# Supporting Information

**Ludwig et al. 10.1073/pnas.1313553111**

## SI Text

**Behavioral Performance.** The performance data are summarized in Fig. S1. For the critical measures—same/different accuracy, foveal target tilt discrimination, peripheral target tilt discrimination, and peripheral selection—the confidence intervals do not include chance performance (in fact, the conditional accuracy measures are also reliably above chance, but this result is less critical). Peripheral target tilt discrimination is somewhat lower than foveal target tilt discrimination (compare second and third bars). There are two explanations for this effect: (*i*) the observer might have fixated the wrong peripheral pattern or (*ii*) even if the peripheral target was fixated, the initial fixation duration was longer than half the total trial duration and less time would have been available for processing the target.

We can assess the first of these two factors by examining peripheral target tilt discrimination conditional upon saccade accuracy. When restricting the analysis to just those trials in which the target was fixated first, performance is a little more accurate (a difference of 3–6%; fourth bar in Fig. S1). However, when taking only those trials in which one of the nontargets was fixated (without subsequent movements to the target), performance drops close to chance (54–56% correct; fifth bar in Fig. S1). Indeed, on these trials, observers were more likely to report the orientation of the nontarget they erroneously fixated (58–66%; sixth bar in Fig. S1). It should be pointed out that observers may not necessarily realize they have fixated the wrong item and therefore report the orientation of what they believe is the target.

**Peripheral Selection Integration Window Derived from Correct Saccade Trials.** The integration windows for peripheral selection shown in Figs. 3–5 were derived from trials in which the first saccade was directed to a nontarget. As such, we compared the contrast noise at the chosen nontarget location with that at the ignored target location. We selected error trials because these are most likely to be diagnostic in this regard. Errors may be expected to occur when the external noise acts to substantially enhance the contrast of a nontarget pattern and/or substantially reduce the contrast of the peripheral target. Correct saccades may of course also be driven (partly) by external noise, such as when a noise sample enhances the target contrast even further away from the nontarget contrast. However, even in the absence of such noise values, the sensory evidence will typically point to the correct target. As such, we would not expect a particularly strong relation between the noise and the saccadic decisions on these trials.

To illustrate this point, Fig. S2*A* shows the raw temporal classification images for peripheral selection for the same observer whose data were shown in Fig. 3 *C* and *D*. The two ignored nontargets now hover close to zero, as might be expected. When the noise is around zero (which it is by definition most of the time), the sensory evidence favors the target. There is a small effect of noise at the target location, in that noise early in the trial that elevates the target contrast may contribute to the correct eye movement decisions.

Fig. S2*B* shows the classification accuracy for the sample as a whole. The green functions are the same as those illustrated in Fig. 4, based on the more informative error saccades. The gray functions are derived from the correct movements only. As expected, the noise is much less predictive of these correct decisions, although the temporal profile, insofar as there is one, is consistent with that derived from the error trials. From this analysis we conclude that there is little to be gained by considering the correct saccades in the identification of the integration window for peripheral selection.

**Random vs. Blocked Variation in Foveal Processing Load.** Our sample of eight observers was split into two groups. One group received the variation in foveal processing load (i.e., magnitude of the mean tilt offset) randomly intermixed. The other group received this variation in a blocked manner (in one experimental session, the foveal load was low in two blocks and high in another two blocks of trials). Our expectation was that in the blocked condition, we might see strategic adjustments in the uptake of foveal information, with potential interactions with the uptake of peripheral information. Fig. S3 shows the temporal processing windows, separately for the two groups and foveal load levels. As in Fig. 5, the functions for the two difficulty levels show a great amount of overlap. This finding suggests that even when foveal processing load is blocked, no strategic adjustment in the processing window was made.

**Peripheral Processing Is Nonunitary.** Both orientation and contrast are coded by early visual mechanisms at the level of primary visual cortex. As a result, it may be that processing peripheral contrast information automatically also involves extracting orientation information.

