

Dynamics of visual masking revealed by second-order metacontrast

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Metacontrast is a powerful visual illusion by which the visibility of a brief stimulus is drastically reduced when it is followed by a snugly fitting second, masking stimulus. There have been longstanding debates about the levels at which metacontrast mechanisms operate and about the temporal unfolding of the masking effect. Here, we use second-order features (texture and movement) in order to set a lower bound to the level at which metacontrast may be found. First, we show that interactions of two second-order stimuli readily produce typical metacontrast masking. We then create second-order single-transient stimuli that induce visual percepts when a random uniform texture is locally replaced by a similar random uniform texture. We show that these ultra-brief stimuli can be used both as target and mask. Using these single-transient stimuli, we seek to disentangle the relative contributions of mask onset and offset. Results suggest that, at least in the context of second-order masking, nearly all of the mask's effectiveness is due to the very first visual event that follows the target.

Keywords: masking, texture, detection/discrimination

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Introduction

When a brief visual stimulus (the target) is shortly followed by a second abutting stimulus (the mask), perception of the first stimulus is dramatically modified, to the point of rendering the target invisible (see [Figure 1A](#)). This masking phenomenon, known as metacontrast, has been extensively studied since its isolation by Stigler (1910; for a comprehensive and recent review, see [Breitmeyer & Öğmen, 2006](#)), as it provides invaluable insights about the early stages of visual perception. Metacontrast has also been widely used in cognitive studies as a means for creating subliminal stimuli—stimuli that are not consciously perceived but yet have an effect on brain and mental processes. Yet, there are unresolved issues about metacontrast. Here, we concentrate on two such issues: the first one is the level in the visual system at which the mask disrupts target processing; the second concerns the temporal features that make a stimulus effective as a mask.

Metacontrast has some strong similarities with simultaneous contrast, hence its name. While in simultaneous contrast the apparent brightness of a target is modified by the luminance of the surround, in metacontrast, the same effect appears distributed in time. Thus, it has been claimed that very basic mechanisms of the visual system such as lateral inhibition could be sufficient to account for metacontrast ([Bridgeman, 1971](#); [Macknik & Martinez-Conde, 2004](#)). According to this perspective, metacontrast is intrinsically a low-level mechanism (see also [Becker &](#)

[Anstis, 2004](#)), for which we could find evidences as early as in the lateral geniculate nucleus and primary visual cortex. More recently, it has been proposed that masking in metacontrast depends on the interruption of recurrent processing in cortical pathways, and this has been proposed on psychophysical ([Di Lollo, Enns, & Rensink, 2000](#)) and physiological ([Fahrenfort, Scholte, & Lamme, 2007](#)) grounds. This presumably implies that the disruptive effects of the mask occur at higher levels in the hierarchy of the visual system. The involvement of recurrent processing is consistent with the fact that higher cognitive processes, such as attention, are known to modulate metacontrast ([Ramachandran & Cobb, 1995](#)). We should note that these lines of evidence are not exclusive: phenomenological metacontrast may be the resultant of a set of different mechanisms, at various levels in the visual hierarchy.

Here, we investigated the level at which metacontrast masking operates by using second-order stimuli both as targets and masks. It is known that the visual system is not only responsive to first-order stimuli, defined by luminance or chromaticity profiles, but also to second-order stimuli ([Cavanagh & Mather, 1989](#); [Sperling, Lu, & Chubb, 1996](#)). In second-order stimuli, overall luminance and color are kept constant across the image, but local variations in contrast, texture, or movement, nevertheless, define shapes and objects. We thus sought to reproduce the phenomena of metacontrast with second-order stimuli, so as to raise the lower bound of the level at which metacontrast is evidenced. We reasoned that if metacontrast is obtained with second-order stimuli, then it cannot

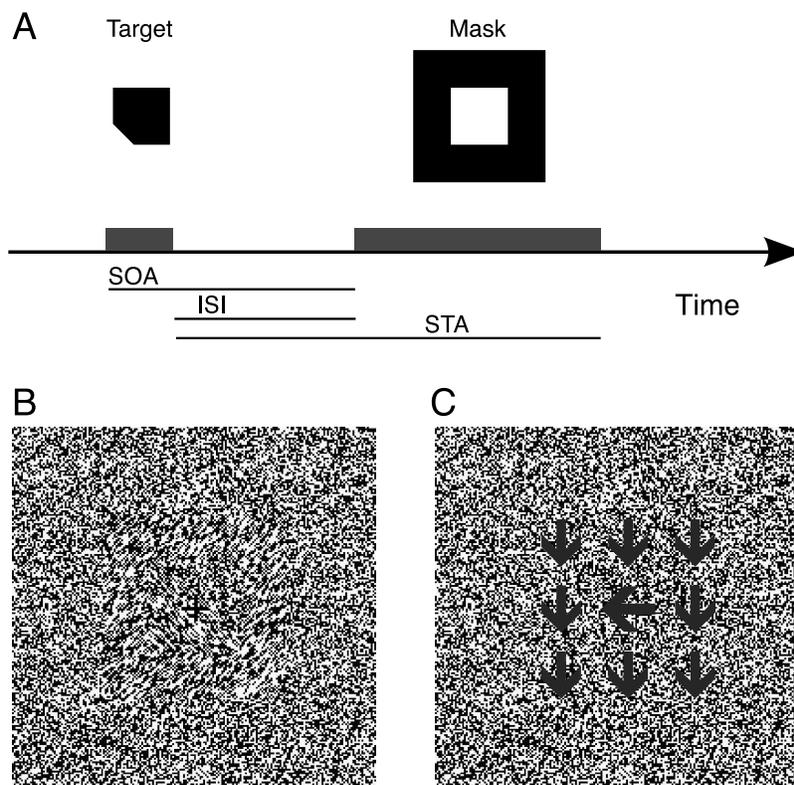


Figure 1. Stimulus. (A) Schematic geometry and time course; SOA: stimulus onset asynchrony; ISI: inter-stimulus interval; STA: stimulus termination asynchrony. (B) Schematic representation of the texture stimuli. Missing corner is in the top right position; target and mask textures are -45° and $+45^\circ$ relative to vertical. (C) Schematic representation of movement stimuli: the texture is random uniform; the central arrow represents the direction of motion of the target, while the eight adjacent arrows represent motion of the mask.

be restricted to lower level areas (notably V1) where no selectivity for second-order properties is found (Orban, 2008).

The time course of metacontrast is yet another set of unresolved issues. Following the onset–onset law formulated by Kahneman (1967), metacontrast has been most often evaluated by comparing visibility of the target at various Stimulus Onset Asynchronies (SOAs). It is usually found that visibility of the target increases monotonously as SOAs increase (“type A” metacontrast) or that visibility starts high at short SOAs, then worsens at intermediate SOAs, before rising again and reaching a plateau as SOAs increase (“type B” metacontrast; this is the classical U-shaped metacontrast function.) However, SOA is only one of many temporal parameters in metacontrast (see Figure 1B), among which are the Stimulus Termination Asynchrony (STA) and the Inter-Stimulus Interval (ISI). Systematic dependence of metacontrast to any of these would point to different physiological events responsible for the decrease in visibility. In particular, one may hope to establish the relative role of the burst of neural activity at the onset and offset of a stimulus, on the one hand, and of the sustained activity during stimulus presentation, on the other hand (Macknik & Livingstone, 1998). Thus, isolating the relevant temporal parameters would constrain critical neural events responsible for masking. However,

discussions on this point are hampered by the sheer size of the parameter space and by the impossibility of decorrelating all of the parameters with traditional first-order stimuli. For instance, it is obviously impossible to vary simultaneously the SOA and the STA without at the same time varying the duration of at least one of the stimuli.

