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Crowding in a detection task: External noise triggers change in processing strategy

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ABSTRACT

External noise paradigms have been widely used to probe different levels of visual processing (Pelli & Farell, 1999). A basic assumption of this paradigm is that the processing strategy is noise-invariant, remaining the same in low and high external noise. We tested this assumption by examining crowding in a detection task where traditionally crowding has no effect. In the first experiment, we measured detection thresholds for a vertically oriented sine wave grating (target) surrounded by four sine wave gratings (flankers) that were either vertically or horizontally oriented. At low noise levels, the detection threshold for the target was unaffected by the orientation of the flankers – there was no crowding. Surprisingly, however, there was crowding for detection at high noise levels: the threshold increased for the similarly-oriented flankers. This suggests that high noise triggered a change in processing strategy, increasing the range of space or features over which the visual signal was sampled. In a second experiment, we evaluated the impact of the spatial and temporal window of the noise on this crowding effect. Although crowding was observed for detection when the spatial and/or temporal window of the noise was localized (i.e. identical to the signal window), no crowding was observed when the noise was spatially and temporally extended (i.e. continuously displayed, full screen dynamic noise). Our results show that certain spatiotemporal distributions of external noise can elicit a change in processing strategy, invalidating the noise-invariant assumption that underlies external noise paradigms. In contrast, spatiotemporally extended noise maintains the required noise-indifference, perhaps because it matches the characteristics of the internal noise that determines the contrast threshold in low noise.

1. Introduction

External noise paradigms have been widely used to examine the processing properties of detection and discrimination mechanisms (e.g. Allard & Faubert, 2006, 2008a; Bennett, Sekuler, & Ozin, 1999; Dosher & Lu, 2004; Legge, Kersten, & Burgess, 1987; Lu & Dosher, 2004a, 2008; Pardhan, 2004; Pardhan, Gilchrist, & Beh, 1993; Pelli, 1981, 1990; Pelli & Farell, 1999; Tjan, Braje, Legge, & Kersten, 1995). Contrast thresholds as a function of external noise contrast show a stereotypical bi-linear, hockey-stick function in log–log units (Fig. 1) where the knee of the curve roughly corresponds to the point at which the external noise begins to markedly influence contrast threshold: below this point external noise has negligible impact and internal noise alone measurably influences contrast threshold whereas above this point, additive internal noise has negligible impact and the threshold is mainly influenced by external noise. If a factor like attention affected the efficiency of extracting signal from noise (e.g. sampling or calculation efficiency), it would lower the contrast threshold along the entire curve (Fig. 2b bottom-right). If a process reduced the impact of additive internal noise (e.g. early contrast gain), it would lower the threshold on the left where it is determined by the additive internal noise but leave it unaffected on the right where it is mainly influenced by external noise (Fig. 2b top-left). Finally, if some process could reduce the strength of only the external noise (e.g. early noise exclusion), it would leave the left portion unchanged but lower the thresholds on the right (Fig. 2b bottom-left). This logic has driven the interpretations of numerous studies in the last five decades but it rests on the fundamental assumption that the processing (Fig. 2a) remains unchanged as external noise is added, i.e. that the most sensitive channel and its properties do not change with external noise level. Indeed, problems in interpretation arise if the most sensitive channel in low noise is not the most sensitive one in high noise or if some property of processing changes with external noise level. In this case, it is no longer possible to unambiguously characterize the effects of additional variable like attention or learning using an observer model which assumes that processing properties are noise-invariant. In this article we will challenge this noise-invariant processing assumption and show that for some types of external noise, the nature of the processing changes dramatically between low external noise and high external noise conditions.

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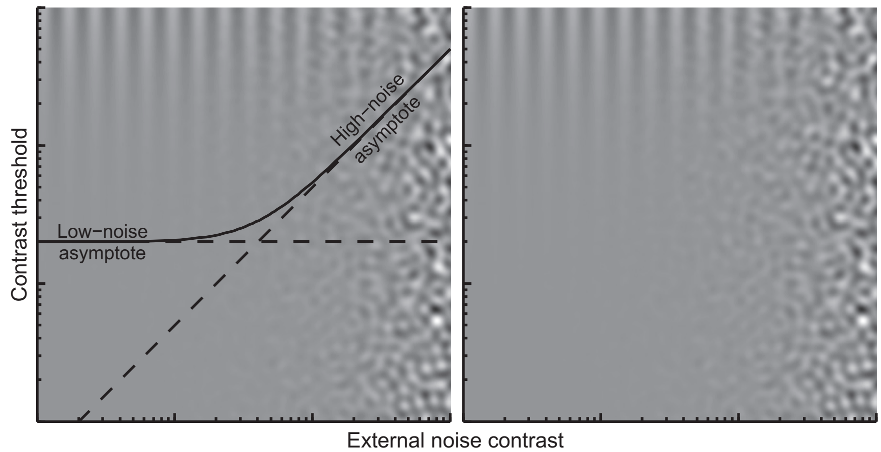

Fig. 1. Left panel: Typical bi-linear, hockey-stick function in log–log units obtained when measuring contrast detection threshold as a function of external noise contrast (solid line). In low noise, contrast threshold is limited by additive internal noise (external noise has no significant impact) and therefore does not vary with external noise contrast (low-noise asymptote). In high noise, contrast threshold is limited by external noise and therefore increases proportionally with external noise contrast (high-noise asymptote with a slope of 1 in log–log units). Right panel: Superimposed gradients of signal and noise on their own to allow subjective judgment of the threshold trajectory.

