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Visual sensitivity to temporal modulations of temporal noise

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Abstract

The present endeavor is meant (a) to provide a direct comparison between first- and second-order temporal modulation and, by so doing, (b) to eliminate all spatial clues that might have contaminated previous assessments of the second-order temporal modulation transfer function (TMTF). The second aim was achieved by means of the temporal modulation of a purely temporal white noise, a stimulus used frequently in psychoacoustics but not used as yet in visual stimulation. Luminance and contrast temporal modulation thresholds were measured with a 2AFC staircase procedure. In the first case, the mean luminance of a spatially homogeneous, 30° field was modulated sinusoidally over time (first-order modulation). In the second case, the luminance of the same or of a 60° field was randomized over time at a rate of 150 Hz and this temporal white noise (the carrier) was modulated sinusoidally over time (second-order modulation). First-order thresholds reproduce the classical (large field) flicker sensitivity. Second-order thresholds (measured for the first time with purely temporal stimuli) are at least 100 times higher than first-order ones, display a low-pass characteristic (at least up to 0.5 Hz) and yield a critical fusion frequency (measured at 100% modulation) of ~10 Hz. The data are in accord with other estimates of the TMTF of the second-order system and thus confirm the effective neutralization of the spatial cues present in these previous studies. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Second-order mechanisms; Temporal luminance; Contrast transfer functions; Temporal noise

1. Introduction

Starting with the pioneering work of Ives (1922), De Lange (1952) in the time domain, and with that of Campbell and Robson (1968) in the spatial domain, and until the late 80s, visual psychophysics was involved mainly in the study of 'first-order' (or Fourier) visual phenomena. Within that context, visual performance (at both threshold and suprathreshold levels) was characterized in reference to the classical first-order modulation (or contrast) transfer function, (MTF; for a review, see Kelly & Burbeck, 1984). Standard functions of this kind were provided by Kelly (1961) in the temporal domain, by Davidson (1968) and Campbell and Robson in the spatial domain, by Robson (1966) and Kelly (1979) in the spatial and temporal domains.

Chubb and Sperling (1989) offered theoretical and empirical arguments to point out that the visual system is perfectly capable of processing second-order (or non-Fourier) modulations of which the most intuitive one is the modulation of contrast (rather than that of luminance). This observation (whose empirical origins can be traced back to Henning, Hertz, & Broadbent, 1975 and to Nachmias & Rogowitz, 1983[1]) triggered a wealth of psychophysical investigations intended to characterize such second-order mechanisms with a particular focus on motion processing (see Cavanagh & Mather, 1988; Sperling, 1989; Chubb & Sperling, 1991; Gorea, Papathomas, & Kovacs, 1993a,b; Lu & Sperling, 1995, 1996). These studies demonstrated the existence of such mechanisms (or, alternatively, of a fundamental non-linearity in the processing of contrast) with a variety of second-order modulations within a limited spatio-temporal frequency range (e.g. Daug-

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[1] In fact, the issue of whether or not the visual system can process second-order modulations or beats has been addressed and answered affirmatively in a number of very early studies such as those of Attneave and McReynolds (1950), Clausen and Vanderbilt (1957), Brindley (1962).

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man, 1985; Derrington & Badcock, 1986; Badcock & Derrington, 1987, 1989; Hammett & Smith, 1994). A few studies have provided a full and direct characterization of the second-order MTF in either space (Gray & Regan, 1998; Schofield & Georgeson, 1999), or time (Holliday & Anderson, 1994; Derrington, 1994; Lu & Sperling, 1995; Derrington & Cox, 1998; Smith & Ledgeway, 1998). A study by Gorea (1995) also allowed the inference of the temporal transfer function of the second-order motion system.

In their vast majority, these investigations pointed to the fact that the second-order system is low-pass in both space and time with spatial and temporal acuities ~ 4 cpd and 10 Hz, respectively. However, at least three such studies present data indicating a strong similarity in temporal sensitivity between first- and second-order systems (Derrington, 1994; Holliday & Anderson, 1994[2]; Lu & Sperling, 1995). The variety of stimuli used (relative to the modulated carrier — e.g. gratings, static or dynamic spatial noise, the type of modulation — e.g. beats or amplitude/contrast modulation, and to their spatial frequency content) may well account for the discrepant experimental outcomes (see Smith & Ledgeway, 1997, 1998).