However, using second-order features, we can create stimuli that are not modeled on enduring physical objects: when a random texture is locally resampled, it creates the vivid percept of a shape even though no permanent features are physically present. These ultra-brief stimuli drastically reduce the parameter space: we are now able to study metacontrast for stimuli that do not induce sustained input activity, as they are defined by only one physical transient. Here, we investigated the relative contributions of the onset and offset of the mask, as it has been claimed that both contribute equally to the mask’s effectiveness (Macknik, Martinez-Conde, & Haglund, 2000). We show that as far as second-order mechanisms of metacontrast are concerned, both contribute to masking, but that the main contribution comes from the very first event.

First, we demonstrate the possibility of metacontrast with second-order stimuli—see Vernoy (1976) for a related demonstration using cyclopean stimuli. We use two types of second-order features (see Figures 1B and 1C): first, we vary local orientation on a random binary texture, and

second, on the same type of textures, we introduce coherent local movement. These two types of second-order features define clearly visible shapes that we use to create both targets and masks. Then, in a second experiment, we simplify the stimuli, so as to yield pure single-transient stimuli (see [Figure 3A](#)), where the shapes are defined by locally resampling a random binary texture. Again, we show that these stimuli readily reproduce the phenomena of metacontrast. In a third experiment, we study the temporal unfolding of metacontrast with the help of these stimuli: by using two mask transients, we seek to study the effects of traditional masks' onsets and offsets, decorrelated from their duration. Throughout the three experiments, we rely on a discrimination task on a centrally presented target stimulus.

Experiment 1: Texture and movement second-order metacontrast

The first experiment studied metacontrast as created by texture and movement features on a background random binary texture. In four separate blocks, we studied the four possible combinations of second-order features for target and mask (texture target/texture mask; texture target/movement mask; ...), in order to reveal any potential asymmetry between the two. We refer to blocks where targets and masks are of the same type as "homogeneous" blocks, as opposed to "mixed" blocks, where targets and masks are of different types.

Material and methods

Participants

Eight participants from a pool of students in local universities (mean age: 23.4, $SD = 1.9$, 3 males) passed each of the four blocks. All had normal or corrected-to-normal vision, were not experienced psychophysical observers, and were naive to the purpose of the experiments. They were paid 8 euros for each of two 1-h sessions, each comprising two blocks with a specific assignment of stimulus type (texture or movement) to the target and the mask. Block order was randomized across participants.

Stimuli

For all the stimuli, we used dark (3 cd/m^2) and light (46 cd/m^2) pixels, so that the mean luminance of the random binary texture was 24 cd/m^2 , while the surrounding screen was gray at 23 cd/m^2 . The background texture was a binary random texture, each screen pixel having a 0.5 probability of being light or dark. Each trial used a new background texture, generated with the same rule.

Textures for the stimuli used one of two diagonal micro-patterns (see [Figure 1B](#)), so that the first-order statistics was the same as in the background uniform texture (mean luminance was also 24 cd/m^2), while the second-order statistics were different. Target and mask always used opposing micro-patterns, but the assignment for the mask and target was random. When a stimulus terminated, it was replaced by the original background texture. Movement stimuli were defined by moving pixels from the background texture in one of four directions: upward, downward, leftward, and rightward. New random pixels were drawn at the trailing edge of the stimulus. Speed was always $2.6^\circ/\text{s}$. Thus, the relative movement of one surface within the stimulus created kinetic boundaries within a texture that had, otherwise, no distinguishable feature. Mask and target never had the same direction of movement, and assignment was random. When stimuli terminated, the displaced pixels stayed still. Texture and movement stimuli so defined were perfectly visible, when presented in isolation (see [Supplementary material](#) for a demonstration).

Geometry and time course

Stimuli were presented on a Sony Trinitron 17-inch CRT screen with a refresh rate of 100 Hz at 1024×768 pixel resolution, in a dimly lit experimental booth. Subjects sat 80 cm from the screen. All stimuli were presented at fixation, at the center of the screen. The geometry of the stimuli was as such: the target was a square (80 pixels, 1.7°) of which one corner was missing (22 -pixel width, 0.5°). The mask was a larger square annulus (200 pixels, 4.3°), within which the target exactly fitted. All stimuli were presented on a background random uniform binary texture (400 pixels, 8.6°), while the rest of the screen was gray. Each trial began with a random foreperiod (sampled from a uniform distribution in the range of 200 – 500 ms) during which the background texture was presented, with a black fixation cross ($0.32^\circ \times 0.32^\circ$) at the center of the screen. The fixation cross remained visible during the entire trial. The target was then presented, centered on fixation, for 3 frames (30 ms), followed by a variable SOA (all durations in 10 -ms steps between 0 and 100 ms, plus 150 , 300 , and 500 ms), then the mask was presented for 10 frames (100 ms). Participants' task was to indicate which corner of the target was missing, using the R, U, C, and N keys, which were readily mapped (on a standard French keyboard), respectively, to the upper left, upper right, lower left, and lower right corners. Emphasis during the instruction and training phases was on accuracy, not speed. Participant's response triggered the next trial.

Procedure

Each block began with the instructions displayed on screen, then a training phase (20 trials), in which the stimuli were the same as in the data collection phase,

to the exception of SOA and size of the missing corner: during training, SOA was set at 800 ms for the first trial, and linearly decreased to 50 ms for the last trial, while the missing corner started at 1.2° for the first trial and linearly decreased to the fixed value of the experiment (0.5°) at the end of training. Participants had to make at most two errors (which was easily achieved) in a training block before engaging in the main experimental blocks. The main experimental phase comprised 560 trials: 40 trials for each SOA (with an equal number of missing corner positions within each SOA), subdivided in 10 mini-blocks. Trials were randomized within each block. Between mini-blocks, participants were encouraged to rest for a short pause that would last at least 30 s.

Results

All analyses are based on percent correct responses. We also ran the same analyses using an estimation of sensitivity (d'), using (Smith, 1982) formulas for 4-alternative forced-choice designs. As the patterns were the same, we here present results with percent correct.

Overall performance across all SOAs was above chance (0.49% correct, chance level: 25%, $t(7) = 5.27$, $p < 0.005$). Crucially, accuracy increased monotonously as SOA increased (see Figure 2).¹ This is a clear signature of “type A” metacontrast masking. As can readily be seen, there was no major difference between the four types of

second-order objects. To assess this statistically, we ran a 4×14 ANOVA with factors of block type and SOA, with subject as random factor. There was an obvious effect of SOA but no effects of block type and no interaction ($F_s \leq 1$). Still, closer inspection of Figure 2 reveals an interesting difference: within the mixed conditions, we notice that, at the shortest SOAs (0 and 10 ms), movement is more efficient than texture as a mask and more robust as a target. This was statistically significant: we ran a 2×9 ANOVA within the mixed conditions and $SOA \leq 80$ with factors of type of stimuli (texture/movement vs. movement/texture) and SOA. Both the SOA and the interaction between the two factors were found significant (SOA: $F(1,7) = 16.83$, $p < 0.001$; SOA \times type of stimuli: $F(1,7) = 8.33$, $p < 0.05$), while there was no main effect of type of stimuli. This analysis reveals a tendency toward U-shaped metacontrast function for the movement/texture stimuli (see inset in Figure 2).

Response times depended significantly ($F(13,91) = 7.16$, $p < 10^{-8}$) on SOA in a U-shaped manner: they decreased from 897 ms at SOA = 0 to 837 ms at SOA = 150 ms, and then went back up at 1017 ms at an SOA of 500 ms. However, this again did not depend on the kind of stimuli ($p > 0.5$; see Figure 5).