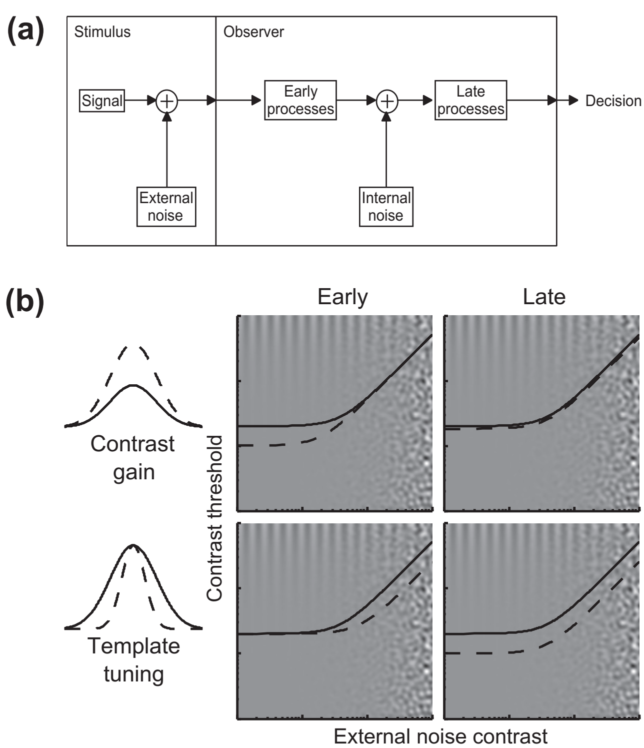

Fig. 2. (a) A generalized observer model including an additive internal noise source determining contrast threshold in low noise. Processes affecting contrast threshold can either occur before (i.e. early) or after (i.e. late) the additive internal noise. (b) Varying external noise contrast over a wide range can be used to evaluate processing when additive internal noise dominates external noise and vice versa. By assuming that processing properties are noise-invariant, this paradigm can localize different effects on sensitivity relative to the main additive internal noise source (i.e. early or late processes) and can characterize whether these affect both the signal and noise by the same proportion (i.e. contrast gain) or change the signal-to-noise ratio (e.g. template tuning). A change in contrast gain has a significant impact only if it occurs *before* the dominating noise source. Thus, different early contrast gains produce its main effect only in low noise (top-left panel) whereas different late contrast gains have no effect (top-right panel). Conversely, processes affecting the noise without affecting the signal (e.g. narrowing the template filter) only have a significant impact if they occur *after* the dominating noise source. Thus, different early template tuning efficiencies (typically referred to as external noise exclusion) produce a significant effect only in high noise (bottom-left) and a change late template tuning (typically referred to as sampling or calculation efficiency) results in a similar effect at all noise levels (bottom-right).

We make this demonstration using a crowding task and specifically the presence of crowding in a detection paradigm. Traditionally, in absence of external noise (i.e. low noise), crowding affects recognition but not detection (Levi, 2008; Levi, Hariharan, & Klein, 2002; Livne & Sagi, 2007; Pelli, Palomares, & Majaj, 2004). Clearly then, the noise-invariant processing assumption predicts that crowding should not be a factor for detection in high noise either. However, for certain types of external noise, we find that crowding does occur for a detection task when external noise is present (high noise) but not when it is absent (low noise) – a result that indicates a change in processing strategy.

1.1. External noise exclusion vs noise-dependent processing strategies

Previous studies have examined the effects of top down or observer factors on performance, whether spatial attention (Dosher & Lu, 2000; Lu & Dosher, 2000; Lu et al., 2009), learning (Betts, Sekuler, & Bennett, 2007; Lu & Dosher, 2004b), dyslexia (Sperling, Lu, Manis, & Seidenberg, 2005), or people who get migraines (Wagner, Manahilov, Loffler, Gordon, & Dutton, 2010). Although the addition of external noise may trigger a change in processing strategy in these cases, the authors of these studies argued that processing remained unchanged as a function of the noise level (i.e. noise-invariant processing assumption) while the specificity of an early filter changed relative to the given manipulation (e.g. attention), excluding external noise more or less efficiently. In our study, the key variable is not an observer variable but a change in the organization of the stimulus: whether the surrounding distractors are parallel or orthogonal to the target. As we will show, this change influenced performance only at high levels of external noise and in our stimulus we can see clearly that this change is the result of using a different strategy (a switch from detection to recognition, where recognition, unlike detection, entails surround interference – crowding). Not only is it obvious that a different strategy is in place at high external noise levels, it is also unlikely that the two stimulus organizations (same or orthogonal orientations of target and flankers) could trigger a change in an early noise filter. In particular, early filter properties would have to be changed by properties of the as-yet undetected target and, in addition, there is no evidence of lateral interactions between target and flanker orientations that might operate prior to detection at the target-flanker separations that we used (Pelli et al., 2004).

