Motion processing: the most sensitive detectors differ in temporally localized and extended noise

Rémy Allard1,2,3 * and Jocelyn Faubert4,5

1 INSERM, U968, Paris, France
2 Institut de la Vision, UMR_S 968, Sorbonne Universités – Université Pierre-et-Marie-Curie, Paris, France
3 CNRS, UMR_7210, Paris, France
4 Visual Psychophysics and Perception Laboratory, Université de Montréal, Montréal, QC, Canada
5 NSERC-Essilor Industrial Research Chair, Montreal, QC, Canada

INTRODUCTION

Arena et al. (2013) used an external noise paradigm to investigate age-related sensitivity losses to motion processing by measuring contrast thresholds for discriminating either the orientation or the direction of drifting gratings. When the dominating noise source was internal because external noise had a negligible impact (i.e., in low noise), they observed an age-related sensitivity loss for both tasks, which could be due, according to the linear amplifier model (Pelli, 1981; Pelli and Farell, 1999), to an increase in internal equivalent noise (e.g., more internal noise with aging) or a decrease in calculation efficiency (i.e., greater signal-to-noise ratios required to perform the tasks with aging). Conversely, when internal noise had a negligible impact because the dominating noise source was external (i.e., in high noise), the two age groups had similar contrast thresholds and thereby necessitated similar signal-to-noise ratios to perform the tasks (i.e., they had similar calculation efficiencies). By implicitly assuming that the calculation efficiency in low noise was the same as the measured calculation efficiency in high noise (i.e., the noise-invariant processing assumption underlying external noise paradigms, Allard and Cavanagh, 2011), they concluded that the age-related sensitivity losses in low noise were due to an increase in internal equivalent noise, not a decrease in calculation efficiency.

However, their data actually suggest that different processes operated in low and high noise, which would invalidate the assumption that the calculation efficiencies in low noise were the same as the measured calculation efficiencies in high noise. In low noise, similar contrast thresholds were observed for discriminating orientation and direction, which suggests that both measured the sensitivity of the same processing system having its operation in low and high noise, which would invalidate the assumption that the calculation efficiencies in low noise were the same as the measured calculation efficiencies in high noise. In high noise, however, contrast thresholds for orientation discrimination were lower than for direction discrimination suggesting that the most sensitive detectors were labeled for both orientation and direction (Watson and Robson, 1981). In high noise, similar contrast thresholds were observed for discriminating orientation and direction, which suggests that both measured the sensitivity of the same processing system having its operation in low and high noise, which would invalidate the assumption that the calculation efficiencies in low noise were the same as the measured calculation efficiencies in high noise. In high noise, however, contrast thresholds for orientation discrimination were lower than for direction discrimination suggesting that the most sensitive detectors were labeled for both orientation and direction. Consequently, in high noise the most sensitive detectors would be labeled for both orientation and direction (e.g., direction-selective complex cells), but in low noise they would only be labeled for orientation, not for direction (e.g., simple cells). If contrast thresholds depended on the sensitivity of different detectors in low and high noise, it would be expected that different processes operated in low and high noise.

Keywords: local noise, extended noise, motion, detection, discrimination
high noise, then the assumption that the calculation efficiency in low noise was the same as the measured calculation efficiency in high noise would be compromised and without knowing the calculation efficiency in low noise it is not possible to determine if the age-related sensitivity loss in low noise was due to an increase in internal equivalent noise or a decrease in calculation efficiency.

As in many studies, Arena et al. (2013) used spatiotemporally localized noise appearing only at the spatiotemporal target location (personal communication), which could explain that the most sensitive detectors were not the same in low and high noise. Indeed, given that internal noise (which dominates in low noise) is spatiotemporally extended (e.g., it does not turn on and off with the stimulus and it is not located only at the stimulus location), the dominating noise source in low and high localized noise have different spatiotemporal windows: extended in low noise and localized in high noise. If the most sensitive detectors differ depending on whether the dominating noise source is localized or extended, this would cause the most sensitive detectors to differ in low and high localized noise, which would compromise the assumption that the calculation efficiency in low noise (i.e., in extended internal noise) is the same as the measured calculation efficiency in high localized noise. For instance, noise that is temporally localized to the target (i.e., turn on and off with the target) introduces strong onset and offset transients, which could result in a greater masking effect on direction selective detectors making detectors labeled for orientation more sensitive than detectors labeled for both orientation and direction.