Despite this plethora of studies, we are aware of no investigation having assessed the 'pure' temporal second-order MTF, that is the sensitivity to second-order temporal modulations without any spatial structure. It is thus possible that the published second-order TMTFs be contaminated by uncontrolled spatial factors. The most obvious way of eliminating such spatial cues is to temporally modulate a temporal white noise with no spatial structure. In auditory psychophysics the second-order MTF (referred to as the TMTF; see Viemeister, 1979) is a standard, well-documented function. Its assessment in vision is useful insofar as it specifies the maximum temporal processing sensitivity, that is in the absence of any spatial information (see Section 3) for second-order stimuli. Moreover, the temporal modulation of temporal white noise has the advantage of evading the possibility of first-order luminance artifacts (such as modulation side-bands, local luminance variations, etc.) having presumably contaminated some of the previous measurements (see Smith & Ledgeway, 1998).

2. Methods

2.1. Stimuli

They were displayed on a RGB P750 NEC MultiSync monitor, 1280 pixels wide and 1024 pixels high driven by a CRS-VSG2/3W card at a refresh rate of 150 Hz. In the main experiments, the screen subtended 30° × 23° at a distance of 57 cm from the observers; a control experiment run with only one observer used a 60° × 46° field at a distance of 28 cm. In both cases the mean luminance, L_0, was 50 cpd/m^2. The stimulation consisted in the temporal modulation of the whole screen in the absence of any spatial modulation. There were three temporal modulation types: (i) sinusoidal luminance modulation, LM; (ii) random luminance modulation over time, that is temporal white noise, TWN; (iii) sinusoidal modulation of the TWN, AM-TWN. The equations for each of these three modulations are given below:

$$\mathrm{LM} \rightarrow L(t) = L_0[1 + m \sin(2\pi f t / F_S + \varphi)]c \tag{1}$$

$$\mathrm{TWN} \rightarrow L(t) = L_0 \pm A_{\mathrm{Rnd}} \tag{2}$$

$$\begin{aligned}\mathrm{AM\text{-}TWN} &\rightarrow L(t)\\ &= L_0 \pm 0.5 A_{\mathrm{Rnd}}[1 + m \sin(2\pi f t / F_S + \varphi)]c\end{aligned} \tag{3}$$

with $L(t)$, the luminance as a function of time; m, the depth of modulation $(0 \leq m \leq 1)$; A_{Rnd}, the amplitude of the white noise carrier (around L_0) drawn randomly within a range [0, A_{Max}]; f, the modulation frequency; F_S, the temporal sampling frequency; φ, the phase of the signal and $c = (1 + m^2/2)^{-0.5}$, an energy correction coefficient used to prevent the observer from employing potential first-order brightness fluctuations over time (see Viemeister, 1979). The sign and absolute value of A_{Rnd} were randomized over time at a rate of 150 Hz with a flat probability distribution. $A_{\max}$ was set at 50 cd/m^2 (i.e. equal to L_0; yielding maximum temporal noise contrast of 100%). To check the generality of the results two additional AM-TWN modulation thresholds were measured with $A_{\max} = 25$ cd/m^2 (i.e. 50% noise contrast) at 1 Hz for, observer CW, and at 4 Hz, for observer CL. For these control conditions the inspection field subtended 30 × 23°; they were meant to demonstrate that the measured AM-TWN functions were independent of the amplitude of the TWN.

For the LM stimuli, m-thresholds were measured at frequencies of 1, 2, 4, 8, 16, 32 and 64 Hz. For the AM-TWN conditions, thresholds were measured at frequencies of 1, 2, 4 and 8 Hz (for these stimuli the detection criterion could not be attained for frequencies higher than 10 Hz) for both observers; observer CL was also run at an AM frequency of 0.5 Hz. All stimuli were presented for intervals of 2 s including an increasing and a decreasing cosine ramp of 200 ms each. To check the extent to which this duration might have been too short (particularly at low frequencies) for a full temporal integration, AM-TWN thresholds were also

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[2] These authors point however to the fact that the sensitivities they have measured for drifting beats above 10 Hz are very likely to be contaminated by the contribution of first-order units.

measured with 4 s presentations. In all cases, the temporal modulation (of both the first- and second-order stimuli) was in sine phase with respect to the temporal window of presentation. An example of the AM-TWN stimulus is shown in Fig. 1.