So this experiment is constructed to reduce the possibility that changes in early noise exclusion filters might play a role. First we

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embed the information needed to trigger any filter change in the stimulus itself, minimizing the available time for implementing the new filter, and we arranged the task to be specifically the simplest of detection tasks so that the detection of target properties necessary to engage the appropriate early filter would also be all that is required to respond in the task, without bothering to implement the filter change. For these reasons, presented in detail in following sections of this paper, we find that, for this task the effects of stimulus organization are seen only in high noise and this pattern of responses is caused by a noise-dependent processing strategy shift and not by a noise-invariant change in early filter properties. We then extend this argument to include observer-specific factors like attention.

Most important, however, is our finding that high external noise triggers the processing change only for external noise that turns on and off with the target (and distractors) or is present only at the target locations. These local noise distributions influence processing very differently from global external noise which extends over the display and is present before, during, and after the display presentation. In this case, the detection of the target remains unaffected by the orientations of the flankers, as is the case with no external noise. Our suggestion is that the global noise distribution closely resembles the nature of internal noise and so increasing its amplitude does not change the strategies already evolved to work with this stimulus-unrelated noise. Most previous studies using the external noise procedure have used local external noise and so, we suggest, are vulnerable to possible strategy changes. If these studies were rerun with global external noise, extended in space and time, there would be less of chance for strategy change that could confound the interpretation of the performance effects at high noise levels.

1.2. Crowding

In standard conditions (low noise), crowding a target with similar flankers is known to impair its recognition, but is typically found to have no impact on its detection (Levi, 2008; Levi et al., 2002; Livne & Sagi, 2007; Pelli et al., 2004). This crowding result suggests that processes required to *recognize* the target are inappropriately integrating some features of the flankers; whereas the processes required for *detecting* the target do not. These results are generally taken as evidence of a two-stage model (see Levi (2008) and Pelli et al. (2004) for reviews) where features are first extracted locally and then integrated over a larger region. Crowding would occur at the feature integration processing stage when some features of the flankers are inappropriately combined with the target thereby impairing its recognition. Here we show that under some forms of external noise, crowding can occur for a detection task suggesting that the strategy switched from a detection to a recognition processing strategy.

2. Experiment 1: crowding and noise masking interaction

Given that crowding affects recognition but not detection in low noise, then assuming that the processing strategy is the same in low and high noise predicts that crowding should not affect detection in high noise. On the other hand, if the processing strategy switches from a detection to a recognition processing strategy in high noise, then crowding may appear in high noise even though it does not in low noise. The goal of the first experiment was to confront these hypotheses so we evaluated the effect of nearby flankers (i.e. crowding) on contrast detection thresholds as a function of external noise contrast. Typically, external noise is turned on and off with the target (temporally localized) and is only modestly larger than the target (more or less spatially localized). In the current experiment, the target and noise had the same spatiotemporal window (i.e. localized) and we found a crowding effect only in high noise, but the subsequent experiment will show that this critically depends on the spatiotemporal window of the noise.

2.1. Method

2.1.1. Observers

Five naïve observers provided informed consent and participated to the study. They all had normal or corrected-to-normal vision.

2.1.2. Apparatus

Stimuli were generated by a homemade program and presented on a gamma-linearized 22" Formac ProNitron 22800 CRT monitor with a mean luminance of 42 cd/m^2 and a refresh rate set to 120 Hz. The noisy-bit method (Allard & Faubert, 2008b) was implemented to improve the screen luminance resolution and make it perceptually equivalent to a continuous resolution. The observers' head was supported by a chin rest positioned at 65 cm of the display. The monitor was the only light source in the room.

2.1.3. Stimuli

We used a two-alternative-spatial-forced-choice paradigm in which observers had to indicate by pressing one of two keys whether a target was presented 5° to the left or to the right of a fixation point (Fig. 3). Four flankers were presented 1.25° (center-to-center distance) above, below, to the left and to the right of each potential target location. The target and flankers were 4 cycles per degree sine wave gratings with a fixed phase: maximal luminance of the grating at the center of the aperture. Dynamic white noise (resampled every 50 ms) was added to both potential target locations. The target, flankers and noises were presented simultaneously for 200 ms and were presented through a 0.5° aperture that faded according to a half-cosine of 0.125°. The contrast of the flankers was set to the maximal value and the contrast of the target varied from trial to trial. Each noise element was 2 × 2 pixels (0.068 × 0.068°) and was selected from a Gaussian distribution centered on zero with a standard deviation varying between 0% and 32% of the mean background luminance. The orientation of the target was always vertical and the orientation of all eight flankers was vertical or horizontal, i.e. parallel or orthogonal to the target, respectively. Note that crowding is orientation specific (Levi et al., 2002), so vertical flankers could potentially crowd the vertical target but horizontal flankers were not expected to have any impact. We chose to manipulate the orientation of the flankers rather than their presence/absence (with or without vertical flankers) to reduce any potential effect due to spatial or temporal uncertainty in the absence of flankers and noise. Indeed, a pilot study revealed that contrast detection thresholds in absence of noise were higher in absence of the flankers compared to the presence

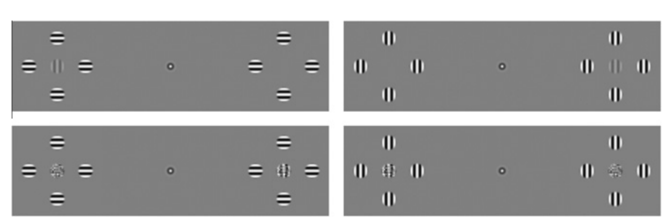

Fig. 3. Stimuli examples in the first experiment. Flankers were either orthogonal (left) or parallel (right) to the target. The target (a vertical sine wave grating) was embedded in different levels of external noise: here either no noise (top) or 32% contrast noise (bottom).