The objective of the present study was to determine if the processes (e.g., most sensitive detectors) involved in discriminating the orientation and the direction of drifting gratings in localized and extended noise differ from the processes operating in absence of noise. More specifically, the goal of the current study was to determine whether the calculation efficiencies in absence of noise (i.e., in extended internal noise) differ for orientation and direction discrimination (as observed by Arena et al. in high localized noise) or not (as suggested by the similar contrast thresholds in low noise). To investigate this, we conducted an experiment similar to Arena et al.’s (2013) in which contrast thresholds were measured for discriminating orientation and direction in absence of noise (i.e., in extended internal noise) and in high noise having different spatiotemporal windows: spatially localized or extended and temporally localized or extended. Given that contrast threshold depends on both the dominating noise source and the calculation efficiency (i.e., signal-to-noise ratio required to perform the task) and that the level of the dominating noise source is known in high noise, calculation efficiency in high noise can be directly measured by measuring contrast threshold in high noise. If the calculation efficiencies in absence of noise (which cannot be directly measured because the internal noise level is unknown) are the same for orientation and direction discrimination, but differ in high localized noise (as measured by Arena et al., 2013) due to the noise being localized, then we would expect the calculation efficiencies in high extended noise to be similar for orientation and direction discrimination. This would show a violation of the noise-invariant processing assumption when using localized noise as the calculation efficiencies measured in localized noise would not reflect the calculation efficiencies in absence of noise. Conversely, if the calculation efficiency in absence of noise is greater for orientation discrimination (as measured in high localized noise by Arena et al., 2013), then the calculation efficiency for orientation discrimination should also be greater in high extended noise. For instance, Arena et al. (2013) hypothesized that the calculation efficiency difference between the two tasks in high localized noise could be due to more neurons responding to orientation than to direction or to the fact that discriminating direction requires more spatiotemporal integration than discriminating orientation. In either case, a similar calculation efficiency (i.e., contrast threshold) difference would also be expected in extended noise.

The current study is not the first to question the use of localized noise within external noise paradigms. Allard and Cavanagh (2011) found that crowding impaired contrast detection in the near periphery in localized noise, but not in absence of noise or in extended noise. We found that aging can impair contrast thresholds in localized noise, but not in extended noise (Allard et al., 2013). Furthermore, we recently argued that using spatiotemporally localized noise that is also localized as a function of orientation and frequency (i.e., contains only the orientation and frequency of the stimulus) makes a contrast detection task switch to a contrast discrimination task (Allard and Faubert, 2013). All these studies focused on the contrast detection of a static target. However, because localized noise introduces strong transients, using localized noise could be even more critical for motion processing. The current study addresses this question using a different paradigm that more directly identifies the underlying process (compared to crowding or aging) by determining if the most sensitive detectors are direction selective or not.

**MATERIALS AND METHODS**

**OBSERVERS**

Three naïve observers, who were financially compensated and provided informed consent, and one of the authors, participated in this study. They had normal or corrected-to-normal vision.

**APPARATUS**

The stimuli were presented on a 19-inch CRT monitor with a refresh rate of 120 Hz. The Noisy-Bit method (Allard and Faubert, 2008) implemented independently to each gun made the 8-bit display perceptually equivalent to an analog display having a continuous luminance resolution. The monitor was the only source of light in the room. A Minolta CS100 photometer interfaced with a homemade program calibrated the output intensity of each gun. At the viewing distance of 114 cm, the width and height of each pixel were 1/64° of visual angle.

**STIMULI AND PROCEDURE**

The signal was a 0.5 cpd sine wave grating drifting at a frequency of 1.875 Hz. Observers were asked to report either the orientation (tilted either −45 or 45° from vertical) or the drifting direction. When the task was to report the orientation, both the orientation (−45 or 45°) and direction were randomized. When the task was
to report the drifting direction, the orientation was fixed for a
given block of trials and the drifting direction was randomized.
The initial phase of the grating was randomized on each trial. The
signal was presented for 267 ms. The spatial window was a circular
aperture of 4° plus a half-cosine edge of 0.5°. The contrast was
controlled by a 3-down-1-up staircase procedure (Levitt, 1971)
with step size of 0.1 log, which was interrupted after 100 trials.
The contrast threshold for a given staircase was estimated as the
geometric mean of the inversions.