Moreover, in *Discussion* in the main text, we raise the possibility of a rapidly shifting serial attention mechanism. In particular, we describe how such a mechanism may give rise to temporal integration windows that mimic genuine parallel processing of foveal and peripheral information. Such an attentional spotlight is typically thought of as a unitary mechanism that is needed to bind different features within the focus of attention together (1). Given the unitary nature of the mechanism, we would expect the uptake of contrast and orientation information from peripheral locations to go hand in hand.

For these reasons, we analyzed the uptake of contrast and orientation information in the periphery, contingent on different saccadic decisions. In these analyses we are really only interested in the uptake of information before movement onset. As such, we only show the noise classification accuracy aligned on movement onset.

Fig. S4*A* shows the uptake of contrast information for peripheral selection (in green, as in Fig. 4). In addition, we plot the uptake of tilt information from the peripheral target location, given accurate selection of the saccade target (in magenta, replicated in all three panels). Note that for the peripheral target, we have to infer the observer's tilt judgment from his/her perceived tilt of the foveal target and the overall same/different judgment.

Some tilt information from the peripheral target is processed while the eyes are still focused on the foveal target. The time course of the two functions suggests that peripheral tilt information starts being processed once the peripheral selection function has reached its peak. This peak represents the point in time that, on average, is most predictive of the ensuing saccadic decision; as such, it may be considered an index of the completion of saccade target selection. Target selection may facilitate processing of visual features from the future fixation position, consistent with presaccadic shifts of covert attention reported elsewhere (2–4). After the saccade, processing of tilt at the peripheral target location is greatly enhanced because the pattern now projects onto the fovea.

Is the presaccadic processing of orientation information specific to the (saccade) target location or does it occur for all peripheral patterns in the build-up to a gaze shift? We address this question by looking at (*i*) the uptake of tilt information from the peripheral target location when a saccade is generated to a different pattern (i.e., an "error" saccade); and (*ii*) the uptake of tilt information from a peripheral nontarget location, given an impending error saccade to that location.

Fig. S4 *B* and *C* show these comparisons; in *B*, we show that no orientation information from the peripheral target is processed before the saccade when the movement is directed elsewhere. Indeed, the divergence of these curves ~175 ms before movement onset may be taken as an estimate of when the presaccadic facilitation at the future fixation position begins.

In Fig. S4*C* we show the uptake of orientation information from a peripheral nontarget location, when that location is about to be fixated. Note that for this analysis, we take the inferred target-tilt judgment and assess it against the true tilt offset at the fixated nontarget location. Responses that are congruent with the tilt offset at that location are considered correct for the purpose of the noise-classification analysis (and incongruent responses are treated as errors).

This final analysis also addresses a concern one might have with the comparison between peripheral selection based on contrast and the uptake of tilt information at the saccade target location. The two curves shown in Fig. S4*A* are based on different subsets of trials; that is, the function for peripheral selection is based on error saccades, but the function for peripheral tilt processing is based on correct saccades. However, Fig. S4*C* demonstrates that the uptake of peripheral tilt information from the future fixation location is the same for correct and error saccades (at least insofar as the presaccadic facilitation is concerned).

These analyses demonstrate that the time course for processing contrast and orientation information from the periphery was very different in the build-up to a gaze shift. Peripheral contrast information is processed at the start of a fixation from all possible saccade target locations (Fig. 3). However, orientation information is only processed at the future fixation position, once saccade target selection is at least partly complete. The differential uptake of contrast and orientation information argues strongly against a rapidly shifting unitary attention mechanism. These results are one reason why we question the utility of an attentional spotlight in accounting for behavior in the present study.

1. Treisman AM, Gelade G (1980) A feature-integration theory of attention. *Cognit Psychol* 12(1):97–136.
2. Kowler E, Anderson E, Dosher BA, Blaser E (1995) The role of attention in the programming of saccades. *Vision Res* 35(13):1897–1916.
3. Deubel H, Schneider WX (1996) Saccade target selection and object recognition: Evidence for a common attentional mechanism. *Vision Res* 36(12):1827–1837.
4. Rolfs M, Jonikaitis D, Deubel H, Cavanagh P (2011) Predictive remapping of attention across eye movements. *Nat Neurosci* 14(2):252–256.

