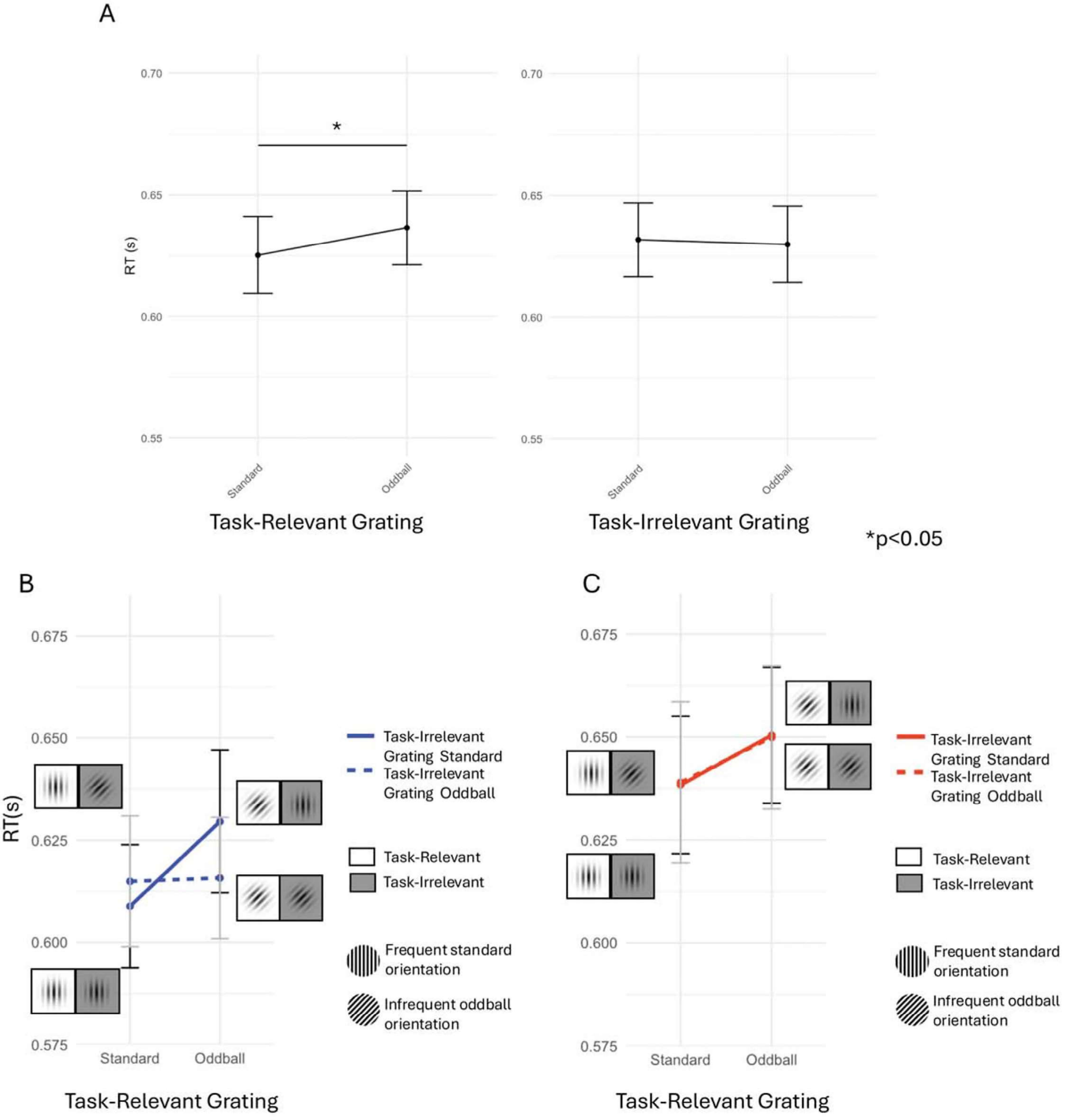

Figure 3. Mean response time per grating orientation (standard or oddball) in the task-relevant-grating (left) and task-irrelevant-grating (right), pooled across both load conditions. Error bars depict the standard error of the mean (**A**). Response time in the low-load condition (**B**) and the high-load condition (**C**). The standard orientation is depicted as 0° and the oddball orientation as 45° for illustrative purposes (note that the allocation of both orientations to standard and oddball stimuli was counterbalanced across participants). The left panel (white) schematically represents the task-relevant grating, and the right panel (gray) represents the task-irrelevant grating for illustrative purposes (note that standard and oddball orientations were presented on the left and right side with equal probability). Error bars depict the standard error of the mean.