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of horizontal or vertical flankers suggesting that the presence of flankers reduced spatiotemporal uncertainty.

2.1.4. Procedure

Contrast detection threshold were measured using a 2down1up staircase procedure (Levitt, 1971). For each noise contrast (0%, 0.04%, 0.08%, 0.16%, 0.32%), two staircases (horizontal and vertical flankers) were randomly interleaved. Each staircase was interrupted after 12 inversions. The five noise contrasts levels were each performed three times in a pseudo-random order. For each condition (5 noise contrasts and 2 flanker orientations), the contrast detection threshold was estimated by averaging the contrast at the last six inversions (step size = 0.05 log) of the three staircases. A feedback sound indicated the correctness of the response.

2.1.5. Data fitting

Contrast detection threshold as a function of external noise contrast has a stereotypical hockey-stick function in log–log coordinates gradually shifting between a flat asymptote (slope = 0) in low noise and a rising asymptote with a slope of 1 in high noise (Fig. 1). The flat asymptote represents the contrast detection threshold in no noise whereas the rising asymptote represents the contrast detection threshold relative to external noise contrast in high noise.

For each flanker orientation and each subject, contrast detection threshold as a function of external noise contrast ($c(n)$) were fitted using the following function:

$$c(n) = \sqrt{a_{low}^2 + (a_{high}n)^2}$$

where a_{low} represents the contrast threshold in absence of external noise (i.e. low-noise asymptote) and a_{high} represents the contrast threshold relative to the external noise contrast required to detect the target in high noise (i.e. high-noise asymptote). Consequently, within this function there is a parameter having a significant impact only in low noise (a_{low}) and another having a significant impact only in high noise (a_{high}). Note that this function is mathematically equivalent to one of the Linear Amplifier Model (Pelli, 1981, 1990), which rather has a parameter having a significant impact only in low noise and another affecting thresholds in low and high noise.

2.2. Results

Fig. 4 shows contrast detection thresholds as a function of the external noise contrast for the 5 observers and their average. In low noise, the orientation of the flankers had no significant impact on contrast detection thresholds. These results were expected since generally crowding is not found in detection tasks in the absence of external noise. However, in high noise, contrast thresholds were significantly higher when the flankers had the same orientation as the target, indicating a crowding effect of the flankers.

Fig. 5 summarizes the results by presenting the crowding effect (geometric mean of the contrast threshold ratios between the two flanker orientations) in low and high noise, i.e. for the flat (a_{low}) and rising (a_{high}) asymptotes, respectively.

2.3. Discussion

The present experiment used a crowding paradigm to evaluate whether additional late processes sensitive to crowding are introduced in a detection task when the target is presented in high noise. With detection in high noise, we do find an increase threshold when the flankers had the same orientation as the target. Attributing this effect to crowding suggests that different processing strategies underlie detection in low and high noise: high-level processing sensitive to crowding would only be triggered in high noise.

Nevertheless, to attribute this effect to crowding occurring at a late feature integration processing stage, we need to rule out the possibility that the observed orientation-specific interaction is due to lateral interaction occurring at the feature detection processing stage. For example, lateral masking (Polat & Sagi, 1993) in which flankers parallel to the target attenuate the target response could contribute to a threshold difference for the target to flanker separations we used here. However, this lateral masking, if present, should have also affected contrast thresholds in low noise as the original effect reported by Polat and Sagi (1993) was measured with no external noise. However, this was not observed.

A second possibility is that the crowding effect that we observe only in high noise (Fig. 2b bottom-left) might be a combination of one factor affecting only low noise performance (Fig. 2b top-left) with a second factor affecting performance at low and high noise levels (Fig. 2b bottom-right) with an effect at low noise opposite to that of the first factor. If the two effects cancelled at low noise levels, it would leave an effect only at high noise. The two factors might be the lateral masking from parallel, same orientation flankers and facilitation from collinear, same orientation flankers. However, the spacing between the target and flankers (1.25° or 25% of the eccentricity) was chosen to be larger than the spacing at which lateral masking and collinear facilitation occurs (Pelli et al., 2004) but within the range for which crowding occurs. Overall, this two factor alternative is unlikely.

However, external noise exclusion (i.e. early filter retuning) is the classical interpretation of an effect seen only in high noise (Fig. 2b bottom-left) and is therefore another possible explanation that must be considered. As mentioned in the introduction, some authors have suggested that some observer factors (e.g. endogenous attention or dyxlexia) could be modulating early filter tuning *before* the presentation of the target thereby affecting contrast threshold only in high noise. For crowding, however, the effect only in high noise depended only on the orientation of the flankers that was unknown before the presentation of the stimulus. Consequently, to explain a crowding effect only in high noise, external noise exclusion would require orientation-specific lateral interaction to modulate early filter tuning. For instance, if lateral interaction causes the presence of flankers to broaden the tuning of similarly-oriented filters, then the filter detecting the target would integrate more noise in the presence of similarly-oriented flankers, thereby degrading performance. Although we know of no evidence suggesting that orientation-specific lateral interaction could modulate early filter tuning, we cannot rule it out. We address this possibility in the following experiment by modulating the spatiotemporal distributions of the external noise.