2.2. Procedure

LM and AM-TWN thresholds were measured by means of a 2AFC staircase procedure. The modulated stimulus was randomly presented in one of two temporal intervals; the remaining interval was either blank (i.e. it contained the steady, uniform screen at L_0), for the LM condition, or contained the non-modulated TWN stimulus, for the AM-TWN condition. The two temporal intervals were separated by 500 ms. In each session, the starting modulation depth was set at 1. It was decreased after two correct responses in a row and increased after one wrong response; this rule makes the staircase converge at 70.7% correct responses. The increment/decrement step was 4 dB at the beginning of a session and passed to 2 dB after the first two reversals. The staircase was terminated after 25 reversals (or after 150 trials at most if the staircase did not converge) and the threshold was taken as the average of the last 10 reversals. The final thresholds were based on at least three repeats per experimental condition and observer. The experimental conditions (characterized by the stimulus type — LM or AM-TWN — and by the modulation frequency) were randomized independently for each observer.

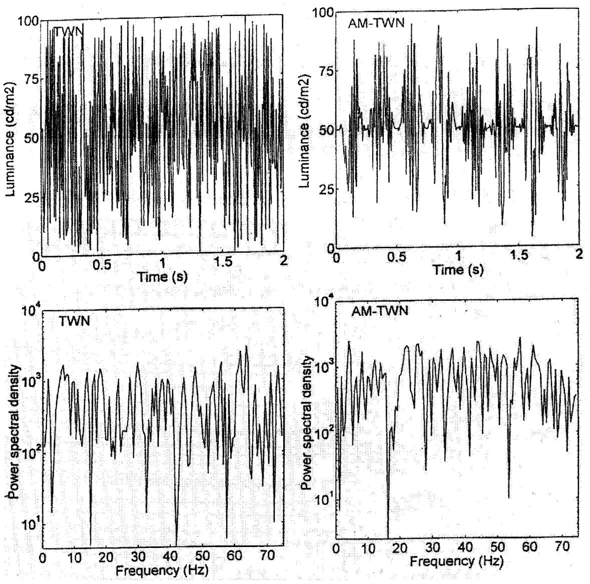

Fig. 1. Top panels: luminance profiles of the TWN (top left), and of the AM-TWN (top right) stimuli used in this study. Bottom panels: their power spectral densities in the luminance domain. Note that the luminance contrast of the noise is 100%.

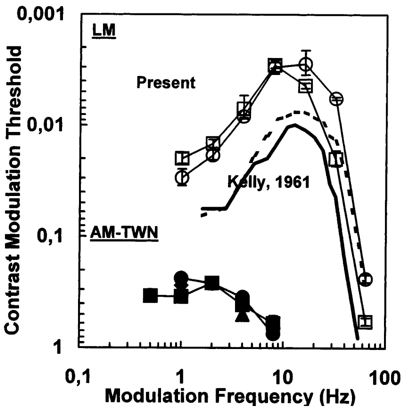

Fig. 2. LM and AM-TWN thresholds (open and solid symbols, respectively) obtained for 2 s presentations and a 30° × 23° inspection field as a function of the modulation frequency. Circles and squares are for observers CW and CL. The AM-TWN datum-points were obtained with a noise contrast of 100%. Vertical bars show ± 1 S.E. of the mean. The continuous and dashed curves are flicker thresholds obtained by Kelly (1961) at 77 and 850 td, respectively.

2.3. Observers

They were the last two authors (ages 22 and 30, respectively). Their vision was normal or corrected to normal.

3. Results and discussion

The data of the main experiments are all shown in Fig. 2 as contrast modulation thresholds (note the inverted ordinate). They were measured for the smallest inspection field (30° × 23°), for stimulus durations of 2 s and, for the amplitude modulated ones (AM-TWN), with a noise contrast of 100%. Open and solid symbols refer to flicker (i.e. LM) and to AM-TWN conditions, respectively. Circles and squares are for observers CW and CL. Continuous and dashed heavy lines are flicker thresholds measured by Kelly (1961) (Table 1 and Fig. 4) for large (65°), uniformly flickering fields set at an average luminance of 77 and 850 td, respectively. These adaptation levels bracket the mean luminance used in the present study (~ 150 td). These classic data are shown for comparison with the present ones under the most similar experimental conditions available.