There were five different noise conditions: no noise and four
noise conditions resulting from the combinations of two spatial
and two temporal windows. The spatial window was either local-
ized or extended, i.e., the same as the signal window or full-screen,
respectively. The temporal window was also either localized or
extended, i.e., turn on and off with the signal or continuously
present (including between trials), respectively. The noise was
binary with element size of 4 × 4 pixels (i.e., 0.0625 × 0.0625°)
and resampled every other frame (i.e., dynamic at 60 Hz). Thus,
the fact that the noise was not correlated over space (across noise
elements) and time (across frames) implies that it was both tem-
porally and spatially white, that is, it had the same spectral energy
at all frequencies (within the limit of the spatial and temporal
resolution of the noise). The noise was superimposed to the sig-
nal (both summed) and to avoid luminance motion drifting cues
within noise elements, there was no spatial or temporal luminance
variation within each noise element.

For each noise condition, contrast thresholds were estimated
for direction and orientation discrimination. To perform the same
number of measurements for orientation and direction discrimi-
nation, a given noise block contained four staircases: direction
discrimination for the two orientations (−45 and 45°) and two
identical orientation discriminations. The four staircases were
blocked and tested in a random order. Each of the five noise
blocks was tested twice in a pseudo-random order resulting in
10 noise blocks (two blocks per noise condition) each composed
of four staircases (two for direction discrimination and two for
orientation discrimination) performed in a random order (not
interlaced). As a result, for each noise condition, the two contrast
threshold estimations were based on the geometric mean of the
contrast thresholds estimations based on four staircases.

RESULTS
Figure 1 shows contrast thresholds for orientation (open symbols)
and direction (filled symbols) discrimination. Contrast thresholds
in the four conditions with noise were substantially higher (by a
factor of about 4) than the condition without noise. This confirms
that these four conditions were performed in high noise, that is,
the impact of internal noise was negligible (i.e., the dominating
noise source was external) so that contrast thresholds therefore
depended solely on calculation efficiency, not on internal equiv-
elent noise. Contrast thresholds were roughly unaffected by the
noise spatial window as similar contrast thresholds were observed
in spatially localized and extended noise both when the temporal
window was localized (SL-TL and SE-TL) and extended (SL-TE
and SE-TE). This was statistically validated by a 2 × 2 × 2 ANOVA
(task × spatial window × temporal window), which revealed no
significant effect of spatial window $[F(1,3) = 1.83, p = 0.27]$ and
no task × spatial window interaction $[F(1,3) = 0.019, p = 0.90]$. On
the other hand, contrast thresholds varied with the noise tem-
poral window $[F(1,3) = 57.9, p < 0.01]$ and varied differently for
the two tasks (task × temporal window interaction, $F(1,3) = 10.4$,
$p < 0.05$). Specifically, contrast thresholds were lower (i.e., higher
calculation efficiency) in temporally localized noise (SL-TL and
SE-TL) relative to temporally extended noise (SL-TE and SE-TE,
respectively) by a factor of about 2 for orientation discrimination
and 1.4 for direction discrimination.

Figure 2 illustrates the contrast threshold ratios for direction
relative to orientation discrimination represented in Figure 1.
Similar contrast thresholds were observed for orientation and
direction discrimination (i.e., ratios close to 1) in absence of noise
and in temporally extended noise (SL-TE and SE-TE), but con-
trast thresholds were substantially better (by a factor of about 1.4
on average) for orientation than for direction discrimination in
temporally localized noise (SL-TL and SE-TL, respectively).

DISCUSSION
Calculation efficiency ratios (which can be directly inferred from
contrast threshold ratios in high noise) of direction discrimination
relative to orientation discrimination varied with the noise tem-
poral window: a substantial difference was observed in temporally
localized noise (threshold ratio of ∼4.0), but not in temporally
extended noise (ratio close to 1). The purpose of external noise
paradigms is generally to estimate the calculation efficiency in
absence of noise by assuming that it is the same as the measured
calculation efficiency in high noise. However, the fact that the
calculation efficiency ratios varied with the noise temporal window
implies that in at least one condition the measured calculation

---

**FIGURE 1** | Contrast thresholds obtained for four subjects (different symbols) in five different noise conditions for orientation (open symbols) and direction (closed symbols) discrimination. In the four noise conditions, the noise was either spatially localized (SL) or extended (SE) and temporally localized (TL) or extended (TE). Each data point corresponds to the average of four staircases. For clarity, the standard error are not shown, but were all smaller than 0.06 log units (i.e., less than a factor of 1.15).
efficiency in high noise did not correspond to the calculation efficiency in absence of noise. Indeed, the calculation efficiency in absence of noise cannot both differ substantially for orientation and direction discrimination as measured in localized noise and be similar for orientation and direction discrimination as measured in extended noise. Thus, in at least one condition, the calculation efficiency measured in high noise did not correspond to the calculation efficiency in absence of noise, which violates the noise-invariant processing assumption and compromises the application of the external noise paradigm.