3. Experiment 2: spatial and temporal window of the external noise

External noise paradigms are based on the assumption that the processing strategy is the same in low and high noise, i.e. when contrast thresholds are determined by additive internal noise and external noise, respectively. However, the results of the previous experiment suggest a violation of this noise-invariant processing assumption. What could trigger this noise-dependent change in processing? In the previous experiment, one difference between the external noise and the additive internal noise was their spatiotemporal window: external noise was matched in space and time to the target but we assume that additive internal noise is spatially and temporally extended. The current experiment therefore evaluated the effects of the spatiotemporal distribution of external noise on processing strategy. If the processing strategy changes in high

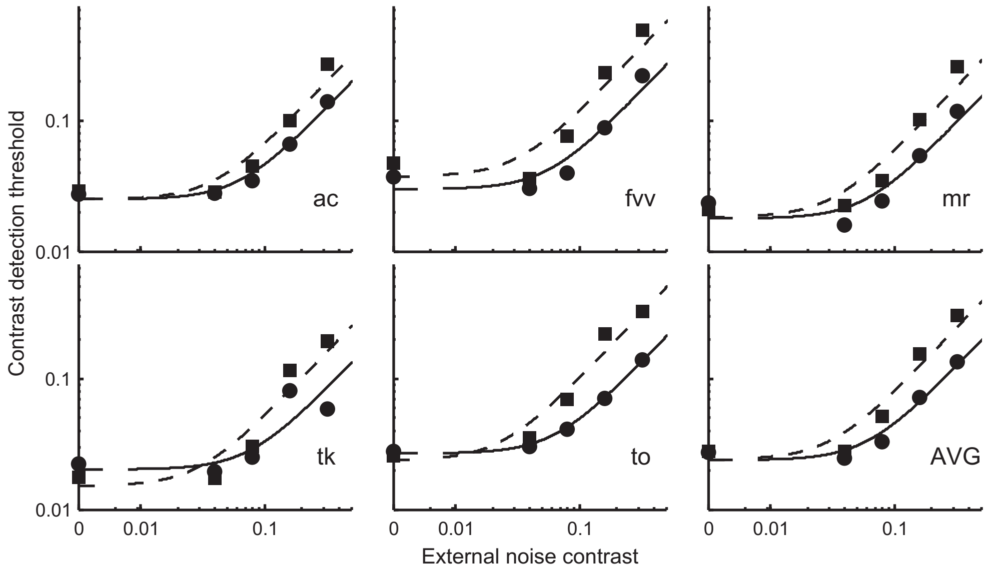

Fig. 4. Contrast detection threshold as a function of external noise contrast for five observers and their average (AVG) in the presence of flankers orthogonal (squares) and parallel (circles) to the target. No significant difference was observed in low noise, but thresholds in high noise were greater when the orientation of the flanker were parallel to the target (i.e. crowding).

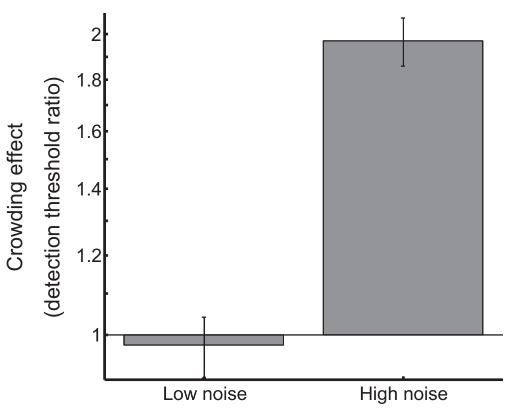

Fig. 5. Crowding effect, i.e. geometric mean ratios between the two flanker orientations, in low and high noise for the flat (a_{low}) and rising (a_{high}) asymptotes, respectively. Data correspond to the fits shown in Fig. 4. A value of 1 represents no crowding effect (same contrast thresholds in the presence of parallel and orthogonal flankers) and a value greater than 1 represents a crowding effect (contrast thresholds higher when the orientation of the flankers was parallel to the target). Error bars represent the geometric standard error of the mean.

noise due to the spatiotemporal distribution of the noise, then no crowding should be observed in spatially and temporally extended noise as no crowding was observed when thresholds were determined by additive internal noise (i.e. in low noise) which is assumed to be spatially and temporally extended (as opposed to contrast-dependent noise (i.e. multiplicative noise) which can mimic the spatiotemporal distribution of the stimulus).

3.1. Method

The task and procedure were identical to the previous experiment except for the noise. As illustrated in Fig. 6, the spatial window of the noise was either localized (same spatial window as the target) or extended (the noise was displayed over the entire screen which was $35 \times 26°$ of visual angle) and its temporal window was also either localized (presented simultaneously with the target) or extended (continuously presented during and between trials). In the previous experiment, we fixed the noise element size to 2×2 pixels rather than 1×1 pixels to increase the noise energy at the target frequency and thereby cover a larger high noise range. In the current experiment, the contrast of the noise was fixed to 32% and the noise element size was 1×1 pixels to be as broad as possible in the frequency domain. Note that this 32% contrast noise had the same spectral energy at the target frequency as the 16% contrast noise in the previous experiment. All other parameters were identical to the first experiment.