The present LM sensitivities are pretty much similar in shape to those of Kelly: they are band-pass with a peak sensitivity ~ 15 Hz, and with a CFF ~ 60–70 Hz. They are however about a factor of three higher than those of Kelly (peak sensitivities of ~ 330 and 100, respectively). The most likely reason for this discrepancy relates to the different procedures used in the two studies. While Kelly collected his data with the method of adjustment (typically yielding a high response criterion), the present thresholds are 2AFC ob-

Table 1
Stimulus characteristics and figure sources of the data presented in Fig. 4[a]

	Original fig. & symbols of the data presented in Fig. 2	General stimulus characteristics	Carrier characteristics	Modulation characteristics	Data shown in Fig. 4 are averages of N no. of observers
Holliday and Anderson (1994)	Fig. 2a, △, □	Field size: 16.7°×12.7°; L_0: 72 cd/m^2; duration: 1 s (including 2×100 ms cos ramps)	2 sine gratings around 1.85 cpd	Beats; beat sp freq, 0.3 cpd	$N=1$
	Fig. 2a, □	Idem	2 sine gratings around 11.8 cpd	Idem	$N=1$ (same as above)
Smith and Ledgeway (1998)	Figs. 2 and 3, ○	Field: circular, ∅ 4°; L_0: 38 cd/m^2; duration: 950 ms (including 2×255 ms Gaussian ramps)	Dynamic noise; pixel size 2.4′ & 6′	AM (2D Gabor) of the noise contrast; modul. freq: 1 cpd	$N=2$
Derrington and Cox (1998)	Fig. 3, ○,□	Field: circular, ∅ 5°; L_0: 26 cd/m^2; duration: 1 s, rectangular	5 cpd sine grating; mean contr. = 10%	AM; modul. freq: 1 cpd	$N=3$

[a] All data were obtained in a direction discrimination paradigm.

tained with a staircase converging at 70.7% correct responses.

As expected from the literature (see Section 1), the sensitivity of the two observers to AM-TWN stimuli is close to low-pass (at least down to 1 and to 0.5 Hz for CW and CL, respectively) and substantially degraded (by at least a factor of 100) relative to the LM sensitivity. It shows a maximum of ~ 3.8 ($m = 0.26$) with a CFF around 10 Hz.

Fig. 3 presents the AM-TWN thresholds from Fig. 2 (open circles and squares) for comparison with a number of control experiments. In panel a, all thresholds were measured with stimuli subtending a 30° × 23° inspection field. The solid symbols in this panel show AM-TWN thresholds measured with 4 s presentations. The two sets of thresholds are practically identical down to 1 Hz for observer CW, but diverge for frequencies of 1 Hz and lower for observer CL. The obvious implication is that for CL temporal summation extends over more than two temporal cycles: at 1 Hz and below 4 s presentations yield sensitivities ~ 1.5 higher than 2 s presentations. In panel a, the open triangle (obs. CW, 1 Hz) and diamond (obs. CL, 4 Hz) show AM-TWN thresholds measured with the 30° × 23° inspection field and for 2 s presentations with a noise contrast of 50% (i.e. $A_{\mathrm{Max}} = 25$ cd/m^2; see Eqs. (2) and (3)) instead of 100% as in all the remaining experiments. Clearly, like in audition (Viemeister, 1979), the manipulation of the contrast of the noise carrier does not affect the sensitivity to AM-TWN. The implication of this observed independence is that the noise carrier does not interact with the processing of its temporal (second-order) modulation[3].

Panel b in Fig. 3 displays CL's AM-TWN thresholds obtained with the 30° × 23° inspection field (from Figs. 2 and 3a; open squares) against the same thresholds obtained with a 60° × 46° inspection field (solid squares). The comparison is made for a noise contrast of 100% and for 2 s presentations. Overall, the data show no significant field size dependency. Had the inescapable edges of the smaller inspection field contributed one way or another to the AM-TWN sensitivity, one would have expected a change in this sensitivity for the larger inspection field. The absence of such a change argues against a putative contamination of the present results by any spatial edge effects. As such, it ascertains the 'purity' of the present temporal modulation. To summarize, the three control experiments show some temporal summation limitations (for observer CL) for stimuli extending over less than four cycles and practically no effect of either the contrast of the noise

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[3] Recent data by Cropper (1998) showed that second-order sensitivity remains unaffected by the contrast of the carrier provided that this contrast is about five to eight times beyond its own detection threshold.

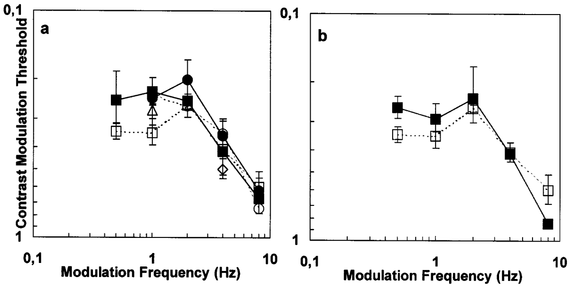

Fig. 3. AM-TWN thresholds with a noise contrast of 100% obtained with (a) a 30° × 23° inspection field for 2 (from Fig. 2) and 4 s presentations (open and solid symbols, respectively) for observers CW (circles) and CL (squares) and with (b) both 30° × 23° (open squares) and 60° × 46° (solid squares) inspection fields for 2 s presentations and for observer CL. The open triangle (obs. CW) and diamond (obs. CL) in panel a show AM-TWN thresholds obtained with a contrast of the noise carrier of 50% at 2 and 4 Hz. Vertical bars show ± 1 S.E. of the mean.