In absence of noise (i.e., in internal noise), no substantial contrast threshold difference was observed (ratios close to 1) as in temporally extended noise. Given that internal noise is expected to be temporally extended (it does not turn on and off with the stimulus) and that contrast thresholds were similar for orientation and direction discrimination as measured in extended noise, this suggests that the calculation efficiencies in absence of noise did not differ between tasks. As a result, there was no evidence of a violation of the noise-invariant processing assumption when using temporally extended noise so the calculation efficiency measured in temporally extended noise likely reflects the calculation efficiency in absence of noise. Contrariwise, the facts that internal noise is not temporally localized and that a different pattern of results was observed in temporally localized noise suggest that the calculation efficiencies measured in temporally localized noise were not both the same as the calculation efficiencies in absence of noise. This shows a violation of the noise-invariant processing assumption, as the measured calculation efficiency in localized noise cannot be assumed to be the same as the calculation efficiency in absence of noise.

The results of the current study suggest that when temporally localized noise dominated the most sensitive detectors were labeled for orientation only (e.g., simple cells), whereas when temporally extended noise dominated (which includes internal noise) the most sensitive detectors were labeled for both direction and orientation (e.g., direction-selective complex cells). Thus, which detectors were the most sensitive depended on the temporal window of the dominating noise source. This suggests that temporally localized noise impaired more the sensitivity of detectors labeled for orientation and direction (e.g., direction-selective complex cells, which would be the most sensitive in absence of noise) than the ones labeled for orientation only (e.g., simple cells). This greater masking for direction selective detectors can be explained by the sharp contrast transient onset and/or offset of the noise. Note that technically, there is more luminance transient between two different noise frames than between a mean gray frame and a noise frame. However, the temporal envelope of the localized noise contains a strong transient (turns on and off, i.e., noise contrast varies from 0 to high to 0) whereas the extended noise does not (it is continuously present, i.e., constant mean contrast). This corresponds to the subjective impression: temporally localized noise suddenly appears causing a sharp transition from a blank to a noisy display whereas temporally extended noise appears to be constantly displayed even if it is dynamic. Thus, the current results suggest that the sharp transients of the noise envelope (i.e., noise onset and offset) impair more the detectors labeled for both orientation and direction than the ones labeled for orientation only.

Given that transients caused by localized noise cause additional masking, one could expect thresholds to be lower (i.e., better) in extended noise than in localized noise, which is opposite to the current findings (Figure 1). Even though adaptation is known to reduce responsiveness of stimulated cells (Giaschi et al., 1993), it is unlikely that it affects contrast threshold in high noise because adaptation would affect the responses related to both the signal and noise leaving the signal-to-noise ratio intact. This would have no impact on contrast threshold given that contrast threshold in high noise is proportional to the noise contrast (Pelli, 1981). Conversely, there are at least two reasons why extended noise could have a greater masking effect than localized noise. First, the visual system has a limited temporal resolution and therefore integrates some noise outside the temporal window (i.e., just before the target onset and after the target offset). Second, localized noise has the advantage of reducing temporal uncertainty, which is obviously not the case for temporally extended noise. Thus, adding noise outside the temporal window of the signal (i.e., passing from localized to extended noise) can facilitate contrast threshold by removing noise onset and offset transient, but impair contrast threshold by introducing more noise and increasing temporal uncertainty. It is therefore not surprising that contrast thresholds in temporally extended noise are higher than in temporally localized noise even though there is no noise onset and offset transient in extended noise.

By compromising the estimation of the calculation efficiency in absence of noise, a violation of the noise-invariant processing assumption also compromises the estimate of the internal equivalent noise. Based on the linear amplifier model (Pelli, 1981; Pelli and Farell, 1999), contrast threshold in absence of noise depends on both internal equivalent noise and calculation efficiency.