No practice effect was found across blocks as regards accuracy ($F(1,7) = 1.8$, $p > 0.2$), while an effect was found on response times, by which subjects were globally faster in the fourth and last session than in the first (673 ms as opposed to 950 ms $F(1,7) = 10.46$, $p < 0.05$). However, comparison between the third and fourth sessions showed

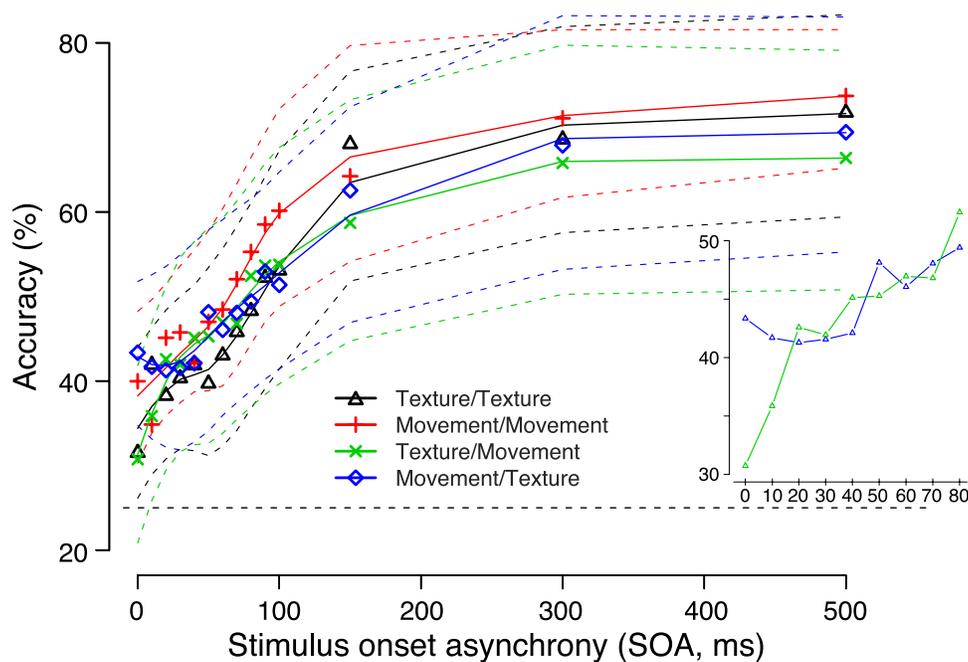


Figure 2. Accuracy as a function of SOAs in Experiment 1 (objective duration stimuli). Plain lines are LOESS fits of the data. Dotted lines represent 95% confidence bands, estimated with 5000 bootstrap replicates, following the procedure of Efron and Tibshirani (1993). The horizontal dotted line represents the chance level (25%). Inset represents the same data for the mixed conditions (same color code), zooming on the interaction and the tendency toward U-shaped metacontrast function for the movement/texture condition.

no difference (756 ms as opposed to 673 ms, $F(1,7) = 0.4$, $p > 0.5$). Thus, it seems that practice effects did not bear on subject's criterion but mostly on learning simple aspects of the task. Furthermore, they seemed to be over by the end of this first experiment.

Discussion

Metacontrast masking is not confined to first-order objects. Indeed, both our stimuli require activation in extrastriate visual areas: V2 for orientation-defined textures and V4 for kinetic boundaries (Orban, 2008; Scholte, Jolij, Fahrenfort, & Lamme, 2008). However, as in traditional metacontrast masking, performances worsened as the SOA between target and mask shortened, with a comparable time scale (Breitmeyer & Ögmen, 2006). Thus, conflicts in processing luminance attributes of both stimuli is not the only cause of metacontrast masking, as overall luminance does not vary in time or space in our stimuli. Quite on the contrary, our results imply that metacontrast can occur between visual percepts computed at higher levels in the visual hierarchy. Note that this leaves open the question of the level at which *interaction* between the target and the mask occurs: since some neurons in V1 respond to texture surfaces, as a result of recurrent processing (Lamme, 1995), it may be that even in our case, masking results from lateral inhibition in V1. Some theories of visual masking (Macknik, 2006) suggest that the same simple mechanism, to wit lateral inhibition, may be active at different levels in the visual hierarchy. According to such a view, our results should be expected since disruptive interactions between the mask and the target should occur at whichever level both are represented. With respect to this issue, it should be important to test the occurrence and time course of metacontrast between first and second-order stimuli.

It is usually assumed that detection of second-order shapes such as our stimuli occurs in a three-tiered fashion: one can distinguish on psychophysical and physiological grounds a first “feature detection” stage, followed by an “edge detection” stage and a “surface” formation stage (Scholte et al., 2008; Scholte, Jolij, & Lamme, 2006). *A priori*, our task could be performed correctly on any of these stages: Remember that it is a feature of our stimuli that pixels in the missing corner of the target do not change from the very start to the end of the trial. Thus, since our target is always presented at the same screen location and contains a fixation cross, it would, in principle, be possible to perform the task on the basis of the location of the permanent pixels. This would harness the decision process on the first stage of the above hierarchy. However, according to this proposition, there should be no variation of performance as a function of the SOA, since the critical feature of the display (location of the stable pixels) for this decision model does not depend on SOA.

Of particular interest here is the contrast between what is predicted for the SOA = 0 conditions if one relies on the first stage and that if one relies on either of the “edge detection” or “surface detection” stage: If observers relied on the simple features of the stimuli, then, when target and mask are simultaneous, they could use the well-defined triangle corresponding to the “hole” in the combination of the target and the mask. However, crucially, performance at this SOA is worse than at any other, longer SOA. This suggests that even though observers might, in principle, detect that triangle, they do not do so in the context of our experiment. This shows that observers perform the task on the basis of the notched square pattern—that is, base their decision on either the “edge detection” or “surface formation” stage, both of which enable representation of the notched square shape of the target. A clear implication of this idea is that observers trained in the detection of the triangle should have much better performance at SOA = 0 than our participants, who only use the notched square shape as a template for the target.

The form of the metacontrast function we obtain is another feature of our results that deserves attention: our metacontrast function is clearly monotonic, yielding higher performances for increasing SOAs, or in other words type A metacontrast. One may wonder why we do not find type B (U-shaped) metacontrast function, as these have also been found with similar stimuli. We should stress that the only case where there seems to be a tendency suggestive of type B metacontrast is the one where the target is strongest among our stimuli (movement) and the mask weakest (texture), which is in agreement with the literature on this issue. We will come back to this important issue in the [General discussion](#) section, as this pattern is also present in the two next experiments.

Finally, the absence of major difference between the two kinds of second-order stimuli is suggestive of some common property, despite their different phenomenological appearance. One such property might be transient local movements. Indeed, even texture stimuli involve local movements: at the onset of a texture, transition from the uniform binary texture to the second-order texture must create pixel level, random movements. Thus, we reasoned that the kind of metacontrast masking that we created may simply require the use of random pixel level movements, without any coherent global motion or texture transition. Therefore, in two further experiments, we defined our stimuli by a transition between two uniform random textures, part of which (the background) remains unchanged (see [Figure 3A](#) and [Supplementary material](#) online for a demonstration). As these stimuli are defined by a single physical transient, they will come as close as possible to ideal pure onset or offset stimuli, without intermediate sustained input activity. This will give us the opportunity to analyze more finely the role of target and mask onsets and offsets. Henceforth, we will refer