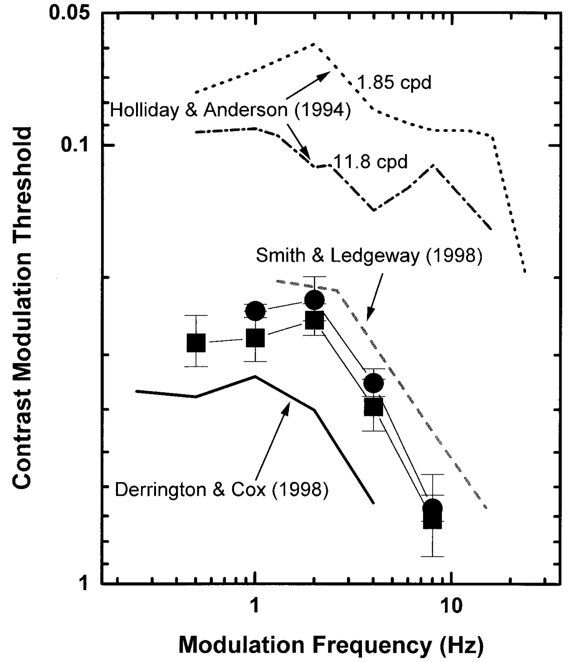

Fig. 4. AM-TWN thresholds averaged (geometric means) over the two presentation durations and obtained for the 30° × 23° inspection field and with a noise contrast of 100%. Circles and squares are for observers CW and CL. Vertical bars are ± 1 S.E. of the mean. Lines without symbols are data from previous studies, as indicated (see also Table 1).

carrier (50% vs. 100%), or the size of the inspection field (30° × 23° vs. 60° × 46°). Taken together, these control experiments support the generality of the present results.

Fig. 4 re-plots the AM-TWN data from Fig. 2 (averaged over the two presentation durations for each observer) together with other estimations of the temporal characteristics of the second-order system. The latter have all been obtained with spatially modulated, moving stimuli whose characteristics are given in Table 1. The present data are well within the sensitivity range assessed by Smith and Ledgeway (1998) and by Derrington and Cox (1998), but they differ significantly from those of Holliday and Anderson (1994). In its turn, the latter study provides sensitivity functions quite similar to those of Derrington (1994) and of Lu and Sperling (1995); not shown). As already noted in the Introduction, the results of the latter three have been questioned on grounds of local failures of equiluminance within the distal and/or proximal stimulus (distortion products). Together with the present results, the literature is thus in good agreement with the notion that second-order temporal mechanisms are substantially less sensitive (by more than a factor of 100 in the present experiments) than first-order ones, that they display near to low-pass characteristics, and have a CFF close to 10 Hz.

It is worth noting that the data of Derrington and Cox (1998) and of Smith and Ledgeway (1998) were obtained with moving stimuli spatially modulated at 1 c/deg, whereas the present ones were collected with 30° (and 60°) uniform fields (that is, a spatial frequency virtually 0). Given the similarity of the three sets of results, one may infer that: (1) second-order motion and flicker sensitivities are sub-served by the same temporal mechanisms and that (2) up to at least 1 cpd spatial modulations, the second-order system processes information by means of a unique spatial channel, that is the one with the lowest available center-frequency. Moreover, if the analogy with the first-order system were to hold, the second-order system should also display a trade-off between the spatial and temporal cut-off frequencies (see Robson, 1966; Kelly, 1979). Accordingly, the present data — because they were obtained with large, spatially homogeneous fields — may be assumed to characterize the highest second-order CFF.

It is, finally, worth noting that although the absence of spatial structure of the stimuli used here prevents the possibility of spatial luminance cues, such potential artifacts cannot be excluded in the time domain. Indeed, first-order processing nonlinearities can always manifest themselves in the temporal summation of random luminance signals (around L_0). It could thus be argued that the present data are not, beyond doubt, void of the contribution of the first-order system. To this, the present study, like the previous ones, cannot offer a definitive counter-argument.

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