3.2. Results

Fig. 7 shows the mean contrast detection thresholds obtained in the four noise conditions and the two flanker orientations. Fig. 8 shows their mean ratios (vertical/horizontal flanker orientations). As expected from the previous experiment, crowding was observed when the noise was spatially and temporally localized. Extending the noise spatially did not significantly affect the crowding and extending the noise temporally increased it. Extending the noise in both dimensions completely eliminated the crowding effect, i.e. flanker orientation had no significant impact on contrast detection thresholds.

3.3. Discussion

Crowding was found with high external noise when the noise matched the target in space or time or both (i.e. spatially and/or temporally localized noise), but critically, no crowding was observed when the external noise was spatially and temporally extended. We speculate that the external noise does not affect the processing strategy when its properties match those of the additive internal noise so that whatever processing works in the presence of only internal noise will remain the optimal strategy when similar external noise is added.

These results also allow us to reject the external noise exclusion hypothesis whereby orientation-specific lateral interaction would modulate early filter tuning. Indeed, if early filter broadening is triggered when the flanker and targets have the same orientation, performance would be degraded in spatially and temporally localized high noise. However, if processing properties are noise-invariant, then this filter broadening should also degrade performance in spatially and temporally extended, high noise. But with the noise

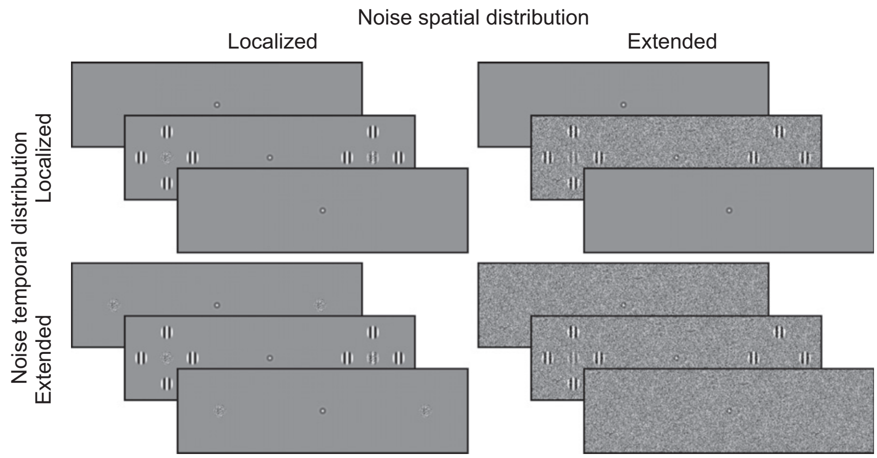

Fig. 6. Stimuli examples in the second experiment. In the spatial dimension, the noise was either localized (only displayed at the two potential target locations) or extended (full screen). In the temporal dimension, the noise was also either localized (only displayed during the presentation of the flankers and target) or extended (displayed continuously). The target and flankers were presented for 200 ms and the noise was resampled every 50 ms.

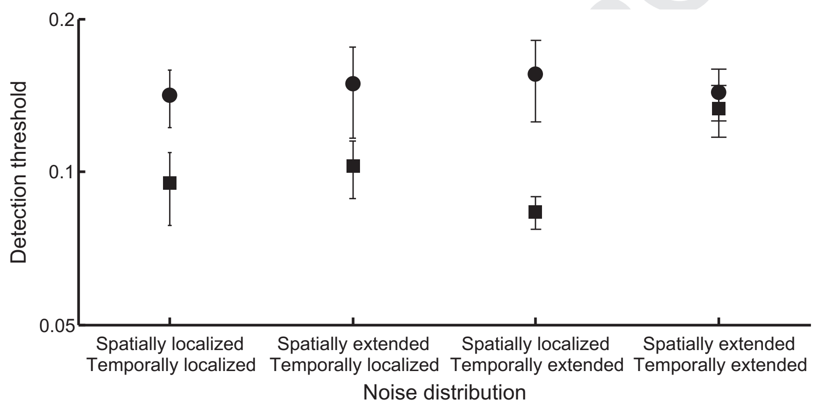

Fig. 7. Contrast detection threshold obtained in the four noise conditions (averaged across five observers) in the presence of flankers orthogonal (squares) and parallel (circles) to the target. Error bars represent the geometric standard error of the mean.

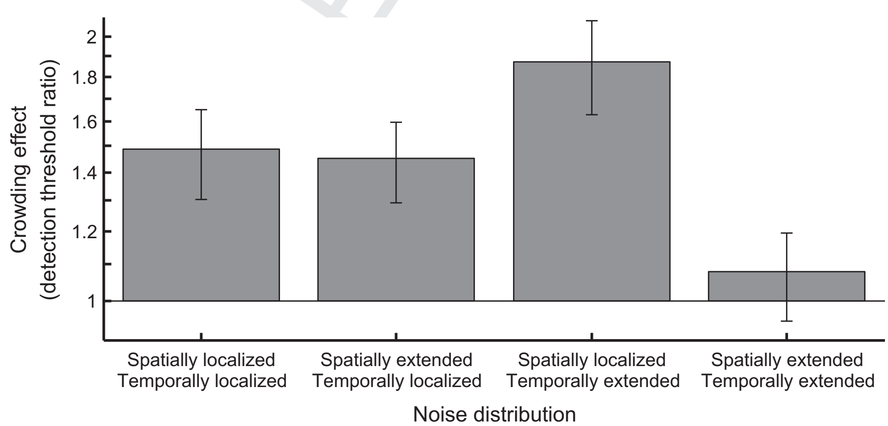

Fig. 8. Crowding effect, i.e. geometric mean ratios between the two flanker orientations, for the different spatiotemporal distributions of the noise. A value of 1 represents no crowding effect (same contrast thresholds in the presence of parallel and orthogonal flankers) and a value greater than 1 represents a crowding effect (contrast thresholds higher when the orientation of the flankers was parallel to the target). Error bars represent the geometric standard error of the mean.