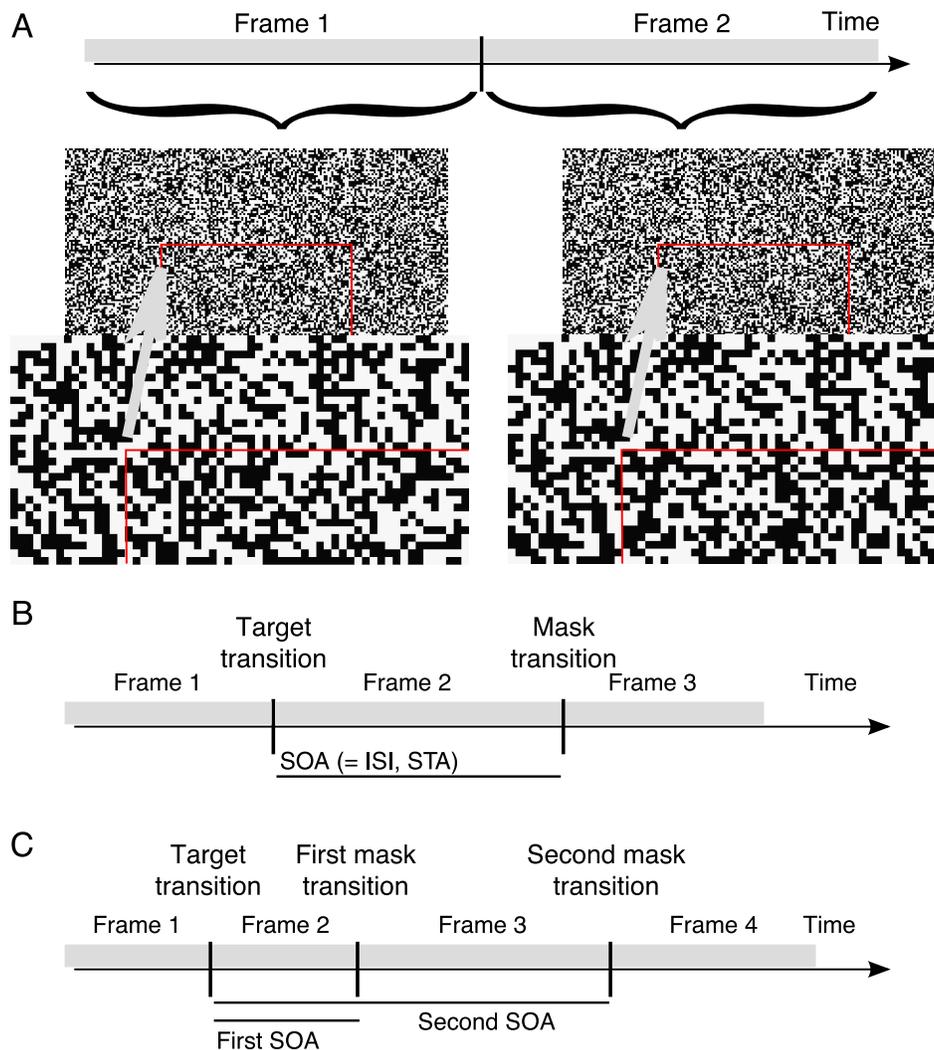


Figure 3. Single transient stimuli (Experiments 2 and 3). (A) Creation of single transient contours. A first random uniform texture (Frame 1) is displayed continuously and followed by a second similar texture (Frame 2). Both are pixelwise identical, except within the central square surface (here highlighted with red lines, which obviously were not in the stimuli), where a new sample of random pixels is drawn. Insets show enlargement of the upper left corner. No object is seen during presentation of any of the two surfaces, but the transition creates a clear percept of a square surface, thus creating a percept to which no sustained input activity corresponds. (B) Time course of events in Experiment 2. A first transition of the kind exemplified above creates the target (same geometry as in Experiment 1). After a variable SOA, a second transition creates the mask. (C) Time course of events in Experiment 3: a third transition is used to create a second mask event, with the same geometry as the first.

to this new type of stimuli as “single-transient” stimuli, as opposed to the “objective duration” stimuli used in Experiment 1.

Experiment 2: Single-transient second-order metacontrast

First, we wanted to ascertain that single-transient stimuli were sufficient to create metacontrast. We thus presented observers with the same task as before, but the

target and the mask were each defined by a single transition (see Figure 3A). We used the same set of delays between target and mask as before. Note that now, since stimuli are defined by a single physical event, SOAs, ISIs, and STAs are one and the same.

Material and methods

We used the same geometrical and temporal properties for the stimuli and simply changed the way textural properties defined the stimuli. Stimuli were created with random uniform textures: during fixation, a first random

uniform texture (same properties as the background texture in the first study) was presented; at the onset time of the target, a second random uniform texture was shown. This second texture was pixel by pixel identical to the first one, except within a central portion having the shape of the target, where a new draw of random pixels was made. This second texture stayed on the screen for the duration of the SOA, at which point it was replaced by a third random uniform texture. This third random texture was pixelwise identical to the second, except for a portion in the shape of the mask, where, again, a new randomization was made (see [Figures 3A](#) and [3B](#)). Thus, the stimuli were formed only as transitions from one random texture to the next. Each texture screen was completely random and did not contain any information about the shape of the stimulus. However, at the time of transition from one texture screen to a different one, random local movements were created, and this was sufficient to elicit clear perception of a shape (see [Supplementary material](#) online for a demonstration).²

Participants, geometry, and procedures were the same as in [Experiment 1](#). SOAs were also identical, but obviously other temporal parameters (durations of the stimuli) could not be identical.

Results

Again, we found clear evidence for metacontrast masking (see [Figure 4](#)). Performance was not significantly

different from chance at SOAs = 0 and 10 ms (32.1%, $t(7) = 1.546$ and 32.8%, $t(7) = 1.366$, respectively) but increased dramatically as SOA increased. Interestingly, overall performance was higher than in the objective duration experiment (59.3% as against 50.4%, $F(1,7) = 9.883$, $p < 0.05$), and the asymptotic performance level was also higher (performances for $\text{SOA} \geq 150$ ms: 82.4% for the single-transient stimuli as opposed to 67.6% for objective duration stimuli, $F(1,7) = 9.499$, $p < 0.05$). If we restrict the analyses to the SOAs below 100 ms, there is a clear linear trend for both objective duration and single-transient stimuli, but the slope is steeper for the single-transient version (0.44) than for the objective duration versions (0.17). We tested the statistical significance of this difference by bootstrap with 3000 samples and found that the 95% confidence interval of the difference was [0.19, 0.33].

Response times were faster than with objective duration stimuli (656 vs. 880 ms) but were similarly U-shaped: they decreased from 716 to 617 ms as SOAs went from 0 to 150 ms, and then went back up to 799 ms at $\text{SOA} = 500$ ms ($F(13) = 7.51$, $p < 10^{-7}$, see [Figure 5](#)).

Discussion

This experiment shows that single physical transient objects can define clear perceptual shapes and can also act as metacontrast masks. Thus, the specific features of the second-order stimuli used in [Experiment 1](#) are less

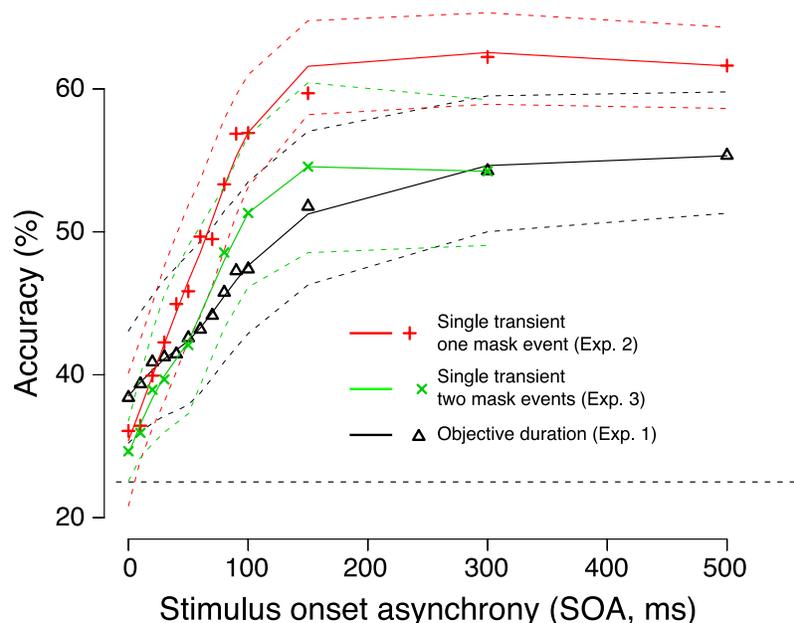


Figure 4. Accuracy as a function of SOAs for the objective second-order stimuli ([Experiment 1](#), all four subconditions aggregated, black), the single event condition ([Experiment 2](#), red), and the two-event mask condition ([Experiment 3](#), green). For this last experiment, each data point represents mean performance for the first mask event SOA, averaged across all second event mask SOAs. Plain lines are LOESS fits of the data. Dotted lines represent 95% confidence bands, estimated with 5000 bootstrap replicates, following the procedure of Efron and Tibshirani (1993). The horizontal dotted line represents chance level (25%).