cued task-relevant grating, independently of load. No RT effects were found for the task-irrelevant grating. Unexpectedly, there was no main effect of the oddball orientation of the task-relevant grating for accuracy. In contrast, the analysis of accuracy revealed a differential pattern regarding task-irrelevant and unexpected orientations in the low-load and the high-load condition. In line with the prior hypothesis of load-dependent processing of task-irrelevant prediction violations, the effects of task-irrelevant and unexpected orientations were only present in the low-load condition. This may be attributed to attentional capture by the infrequent stimulus under low-load conditions. Such a "spillover" of attentional resources would be restricted if the processing of the task-relevant stimulus fully consumed attentional resources under high-load conditions.

Previous studies on the modulation of predictive processing by attention/task-relevance often focused on the MMN component of the event-related potential or functional magnetic resonance imaging (fMRI) responses as markers of predictive processing. Here, multiple studies reported at least a modulatory role of attention or task-relevance on the MMN amplitude (i.e., an attenuated response to prediction violations with less attention) (Alain & Woods, 1997; Hisagi et al., 2015; Smout, Tang, Garrido, & Mattingley, 2019; Woldorff et al., 1998). One recent fMRI study even observed completely abolished prediction (expectation suppression) effects without attention (Richter & De Lange, 2019). This starkly contrasts with studies that demonstrated minimal or no effects of attention or working memory load manipulations on neural signatures of predictive processing (Garrido et al., 2016; Kok, et al., 2012).

A similar heterogeneity has been reported in purely behavioral studies. While some studies have reported that visual statistical learning of regularities can occur independently from explicit top-down attention (Duncan & Theeuwes, 2020; Gao & Theeuwes, 2020), or that learning of contingencies occurs even with task-irrelevant cues (Tavera & Haider, 2025), Duncan and colleagues demonstrated that incidental learning of the probability of a non-target location in a visual search task is no longer observed when attention is further engaged by using a color subset search or an exogenous cue (Duncan et al., 2024).

The present results show that both effects (present or absent prediction violation effects at uncued task-irrelevant locations) can be observed within the same task if task demands (perceptual load) are varied (i.e., by individually calibrating stimulus features to induce different load conditions). Hence, load may be one crucial factor leading to differences in the effect of attention on predictive processes. Interestingly, in the fMRI study by Richter and de Lange (2019), in which prediction effects critically depended on attention, participants were simultaneously presented with naturalistic images of objects and alphanumeric characters (inducing competition between both types of stimuli). In a pre-scanning session, participants learned the identity of leading and trailing objects so that one object predicted the identity of the second object. At the behavioral and neural level, expectation suppression effects for the expected objects were only present when participants performed an object classification task (electronic versus not electronic) but not when they performed a character classification task (letter vs. non-letter). One could speculate that the simultaneous presentation of task-relevant and task-irrelevant stimuli and the demands of the classification task summoned perceptual resources extensively, thereby making prediction effects vulnerable to attentional withdrawal. On the other hand, many studies demonstrating preserved prediction violation (MMN) responses without attention often used salient auditory deviants, presented the stimuli of the concurrent attention-demanding task in a different sensory modality (e.g., Restuccia, Della Marca, Marra, Rubino, & Valeriani, 2005), or did not control the task demands to ensure that attention was indeed withdrawn effectively (e.g., Kimura, Schröger, Czigler, & Ohira, 2010). Hence, one could argue that these conditions lead to spare resources for processing prediction-related signals outside the current attentional focus.

At first glance, our present findings are at odds with the results of the EEG study by Garrido et al. (2016). The authors recorded EEG data while participants listened to Gaussian-distributed frequencies and measured the response evoked by the mean versus odd frequencies. Simultaneously, participants were engaged in a visual working memory task with high or low difficulty, which did not modulate the MMN response. As mentioned above, the fact that the paradigm involved stimuli in different sensory modalities may have reduced their mutual influence. Moreover, it is important to consider the specific task demand/type of load manipulation. Whereas *cognitive* load refers to control processes required for maintaining task priorities (Lavie, Beck, & Konstantinou, 2014), *perceptual* load has been conceptually related to the amount of information required to process behaviorally relevant stimuli (Macdonald & Lavie, 2011). Perceptual and cognitive (e.g., working memory) load may have opposite effects, with cognitive load *increasing* rather than *decreasing* distractor interference (Lavie et al., 2014). Although no load effects were observed by Garrido et al. (2016), another EEG study reported enhanced neural responses to both frequent and infrequent stimuli during a difficult as compared to an easy task (Pazo-Alvarez, Amenedo, & Cadaveira, 2004). The latter is opposite to the effects observed in the present study. However, because their task involved responding to numbers smaller than five irrespective of color (easy) or responding to blue numbers smaller than five or green numbers larger than five (difficult), it could be more akin to a manipulation of cognitive rather than perceptual load.