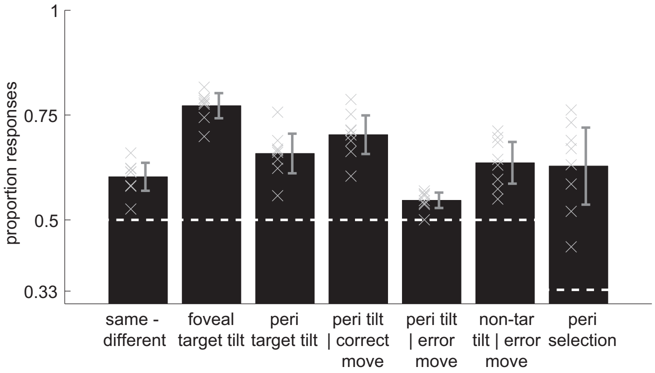

**Fig. S1.** Overall performance accuracy. From left to right: same/different judgment; foveal target tilt discrimination; inferred peripheral target tilt discrimination, regardless of the saccade endpoint; peripheral target tilt discrimination, given an accurate target-directed movement; peripheral target tilt discrimination, given an error movement to a nontarget; and inferred "nontarget" tilt discrimination, given a movement to that nontarget; peripheral target selection accuracy with the first saccade. Bars correspond to the means across all observers; error bars show the 95% confidence intervals, corrected for between-subject variability; crosses indicate individual observers' performance. The white dashed lines indicate chance levels.

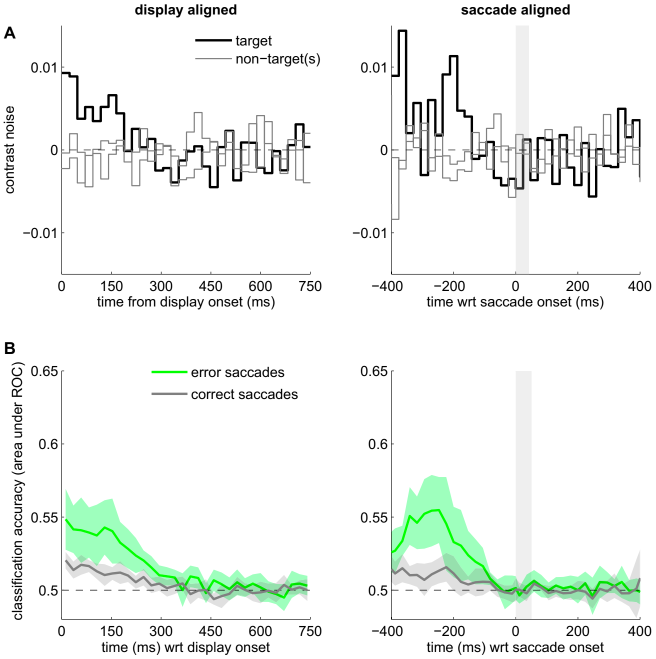

**Fig. S2.** Noise classification analysis for peripheral selection based on correct saccades only. (*A*) Raw temporal classification images for one observer. The two nontargets were labeled 1 and 2, after rotating the configuration of three peripheral patterns in a clockwise direction to coincide with the "top" configuration shown in Fig. 2. Nontarget 1 is then the rightmost nontarget (e.g., if the target was horizontal right, nontarget 1 would be the top pattern). (*B*) Noise classification accuracy for the total sample of eight observers, shown separately for error saccades (the same green curves as in Fig. 4) and correct saccades (gray functions). The noise values from the two nontargets are pooled together in the "ignored nontarget" distribution for the purpose of this analysis (i.e., this distribution will have twice the number of values at each point in time to the number of "chosen target" samples). The shaded regions around the functions show the 95% confidence intervals across subjects. In the saccade-aligned plots (*Right*), the average saccade duration is shown by the gray shaded box.