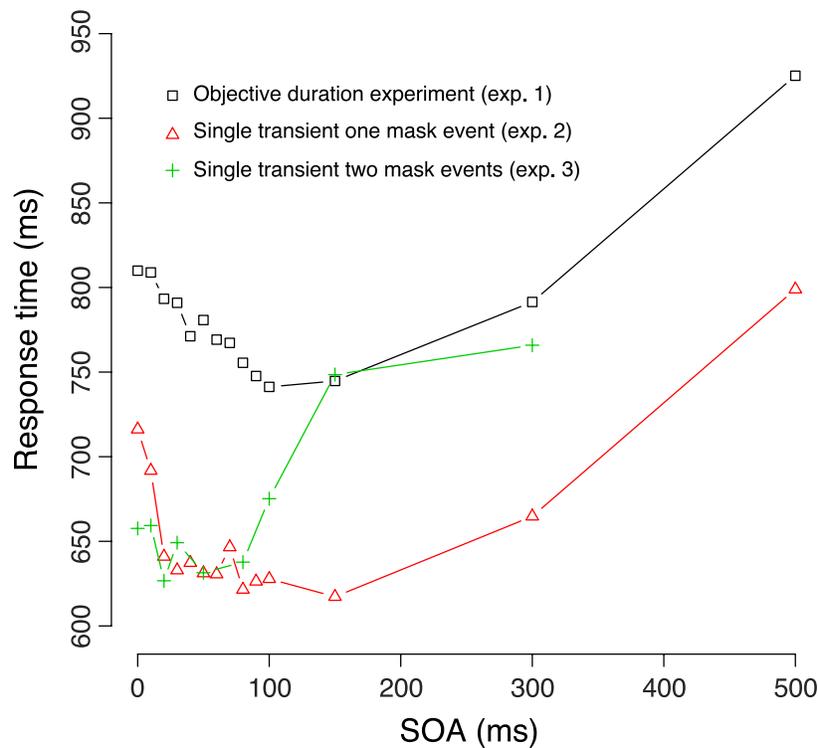


Figure 5. Mean of median response times for the three experiments. For [Experiment 3](#), each data point represent response times aggregated over each SOA 1 condition.

important than random, local, pixel level movements. These constitute the basic feature shared by all our previous stimuli. Furthermore, the overall similarity of the masking function in [Experiments 1](#) and [2](#), even though mask and target durations are very different, suggests that, within the range here employed, this function is only moderately dependent on timing. Thus, one would expect that stimuli of intermediate durations would again yield similar type A metacontrast function.

It is important to stress that in the single-transient version of the stimuli, target and mask still constitute two interfering percepts. High performances in the task are not achieved through detection of local inhomogeneities within the random texture: first, stimuli are always spontaneously described as shapes, albeit fleeting, by all observers. Second, chance performance at SOA = 0 ms is here even more striking than in [Experiment 1](#): note that by design, when the target and the mask are simultaneous, the stimulus consists of two frames creating one transition. During the transition, the combination of the mask and the target changes while a triangular hole remains untouched. Since observers seem able to perform a shape discrimination on this kind of transition, as is apparent from the high performance level at long SOAs, if they were using any other information than the notched square pattern to perform the task, they should have had very good performance at this SOA. Quite on the contrary, their performance there is the poorest. This shows that

observers harness their decision process on the perceived notched square shape. The complete contour information is needed to perform the task while local features or unbound edges are not sufficient. Still, it is important to realize that detection of the triangular hole in the mask + target combination might be intrinsically more difficult than discrimination of the target's shape. Indeed, signal strength is clearly much lower, due to the small size of this triangle; in addition, a response based on four separate locations might require attentional scanning, which may require a longer time window. Further experiments are here needed to resolve these issues.

Thus, again, the defining property on which observers seem to base their decision is not available at lower levels in the visual system hierarchy. It must be computed at higher levels, even though the interference creating the typical metacontrast function may well occur in V1.

In this experiment, the metacontrast function is very clearly two-tiered: in a first phase (0–100 ms), performances build up linearly with SOA, while for longer SOAs (150–500 ms) they reach a maximum and level off. This shape suggests that the burst of activity caused by texture transitions triggers a shape formation process that is not completed until roughly 100 ms after target presentation. This is in agreement with the physiological data (Scholte et al., 2008) for similar texture-defined shapes.

This experiment opens up a new line of inquiry for the precise investigation of the time course of metacontrast.

Indeed, first-order stimuli must have both an onset and an offset. Thus, determination of their respective role in metacontrast is difficult, because durations of the stimuli are by construction confounded with intervals between onset and offset. Thus, with first-order stimuli, we cannot weigh the relative contributions of the mask's onset and offset while holding constant the contribution of the sustained input activity evoked by the mask's continuing presence between its onset and offset. The single-transient stimuli may provide for a very profound simplification: we may use them to create a two-event mask that will mimic the pure effects of the temporal edges of the mask, without any intervening presence. Of course, rigorously speaking, each of these events has an onset and an offset, the beginning and the end of the physical transient. Thus, the situation that we create is in effect the application of two ultra-brief masks, with a delay between them. Some more evidence is needed before we can assert that the activity caused by our single physical transients is akin, physiologically and psychophysically, to the burst of activity at the onset and offset of a physically enduring object.

Experiment 3: Single-transient, two-event mask second-order metacontrast

In this experiment, we wanted to determine what added masking would result from the inclusion of an additional mask event in stimuli otherwise identical to those of [Experiment 2](#).

Material and methods

Stimuli and geometry were the same as in [Experiments 1](#) and [2](#). However, we now used a mask defined by two transients. Thus, the target was defined by one frame transition, and after a variable delay (SOA 1), a second frame transition was used to create a first mask event; however, in this experiment, after a second variable delay (SOA 2), another frame transition created a second mask event (see [Figure 3C](#)). We used the following subset of 10 out of the 14 SOAs used in the first two experiments: 0, 10, 20, 30, 50, 80, 100, 150, 300, and 500 ms and crossed them so as to obtain 45 temporal conditions.

Participants were the same 8 participants as in the two previous experiments.³ Each passed two sessions within a week. Each session contained 12 repetitions for each 45 temporal conditions, randomized across the sessions and separated in 10 blocks of 54 trials. Each session started with a training block of 20 training trials, starting with wider missing corners and long SOAs.

Results

We first compared the metacontrast function in this condition with the metacontrast function in the two previous experiments. When averaged across all SOAs for the first mask event, performances showed the typical monotonic increase characteristic of metacontrast (see [Figure 4](#)). Overall performances in this condition were above chance (48.9%, chance = 25%) but below performances in the previous experiments for the corresponding SOAs (49.3 for the objective duration experiment and 56.2% for the single-transient one-event mask condition). However, a 3×9 ANOVA with factors of stimulus type (objective duration, single-transient one-mask event, single-transient two-mask events) and SOA 1 (0, 10, 20, 30, 50, 80, 100, 150, and 300 ms) revealed a more complex pattern: The two main effects were significant (SOA: $F(8,56) = 76.6$, $p < 10^{-10}$, stimulus type: $F(2,14) = 8.66$, $p < 0.001$), but there was also a significant interaction: ($F(16,112) = 5.45$, $p < 10^{-7}$). A closer look revealed that there was no difference between the objective duration stimuli and the single-transient two-mask-event stimuli ($F(1,7) < 1$), while a difference with the single-transient condition was indeed present ($F(1,7) = 19.4$, $p < 0.001$). Performances for the two-event conditions differed (all $p_s < 0.05$) from performances for the corresponding one-event conditions at all SOAs except the four shortest ones (0, 10, 20, 30 ms)—for which performances were already at or near chance in the one-event mask condition.