In the present study, the effects of perceptual load-dependent prediction violations for task-irrelevant and task-relevant stimuli were shown with purely behavioral measures. This approach significantly differs from the above-mentioned EEG and fMRI studies, which primarily or exclusively focused on neural responses. Although the characterization at the behavioral level is an advantage of this study's novel paradigm, we cannot rule out that prediction violations outside the focus of attention were associated with neural prediction error responses without consequences for behavior in the high-load condition. Future work could therefore adapt this paradigm for EEG or neuroimaging to shed light on this open question. This will also enable further testing of the putatively different modulations of neural processing by attention and prediction (Kok, Rahnev, Jehee, Lau, & De Lange, 2012; Marzecová, Widmann, SanMiguel, Kotz, & Schröger, 2017) in relation to load and behavioral performance. The present study also cannot reveal whether high-load conditions prevent the generation of predictions per se or inhibit the propagation of the prediction errors to higher processing stages.

It should be noted that we did not observe any significant changes in accuracy induced by the unexpected orientation in the *task-relevant* grating for the high-load condition (nor did we observe an interaction effect of task-relevant and task-irrelevant orientations). Oddball effects in this condition could have been expected especially if more attentional resources were allocated to the task-relevant stimulus in this condition. However, this missing oddball effect could be attributed to the fact that orientation was an irrelevant feature for the spatial frequency judgment task. Increased attentional load was achieved by increasing task-difficulty of spatial-frequency judgments. Therefore high-load conditions may have led to a shift of attentional resources away from the stimulus orientation towards spatial frequency. This lack of attentional resources allocated to the orientation dimension may thus have prevented oddball effects, even though both visual dimensions were features of the same object.

An intermediate load condition could potentially reveal whether load restricts attentional resources to the task-relevant grating while still allowing spillover to the task-irrelevant orientation. This question cannot be addressed with the present design but warrants further investigation. Still, we observed a significant main effect of the oddball orientation of the task-relevant grating in RTs, irrespective of load. This could suggest that participants switched to a strategy prioritizing correct responses at the expense of longer RTs.

One surprising effect in the novel paradigm concerned the performance in the double-oddball condition in the low-load condition, in which both test gratings were presented with the unexpected orientation. Although one could have expected lowest accuracies in this condition because of an additive effect of prediction violations, accuracy was the same (numerically even higher) compared to the task-relevant-oddball/task-irrelevant-standard condition. The result in this condition may point to a potential role of the congruency of the two grating orientations, with incongruent orientations being more salient and capturing exogenous stimulus-driven attention automatically, leading to lower accuracy than congruent gratings. Hence, saliency-driven attentional capture might potentially explain the pattern observed in accuracy, as the incongruent configurations led to significantly lower accuracies compared to the congruent configuration. It is also possible that task-difficulty (e.g., retrieving spatial frequencies when a global feature is spread across two locations) is higher with competing orientations in the incongruent configurations. Still, if incongruency drove the observed patterns, we should have observed a significant decrease in accuracy when contrasting the double oddball condition (congruent but unexpected orientation of both gratings) to any of the single oddball conditions (task-relevant oddball/task-irrelevant standard or task-relevant standard/task-irrelevant oddball). Post-hoc tests did not yield significant effects for these comparisons. Therefore we believe that stimulus congruency alone cannot fully explain the present results but that it could have contributed to the observed pattern.

Moreover, the results in the double oddball condition could be caused by the contingencies of congruent versus incongruent orientation conditions in the present task: conditions in which both gratings were presented with the identical (standard or oddball) orientation were more frequent than conditions with different orientations, so that this additional prediction effect of the orientation similarity may have diminished the oddball impact in the double oddball conditions. Interestingly, this effect was not observed in the high-load condition.

Conclusions

In conclusion, our results show that the presence of prediction violation effects for task-irrelevant (as well as task-relevant) stimuli critically depended on the level of perceptual load.

Keywords: task-relevance, attention, prediction error, perceptual load, oddball effects

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