extended in both space and time, no crowding was observed. These results therefore suggest that no early noise exclusion process can explain our results. More generally, to explain our results without violating the noise-invariant processing assumption would require a processing property that, by being altered by flanker orientation, would affect performance in localized noise but not in no or extended noise. This seems unlikely so we conclude that the performance change at high noise must be due to a change in processing strategy.

Interestingly, spatially localized and temporally extended noise caused the greatest crowding effect. A particularity of this noise condition is that it creates a differential adaptation across the

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border of the continuously displayed dynamic noise. Differential adaptation is known to affect some border-related process as turning off continuously presented dynamic noise can cause a twinkle aftereffect which spreads from the adapted noise borders (Hardage & Tyler, 1995; Ramachandran & Gregory, 1991; Tyler & Hardage, 1998). Although this adaptable process is not well understood, the greater crowding effect when using spatially localized and temporally extended noise could be due to some interaction between differential adaptation and crowding. Investigating this interaction is interesting but is beyond the scope of the present study. For our present purposes, the important finding is that the processing strategy effective in absence of noise, which is not sensitive to crowding, switched to a processing strategy sensitive to crowding when the noise was spatially and/or temporally localized but not when the noise was spatially and temporally extended.

4. General discussion

We challenged the noise-invariant processing assumption of the external noise paradigm by examining crowding in a detection task where, traditionally, crowding has no effect. As expected, detection thresholds did not vary with flanker orientation in low external noise: there was no crowding effect in this detection task. If processing strategy was independent of the external noise level, we should have also found no crowding in detection in high noise. However, we did find a crowding effect for high levels of localized, external noise suggesting that the external noise triggered a change in processing strategy. In our second experiment, we showed that the presence of crowding with external noise depended on the spatiotemporal distribution of the noise: crowding was observed when the noise was spatially and/or temporally localized but not when it was spatially and temporally extended. We conclude that some types of external noise will elicit a change in the processing strategy, contrary to the noise-invariant processing assumption of external noise paradigms.

Given that crowding is typically found to affect recognition but not detection, the crowding observed with spatially and/or temporally localized noise suggests that the observers switch to a shape recognition strategy to detect the target for these conditions. With a shape recognition strategy, observers would determine which side of the display had the pattern more similar to the target in the center of the flankers whereas in low noise, detection requires only determining which side had anything present at the center of the flankers. However, the noise distributions had different effects and this tells us about the nature of the processing strategy that drives detection in low external noise, i.e. in additive internal noise that we assume to be spatially and temporally extended. In particular, no crowding was seen in spatially and temporally extended noise (Fig. 9 last row), suggesting that the standard detection strategy – is anything present in the center of the flankers? – can operate efficiently in this noise distribution. However, if the noise is localized in space and time, the energy level in the center of the flankers will increase whether the target is presented or not (Fig. 9 second row) and the standard detection strategy will therefore fail, shifting the optimal strategy to one of target recognition. Interestingly, the strategy switch is also seen when the noise is either only temporally or spatially localized (Fig. 9 third and forth rows, respectively) suggesting that the standard detection strategy windows the stimulus signal in both space and time.

Note that the flanker interference observed in trials with localized noise does not necessarily imply that processing was based on a recognition strategy. There could be two distinct detection processing strategies (or channels) operating in parallel and the most sensitive one in localized noise could be sensitive to flanker interference. The two processing strategies could also be contrast detection and contrast discrimination with only the later being sensitive to