The metacontrast function was clearly two-tiered, as in the single-transient one-mask-event condition, but, interestingly, the slope during the buildup phase (SOAs < 100 ms) was 0.33. It was thus intermediate as compared to the slope in the single event mask experiment (0.44) and in the objective duration experiments (0.18). We assessed the significance of this difference by bootstrap resampling and found that the 95% confidence interval for the difference in slope between the double mask event condition and the single event was [0.03, 0.19] and that it was [0.09, 0.21] between the objective duration experiment and the single-transient double mask event experiment.

Furthermore, plateau performances (for SOAs > 100 ms) were below those of the single event mask experiment (68.8% vs. 82%, $F(1,7) = 17.02$, $p < 0.005$) and not significantly different to those in the objective duration experiment (68.8% as against 67.6%, $p > 0.16$).

In brief, this single-transient two-mask-event condition shared with the objective duration condition its asymptotic performance level, while the speed of buildup was in between the speeds in the first two experiments.

Next, we wanted to assess more precisely how the second mask event contributed to masking. Since the first SOA used in this experiment was a strict subset of the SOAs in the first single-transient experiment, we could compare performances, within each SOA 1 condition, for each SOA 2 (see [Figure 6](#)). This showed that performances within each SOA 1 condition was only modestly

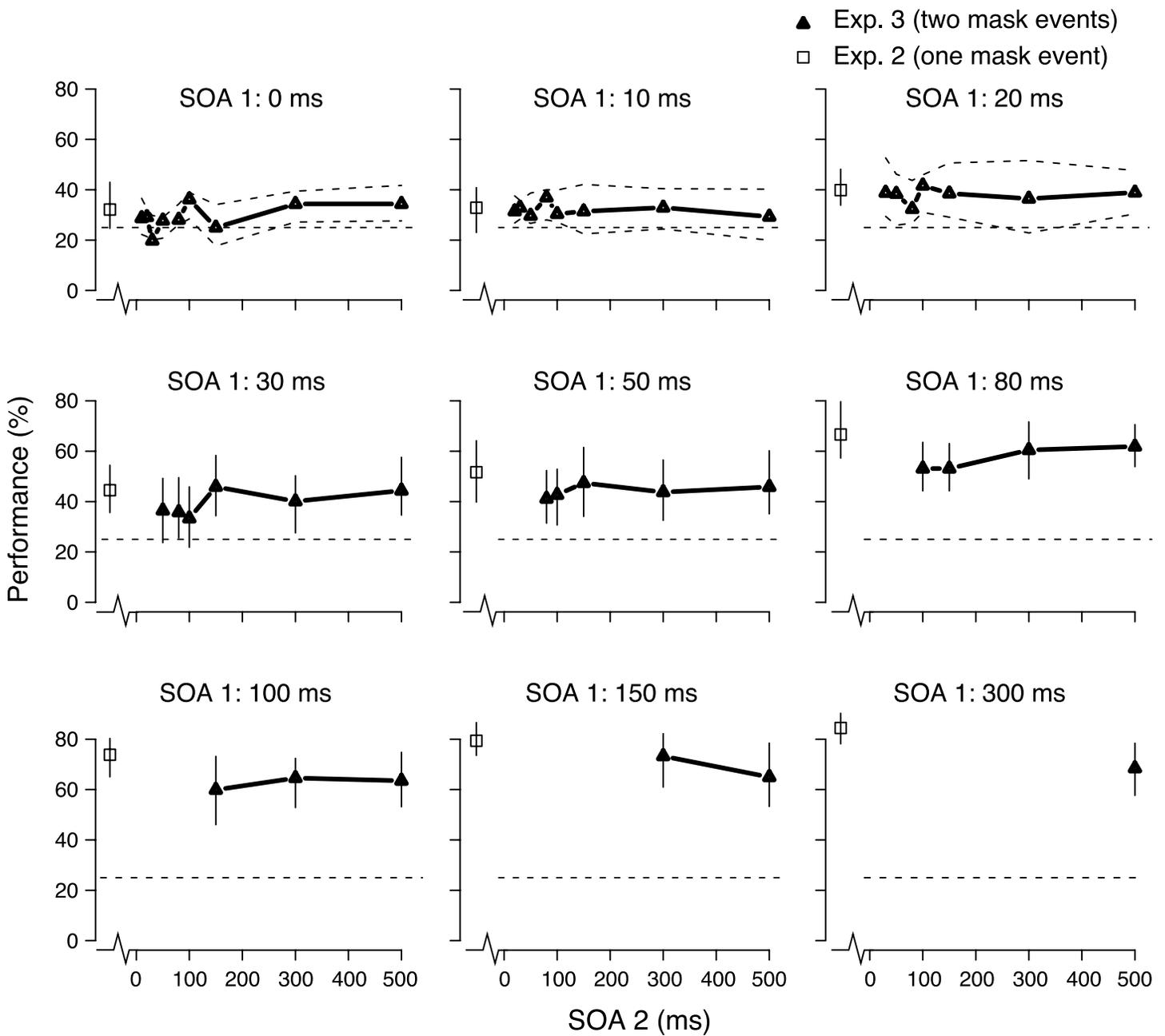


Figure 6. Performances in the two-mask-event condition (Experiment 3), for each combination of SOAs. Within each panel are the data for a fixed SOA 1, and performances (filled triangles) are plotted as a function of SOA 2. For comparison, within each panel, performances in the one-event condition (Experiment 2) are plotted on the left side of each panel (open square). Dotted lines are 95% confidence bands, computed on bootstrapped LOESS fit of the data, and when not applicable, 95% bootstrap confidence intervals are shown for the data point. The horizontal dotted line represents chance level. A totally different pattern emerged when the same trials were categorized according to each SOA 2 condition (see Supplementary Figure 1).

modulated by the second mask event, and this effect was mostly constant across all SOAs. In order to assess statistically this modest impact of the second mask event, we regressed performances on SOA 2, within each SOA 1 condition. We estimated the significance of the slope of the regression by bootstrap resampling. Regression slopes

were comprised between 0.000241 (for SOA 1 = 80 ms) and -0.00041 (for SOA 1 = 150 ms), and none of them reached significance at the 0.05 level, as calculated on 4000 bootstrap samples. Confirming previous analyses, intercepts of the regression were significantly below performances in the one-mask-event experiment, at all

SOA 1 above and including 50 ms, indicating again that at these SOAs, the second mask event impacted performances even though it did not itself depend on its SOA.

Thus, the second mask event did not impact performance through the same mechanisms as the first mask event. It is of course difficult to predict the quantitative decrement in performances that it should have entailed if it simply duplicated the mechanisms of the first mask event. Still, a clear qualitative prediction is that it should have lost its effectiveness at increasing SOAs—because this is the hallmark of metacontrast with our stimuli. This is obviously not substantiated by our data.

However, this second mask event might have had different roles according to some coarser time frame. Indeed, both [Experiment 2](#) and the models of performance with texture stimuli such as ours (Fahrenfort et al., 2007; Scholte et al., 2008) suggest that the first 100 ms after presentation of the stimulus are a critical period of shape formation. Thus, we reasoned that presentation of a second mask event within this time window should impact performance more than outside this window. Accordingly, we performed a 5×2 ANOVA with factors SOA 1 and SOA 2 (categorized as below and including 100 ms or above 100 ms). The two main effects were significant (for SOA 1: $F(5,35) = 16.51, p < 10^{-8}$; SOA 2 below 100 ms: 38.1% correct, above: 41.3% correct, $F(1,7) = 5.91, p < 0.05$), while there was no interaction ($F < 1, p > 0.4$).

Response times, when computed as a function of SOA 1 displayed a clear dissociation (see [Figure 5](#)): when aggregated over the first SOAs, for SOAs below 100 ms, response times followed those of the single-transient one-event condition, while they clearly followed those of the objective duration experiment for SOAs above 100 ms; SOA 1 = 100 ms gave intermediate response times. This suggests that when the second mask event is close enough to the first one both are lumped together and do not impact response time separately. In order to assess more precisely this effect, we computed response times within each SOA 1 condition as a function of SOA 2 (see [Figure 7](#)). A general pattern is apparent: for SOA 2 below 100 ms, there seem to be strictly no effect of SOA 2 on response times. As opposed to that, for SOA 2 above 100 ms, increase of SOA 2 led to a linear increase of response times. We quantified this impression by running separate regressions of response times on SOA 2, both for SOA 2 above and below 100 ms, within each SOA 1 condition. Below 100 ms, slopes were comprised between -0.43 and 0.26 , and none of them reached significance. On the contrary, above 100 ms, regression slopes were comprised between 0.58 and 0.44 and all ps were < 0.1 .