![Figure 2: Contrast threshold ratios for direction discrimination relative to orientation discrimination derived from Figure 1 for four subjects (different symbols). A value of 1 represents the same threshold for both tasks. A value greater than 1 means that contrast thresholds were higher (or calculation efficiencies were lower) for discriminating direction compared to orientation.](image-url)
knowing the contrast threshold in absence of noise and by assuming that the calculation efficiency in absence of noise is the same as the measured calculation efficiency in high noise, the internal equivalent noise can be calculated. If the calculation efficiency in absence of noise cannot be assumed to be the same as the measured calculation efficiency in high noise, then the internal equivalent noise cannot be calculated. For instance, Arena et al. (2013) observed that aging affected contrast thresholds in low, but not in high, localized noise. Given that contrast thresholds in high noise depend only on the calculation efficiency and not on the internal equivalent noise, they concluded that the calculation efficiency in low noise was not affected with aging and therefore attributed the age-related sensitivity losses in low noise to an increase in internal equivalent noise. However, given that the measured calculation efficiency in absence of noise does not correspond to the measured calculation efficiency in high localized noise (as suggested by the current findings), both the calculation efficiency in absence of noise and the internal equivalent noise remains unknown and it is not possible to determine whether the age-related sensitivity loss in low noise was due to a lower calculation efficiency or higher internal equivalent noise.

The current study found that the most sensitive detectors underlying motion processing varied with the noise temporal window. In temporally extended noise (which includes internal noise), the most sensitive detectors were labeled for both orientation and direction, whereas in temporally localized noise, they were labeled for orientation, but not direction. In absence of noise (i.e., in internal noise), the most sensitive detectors would be labeled for both orientation and direction, which suggests, as expected, that internal noise limiting motion processing is temporally extended. Thus, to characterize motion processing in absence of noise, such as measuring internal equivalent noise and calculation efficiency, external noise should be temporally extended to avoid violating the noise-invariant processing assumption.

ACKNOWLEDGMENTS
This research was supported by NSERC discovery fund to Jocelyn Faubert and Essilor International.

REFERENCES
Allard, R., and Cavanagh, P. (2011). Crowding in a detection task: external noise triggers change in processing strategy. Vision Res. 51, 408–416. doi: 10.1016/j.visres.2010.12.008
Allard, R., and Faubert, J. (2008). The noisy-bit method for digital displays: converting a 256 luminance resolution into a continuous resolution. Behav. Res. Methods 40, 735–743. doi: 10.3758/BRM.40.3.735
Allard, R., and Faubert, J. (2013). Zero-dimensional noise is not suitable for characterizing processing properties of detection mechanisms. J. Vis. 13, 1–3. doi: 10.1167/13.10.25
Allard, R., Renaud, J., Molinatti, S., and Faubert, J. (2013). Contrast sensitivity, healthy aging and noise. Vision Res. 92, 47–52. doi: 10.1016/j.visres.2013.09.004
Arena, A., Hutchinson, C. V., Shimozaki, S. S., and Long, M. D. (2013). Visual discrimination in noise: behavioural correlates of age-related cortical decline. Behav. Brain Res. 243, 102–108. doi: 10.1016/j.bbr.2012.12.039 doi: 10.1016/j.bbr.2012.12.039
Giaschi, D., Douglas, R., Marlin, S., and Cynader, M. (1993). The time course of direction-selective adaptation in simple and complex cells in cat striate cortex. J. Neurophysiol. 70, 2024–2034.
Levitt, H. (1971). Transformed up-down methods in psychoacoustics. J. Acoust. Soc. Am. 49(Suppl. 2), 467+. doi: 10.1121/1.1912375
Pelli, D. G. (1981). The Effects of Visual Noise. Ph.D. thesis, Cambridge University, Cambridge.
Pelli, D. G., and Farell, B. (1999). Why use noise? J. Opt. Soc. Am. A Opt. Image Sci. Vis. 16, 647–653. doi: 10.1364/JOSAA.16.000647
Watson, A. B., and Robson, J. G. (1981). Discrimination at threshold: labelled detectors in human vision. Vision Res. 21, 1115–1122. doi: 10.1016/0042-6989(81)90046-4

Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Received: 29 January 2014; paper pending published: 03 March 2014; accepted: 22 April 2014; published online: 15 May 2014.
Citation: Allard R and Faubert J (2014) Motion processing: the most sensitive detectors differ in temporally localized and extended noise. Front. Psychol. 5:426. doi: 10.3389/fpsyg.2014.00426
This article was submitted to Perception Science, a section of the journal Frontiers in Psychology.

Copyright © 2014 Allard and Faubert. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) or licensor are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.