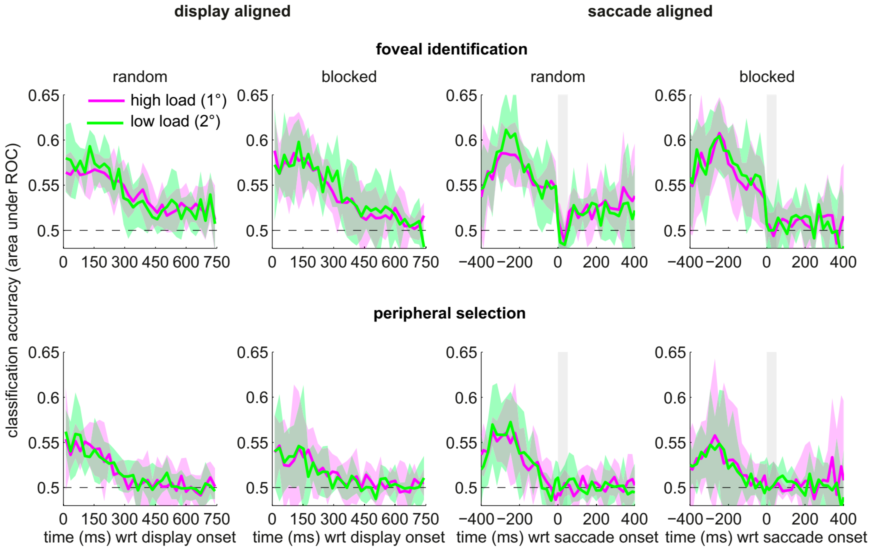

**Fig. S3.** Noise classification accuracy for foveal identification and peripheral selection for the two levels of foveal processing load. Functions are averaged over the four observers in each group. In the saccade-aligned plots (third and fourth columns), the duration of the saccade is shown by the shaded vertical box. Shaded regions around the functions are 95% confidence intervals; these are larger than in Figs. 4 and 5, because each function is now based on only half the subject sample.

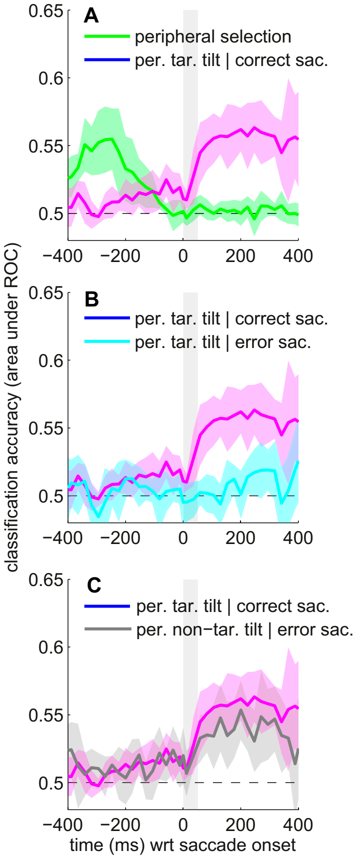

**Fig. S4.** Noise classification accuracy for peripheral selection and peripheral tilt discrimination, contingent on the accuracy of saccade target selection. (*A*) Processing of target contrast (green) compared with the processing of target tilt (magenta), contingent on an accurate target-directed saccade. The green function is based on error saccades, and is replicated from Fig. 4, *Right*. (*B*) Processing of target tilt contingent on error saccades (light blue). The function derived from correct saccades is replicated for comparison. (*C*) Processing of non-target tilt contingent on error saccades to that nontarget (gray). The function derived from accurate saccades is replicated for comparison. All functions are averaged across eight observers. The vertical shaded box indicates the saccade duration. Shaded areas around the functions correspond to 95% confidence intervals.