Discussion

Three main results emerge from this experiment: first and foremost, within the context of our second-order single-transient stimuli, the second mask event does not

simply duplicate the effect of the first mask event. Such a model would predict that as the second SOA increases, performance within each first SOA condition would increase too. We found a more complex pattern: when the first SOA is below 50 ms, the second mask event does not seem to have any noticeable effect, as if the first mask had already exerted all masking effects; above 50 ms and below 100 ms, we found an effect of the second mask event, but this effect was constant across the second SOA conditions, suggesting that it reflects either a modulation of masking strength or a different mechanism that does not depend on SOA. Finally, above 100 ms, we found that the second mask event had a lessened effect on response accuracy. In addition, response time patterns for this two-mask-event conditions were sharply distinct below and above SOA 1 = 100 ms: below, it seemed as though the second mask event had no impact on response times, while above, the second mask event clearly slowed response times.

These results are compatible with a model where the effect of the mask depends on the time of its occurrence as relates to the three stages, outlined above, of feature extraction, edge detection, and surface formation. When the mask occurs before 100 ms after the target, it disrupts edge detection and surface formation stages, thus if two mask events are presented, they constitute a single, more powerful mask. Alternatively, when the second mask event is presented outside the 100-ms window after target presentation, the two events are segregated: impact of the second event on performance is diminished, while at the same time it has a separate effect on response times. Therefore, we tentatively propose that in this case, the second mask event affect performances through a different mechanism. For instance, a late second mask event may affect the sensory memory for the target (Sperling, 1960).

General discussion

Our experiments have the following main imports: first, second-order stimuli can not only elicit vivid percepts, they can also function as masks; second, within the class of second-order stimuli, we propose a tentative parsing of the time course of target perception and masking, with the help of second-order stimuli that do not, arguably, induce sustained input activity.

Thus, our results raise the lower bound of the level at which metacontrast may operate. We show that the mechanisms responsible for metacontrast are still active when stimuli are defined by second-order properties, that is, even when we control for the effect of the first-order level factors (luminance or chromaticity). In fact, extraction of forms with our stimuli must operate in visual areas beyond V1: in order to be able to extract the critical form information, the visual system must first compute local

▲ Exp. 3 (two mask events)
 □ Exp. 2 (one mask event)

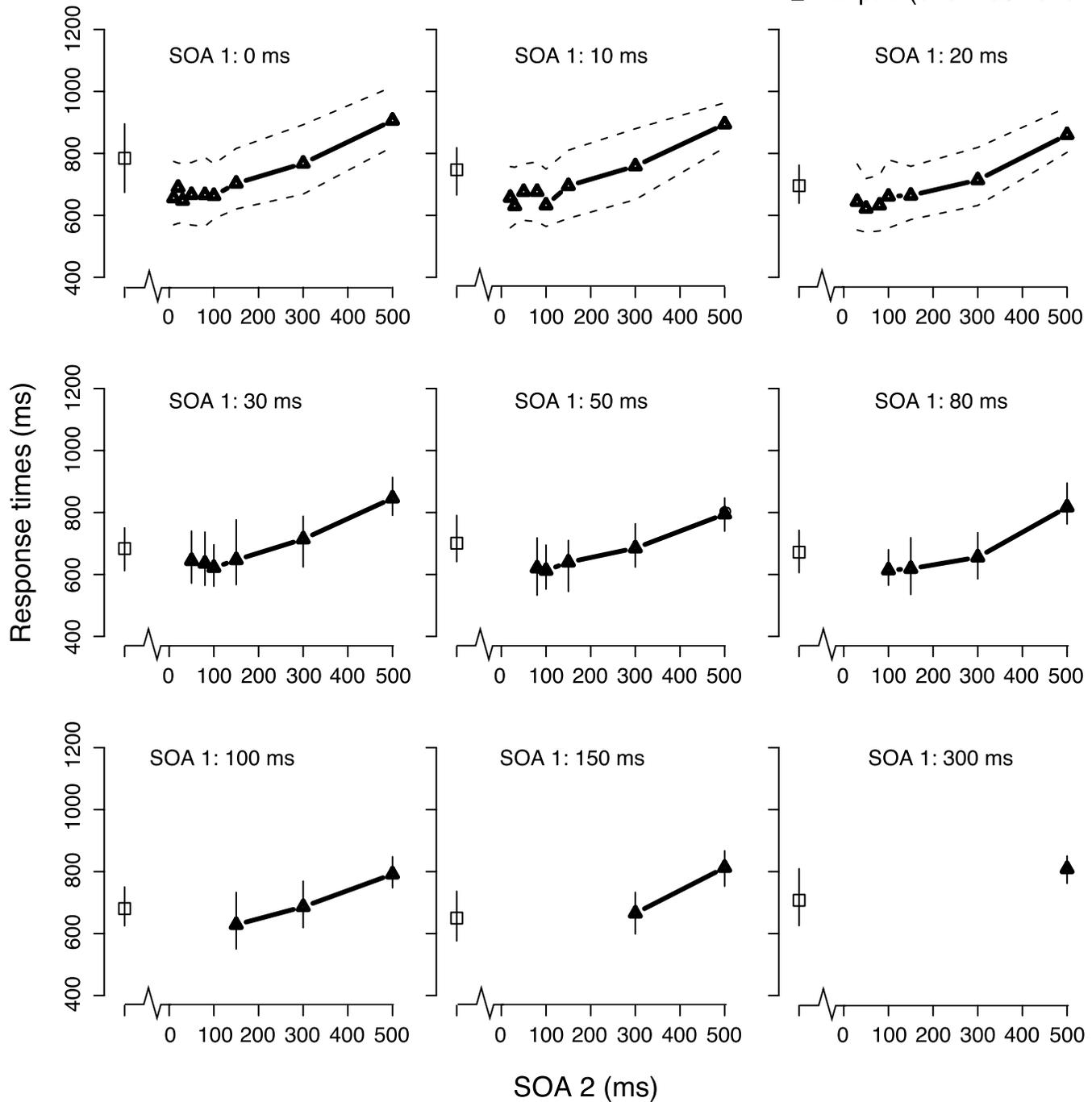


Figure 7. Response times in the two-event condition (Experiment 3), for each combination of SOAs. Within each panel are the data for a fixed SOA 1. Response times (filled triangles) are plotted as a function of SOA 2. For comparison, within each panel, performances in the one-event condition (Experiment 2) are plotted on the left side of each panel (open square). Dotted lines are 95% confidence bands, computed on bootstrapped LOESS fit of the data, and when not applicable, 95% bootstrap confidence intervals are shown for the data point.

pixel-by-pixel movements. Yet, it is implausible that this information be available in V1 in a first feedforward sweep, considering the fact that our stimuli do not correspond to any simple attribute characteristic of V1

(Orban, 2008). Thus, our results strongly suggest that the mechanisms responsible for metacontrast are available at higher levels in the hierarchy of the visual system. This conclusion is in agreement with some recent studies that

investigated different masking paradigm (Hirose & Osaka, 2009), pitted metacontrast against binocular rivalry (Breitmeyer, Koç, Ögmen, & Ziegler, 2008), or used fMRI to investigate directly the areas implicated in metacontrast masking (Haynes, Driver, & Rees, 2005).