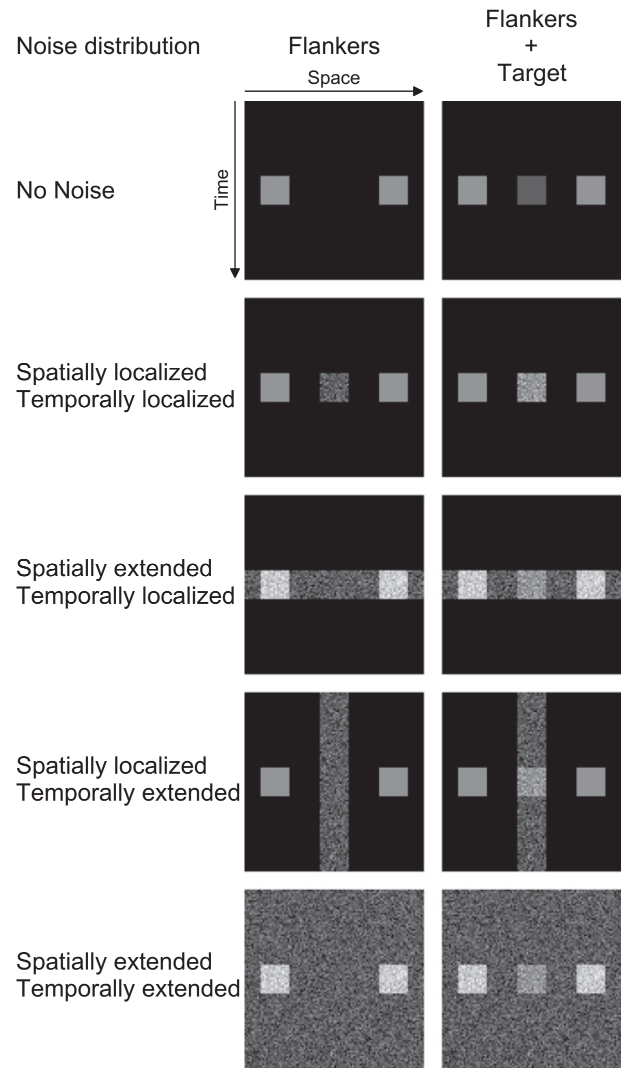

Fig. 9. Energy distribution as a function of space and time for flankers-only (left) or flankers-plus-target (right) stimuli embedded in different noise distributions. Note that we illustrated only one spatial dimension (horizontal or vertical slice) so only two flankers are represented.

crowding (Saarela, Sayim, Westheimer, & Herzog, 2009). In any case, all these interpretations (two detection strategies/one detection and one discrimination strategy/one detection and one recognition strategy) have the same implication: they violate the noise-invariant processing assumption underlying external noise paradigms. However, we consider the detection/discrimination hypothesis as unlikely because crowding was found to affect contrast discrimination only when the flanker and target were highly similar (Saarela et al., 2009) and in our case, crowding was observed when they largely differed in appearance: markedly different contrasts and noise added only on the target. Thus, given that the common finding is that crowding affects recognition but not detection, we favor identifying the two strategies as detection and recognition.

Since we suggest that the target can be processed by different processing strategies depending on the noise conditions, we asked two observers to describe what the target looked like just above their contrast threshold in three noise conditions: no noise, spatially and temporally localized noise, and spatially and temporally extended noise. Both observers reported that the target in localized noise was different from the targets in no noise and extended noise. They described the targets in no noise and extended noise as a low contrast grating whereas the target in localized noise was seen as a high contrast, noisy grating (note that the physical contrast of the targets in localized and extended noise were similar here). For the localized noise condition, one observer reported seeing only a fragment of the target and the other reported that the target was twinkling (he did not experience this for the extended noise condition). Their qualitative descriptions are consistent with our main claim that the target in no noise and extended noise are detected by the same processing strategy which differs from the one used in localized noise.

Our conclusion that external noise can trigger changes in processing strategy is based on a detection task with crowding flankers. We can ask whether this failure in the basic assumption of the external noise paradigm logic is just a particular property of this crowding task and no other. Future studies should answer this question empirically, but there is no reason to think that this result is task-dependent. We speculate that our experiment revealed a general effect of noise on detection strategies, not a change that depended on the presence of the flankers. To illustrate this, consider the same detection task but without any flankers. If the change of processing strategy was particular to crowding, then without any flankers the processing strategy would not change with higher levels of external noise. But for some distributions of noise, we suggest we would again shift the optimal strategy from detection of anything to recognition of the target pattern as soon as the internal target structure had higher signal-to-noise ratio. Indeed, we argue that a standard detection strategy consisting in determining whether anything was presented (i.e. energy increase) could work in spatially and temporally extended noise, but would fail in spatially and temporally localized noise. So at least for detection paradigms using external noise, we predict that the strategy change triggered by the noise would be a general property as the noise will change the most effective signals for the detection response.

With the exception of a few studies (Engstrom, 1974; Pelli, 1981, 1990; Rose, 1948; van Meeteren & Boogaard, 1973), most previous external noise experiments have used noise that either spatially and/or temporally localized. Typically, the target and noise are simultaneously onset and offset (i.e. temporally localized noise) and the spatial window of the noise is only slightly larger than the target. Thus, conclusions based on the assumption that the processing strategy is the same in low external noise (i.e. in additive internal noise which is assumed to be spatially and temporally extended) and in high external noise could be compromised if the processing strategy is dependent on the spatiotemporal distribution of the noise. For instance, we cited in the introduction manipulations affecting contrast thresholds in high but not in low noise. In most cases, authors have attributed such effects to the modulation of an early external noise exclusion process. The effect of endogenous attention (Dosher & Lu, 2000; Lu & Dosher, 2000; Lu et al., 2009) and learning (Lu & Dosher, 2004b) have been attributed to greater external noise exclusion efficiencies, while dyslexics (Sperling et al., 2005) and people who get migraines (Wagner et al., 2010) were considered having lower external noise exclusion efficiencies. Again, these conclusions were based on the noise-invariant processing assumption and none of these studies used spatiotemporally extended noise. By challenging the noise-invariant processing assumption, the current study suggests another possible interpretation: processing strategy is sensitive to the spatiotemporal distribution of the noise and these previously reported effects were due to different efficiencies of a process only triggered in localized, high noise. Our results here suggest that spatiotemporally extended noise matching the likely characteristics of internal noise should be used to dissociate external noise exclusion from a change in processing strategy. If the previously reported effects seen only in high noise were due to a processing strategy change caused by the localized spatiotemporal distribution of the noise, no effect should occur when using spatiotemporally extended noise, as we observed for crowding. If, however, they were due to early noise exclusion (Lu & Dosher, 1998, 2008), then the change of noise distribution should not affect the outcomes.

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