At first, this seems to contradict previous analyses of metacontrast that insisted on interaction within lower level channels in the visual system (see, for instance, Becker & Anstis, 2004). It is well known that classical, first-order metacontrast masking is highly dependent on low-level states of the visual system, such as retinal adaptation (see Breitmeyer & Ögmen, 2006, pp. 53–66), and our results do not challenge this. Rather, they suggest that one should not try to pinpoint one and one level only at which metacontrast operates. Metacontrast may be construed as a generic mechanism that may operate at various levels in the visual hierarchy. For instance, following the notion that metacontrast have been obtained as a result of interruption of recurrent processing (Di Lollo et al., 2000; Fahrenfort et al., 2007; Lamme, 2003), we suggest that recurrent loops may be present at various levels in the visual system hierarchy. One obvious follow-up of our experiments would be to directly pit first and second-order metacontrasts against each other, so as to try to evaluate whether metacontrast is the upshot of a generic mechanism that is replicated at various levels in the visual system hierarchy or whether it is a consequence of a mechanism that is instantiated only once but operates on inputs from various levels. So far, our results cannot resolve this issue.

An interesting feature of our results is the decidedly monotonic shape of the masking functions obtained. This is intriguing considering that many metacontrast paradigms yield U-shaped (“type B”) masking functions, leading to worst performance or visibility not at the shortest SOAs but at intermediate SOAs. Most often, explanations (see, for instance, Francis & Herzog, 2004) of the transition from types A to B metacontrast resort to the energy ratio between the target and the mask. It is claimed that there is a critical value (usually 1), such that monotonic functions are obtained when the stimulus/mask energy ratio is less than this value, and U-shaped functions are obtained when it is greater. This might be a valid explanation for our results, where the energy ratio of our stimuli must be close to the ratio of the areas (0.18). Notice that in Experiment 2 the energy ratio is *exactly* the ratio of areas, since both target and mask are defined by the very same physical transformations of a random binary texture: since each stimulus consists of a single frame transition, the amount of local random movement in each must be, on average, proportional to the areas. Since random local movement is the only information that the visual system can pick up, signal strength ratio must itself be equal to the ratio of the areas. We may speculate that this ratio is an upper bound for the one in the other two experiments, where either the mask duration (in Experiment 1) or the second mask event (in Experiment 3)

should arguably strengthen the mask’s power. Thus, in our three experiments, the energy ratio of the target and the mask should be well under 1 and that in itself seems sufficient to explain the monotonic shape of the metacontrast function. Note that, as discussed after Experiment 1, in the one case where the signal strength ratio should be more in favor of the target, we find some hints of a type B, U-shaped metacontrast function.

One should note that other experimenters, using somewhat similar stimuli, obtained concordant results. Notably, Vernoy (1976), working with cyclopean stimuli, created isoluminant target and mask composed of random dots and obtained a clear type A metacontrast function. In his experiment again, an upper bound for the target/mask energy ratio can be equated to the ratio of the areas, which is 0.33. Interestingly, building on this result and also with cyclopean stimuli, Phinney and Homolka (2008) obtained type B (U-shaped) metacontrast with a target/mask energy ratio of 1. Most importantly, Tapia, Breitmeyer, and Jacob (2010a, 2010b),⁴ using stimuli quite similar to ours, obtained type B metacontrast but again with a target/mask energy ratio slightly above 1. Further experiments using our stimuli may investigate the transition from “type A” to “type B” metacontrast as the size of the square mask annulus is progressively diminished. Finally, following Breitmeyer et al. (2006) and Tapia et al. (2010a, 2010b), it might also be important to distinguish tasks that require a judgment on the surface appearance of the target as opposed to tasks requiring contour discriminations, as these might imply different time courses and, consequently, may have yield different metacontrast functions.

The second major result of our study is the weak additional masking created by the second mask event in the two-transient mask condition. Many theories of metacontrast have insisted on the importance of spatiotemporal edges of stimuli in producing visual percepts and, thus, in erasing them in the case of masking (Macknik & Livingstone, 1998; Macknik et al., 2000). However, the question as to *which* spatiotemporal edges are critical has remained controversial. In our last experiment, we aimed at getting rid of stimulus duration effects, as there was no physical stimulus on the screen in between the two physical transients. Thus, we tried to recreate the pure bursts of activity at the edges of the mask, so as to assay their respective weight.

Our data clearly indicate that the first mask event conveys most of the masking effect. More precisely, when the second mask event does have an impact on performance, it does not seem to arise from an additive effect on the first mask event. Rather, if the second mask event falls within a short time window after target presentation (0–100 ms), it seems to combine with the first so as to increase its effectiveness, irrespective of its precise SOA. Else, if it occurs outside this short window, it seems to operate through a different mechanism that, again, does not depend on its exact SOA. We found a signature of this differential effect also in analyses of response times on

which the second SOA appeared to have no effect when it fell within this 100-ms window after stimulus presentation.

Thus, in agreement with physiological studies in monkeys and imaging studies in humans (Fahrenfort et al., 2007; Lamme, 1995; Orban, 2008; Scholte et al., 2008), it seems possible to draw the following picture of second-order metacontrast with our stimuli: immediately after target presentation, the visual system starts a process of shape and surface formation based on transient changes in features. The full contour of the shape is not obtained until 100 ms after target presentation. Effectiveness of the mask is increased when it is duplicated within this initial time window. After this window of shape and surface formation is over, mask events have a markedly different effect: their effects on performance are diminished, while they start to impact response time. Thus, we speculate that whatever effect late mask events have on performance may be mediated through distinct mechanisms. Since late mask events lengthen response times, it is conceivable that they should impact sensory buffers (“iconic memory”, see Graziano & Sigman, 2008; Sperling, 1960). Thus, the decrease in performance that we see even for late mask events might be due to greater decay in iconic memory when responses are delayed due to the second late mask event. Given that the time scale of the effect of the second mask is perhaps beyond the classical range of iconic memory decay, another possible explanation might be that the second mask event should modulate attention in a non-specific fashion. Further experiments, using different stimuli, perhaps even non-visual, as second transient, might help us resolve this issue.

Extrapolations to classical, first-order stimuli are, of course, difficult. However, our results lead to the notion that Stimulus Onset Asynchrony is a critical parameter: thus, it would seem that the first burst of activity generated by the mask exerts most of its disruptive effect. Another direction for generalization would be to take into account the fact that surface formation, in the case of second-order stimuli, is itself a complex and lengthy process. In order to clarify this issue, it would be of tantamount importance to compare contour information tasks with surface information tasks (see Breitmeyer et al., 2006). Essentially, the most important time parameter that we found was whether the second transient event occurred during or after this process was complete. Thus, we may speculate that, irrespective of the kind of metacontrast involved, the relative roles of mask *onset* and *offset* critically depend on the timing of their occurrence relative to the availability of the visual features on which the task is performed. The general rule would be that salient mask events (onset or offset) bear maximal weight when they occur before the initial processes leading to availability of these features are over.

The significance of our results should be qualified by the relatively small amount of data with which they can be compared. The literature on second-order metacontrast is inchoate at best, as opposed to the extensive literature on

metacontrast in the luminance domain. Thus, some peculiar aspects of our study might have had inordinate weight. Among these, we can think of the relatively large size of our stimuli (1.7° target, 4.3° mask), as compared with what is more customary in the field (0.5°–1.5°). Finally, the question of the mechanisms involved in second-order metacontrast might await electrophysiological investigations to be fully resolved.

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Footnotes

¹Following the cautionary advice of Albrecht, Klapötke, and Mattler (2010) and Bachmann (2010), we looked for any important individual differences in our data. Critically, all subjects in all three experiments had obvious type A metacontrast functions.

²Clearly, our “single transient stimuli” are very different from those of Breitmeyer and Rudd (1981), where masking effects on a *very long duration* target are demonstrated. Although not identical, they bear some similarity to those of Bellefeuille and Faubert (1998), in which a certain proportion of pixels reversed polarity from frame to frame.

³After completion of the four randomized conditions of [Experiment 1](#), participants first ran one session of [Experiment 3](#), then [Experiment 2](#) (one session), then another session of [Experiment 3](#), all within a week. This procedure

and the fact that practice effects were limited within **Experiment 1** ensure that comparisons across experiments are possible.

⁴Our attention was drawn to these presentations during the review process.

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