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Running Head: Feature binding is enhanced by 40 Hz flicker

**Synchronous Information
Presented in 40 Hz Flicker
Enhances Visual Feature Binding**

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Abstract

Recent neurophysiological studies (e.g. Eckhorn et al. 1994; Engel et al., 1990; Gray & Singer, 1989; Gray et al., 1990; Kreiter & Singer, 1992) have encouraged speculation that the synchronization of spatially distributed neural assemblies (at around 40 Hz in the neocortex) is responsible for the ‘binding’ of discrete stimulus components into coherent ‘wholes’ during visual object perception (Crick & Koch, 1990; Eckhorn et al., 1990; Engel et al., 1992; von der Malsburg, 1981; Singer, 1993). Using a novel paradigm, we show specific figural priming under 40 Hz stimulus modulation conditions. Further, under these conditions, observers are neither aware of the prime’s existence, nor does the prime act as a stimulus-driven attentional cue. These findings provide the first psychophysical support for a theory of preattentive visual object coding, based upon an externally entrained and thereby synchronized 40 Hz feature binding mechanism.

Introduction

We tested the hypothesis that variations in the timing of external events would influence the performance of a psychophysical task requiring the integration of visual features into a coherent ‘figural’ representation. Two experiments were conducted, in which observers produced a reaction time (RT) response, as rapidly and accurately as possible, to the presence or absence of a target Kanizsa-type figure (a square defined by the collinear arrangement of 90° corner junctions) (experiments 1 and 3). One further experiment examined observers’ perception of figural information presented within an oscillating pre-target stimulus display (experiment 2). In each experiment, following a brief computer-generated tone, observers were presented with an oscillating 3 x 3 matrix of premask crosses (Fig. 1a). After a given presentation time (Fig. 1b), the pre-mask crosses reduced to simple 90° corner junctions by removal of redundant line segments. Observers had either to discern the presence of a Kanizsa square within this matrix of corner junctions and produce a present/absent RT response (experiments 1 and 3), or were required to discern the spatio-temporal structure of the oscillating 3 x 3 premask matrix (experiment 2).

Figure 1 about here

On the basis of evidence for oscillatory visuo-cortical and subcortical activity, which is time-locked to stimulus onset and can display periodic activity within the upper beta and gamma bandwidths (from 20-70 Hz) (Bullier et al., 1994; Hawken & Shapley, 1991; Hubel & Wiesel, 1959; Levitt et al., 1994; Gur & Snodderly, 1997; Steriade et al., 1996; Tallon-Baudry et al., 1997), we hypothesized that oscillatory

stimulus activity should generate processing states closely resembling those generated by internal synchronizing mechanisms (Gray et al., 1990; Singer, 1994). Given a relationship between synchronized neural oscillations in early visuo-cortical areas and psychophysical binding operations, our specific assumption was that, under appropriate presentation frequency conditions, the temporal pattern of stimuli presented would entrain neural systems coding those stimuli.

Methodological Considerations. The following four considerations ((i) to (iv)) determined the specific stimulus and task parameters realized in our experimental paradigm.

(i) There has been speculation (Crick & Koch, 1990) that binding by synchronous activation of neural assemblies is a result of attentional engagement. However, psychophysical investigations of object coding have identified a preattentive stage of feature binding involving low-level figural grouping processes (e.g. Duncan & Humphreys, 1989; Davis & Driver, 1994; Grossberg et al., 1994; Rensink & Enns, 1995). We expected these processes to be specifically sensitive to external frequency modulation within a time period leading up to the explicit detection of a target object within the visual field. A potential confound within this context might arise from the availability of response criteria based upon textural, boundary, or spatial stimulus characteristics. It has been noted (Fahle, 1993; Leonards et al., 1997) that these properties may compete with temporal stimulus characteristics and determine performance during tasks requiring target discrimination, obscuring any potential effects arising from the presence of relevant, temporally encoded visual information (Fahle & Koch, 1995; Keele et al., 1987; Kiper et al., 1997).

To avoid this confound, we employed a premask paradigm in which task-relevant information was embedded within an oscillating 3 x 3 matrix of premask crosses. This paradigm permitted presentation frequency to be manipulated independently of a task-relevant target display, while establishing a relationship between temporally coded premask information and the figural information presented within the target display. This relationship was determined by the temporal composition of the premask display: Premask crosses comprised four subsets the elements of which were presented simultaneously but asynchronously relative to the elements of other subsets (Fig. 1a). This design permitted two premask conditions to be defined, the 'synchronous' and 'random' conditions. In the synchronous condition, one subset of premask elements consisted of four crosses presented at the display locations subsequently occupied by corner junctions defining a target Kanizsa square. In the random condition, there was also one subset comprising four elements which were, however, presented in pseudo-random arrangement that did not correspond to a square.

(ii) A second consideration concerned the temporal stimulus parameters. The range of oscillatory frequencies observed in neurophysiological studies varies between 20 and 70 Hz. Accordingly, we assumed that feature binding processes might be sensitive to entrainer frequencies across the entire beta bandwidth. However, given the theoretical association of gamma bandwidth (35-50 Hz) oscillations with psychophysical binding operations, and in the light of evidence for stimulus-locked 30-60 Hz oscillations (Gur & Snodderly, 1997; see also Tallon-Baudry et al., 1997), we expected optimal frequency effects to be found within the narrower 30-50 Hz range.

(iii) The lower end of the range of premask frequencies was determined to preclude explicit awareness of critical (synchronous) premask structure. If observers became aware of synchronous premask structure, they might use this information as a cue to guide spatial attention to a potential target location in advance of target presentation. As a result, effects due to the formation of a pattern of temporal activity within object coding mechanisms might be confounded by spatial-attentional effects. Thus, to preclude awareness of premask structure, we conducted a pilot experiment with varying premask frequencies in order to determine the 75% threshold for detecting a synchronous premask (using an adaptive staircase procedure [Footnote 1]). There was a logarithmic decrease in detection performance with increasing presentation frequency (goodness of fit: $r^2 = 0.964$), with the 75% threshold corresponding to 21 Hz. Accordingly, we presented premask stimuli below this threshold, at frequencies within the range 25-100 Hz (see Fig. 1). In addition, premask presentation times (300, 600, 1200, 2400, and 4800 ms) were varied in consideration of the variability in electrophysiological estimates of the time required for beta and/or gamma-bandwidth oscillatory activity to become established (around 100 ms [Freiwald et al., 1995; Tallon-Baudry et al., 1996, 1997]; between 200 to 5000 ms [Eckhorn et al. 1994; Engel et al., 1990; Gray & Singer, 1989; Gray et al., 1990; Kreiter & Singer, 1992; Sillito et al., 1994; Tallon et al., 1995], including activity around the stimulus-bound P300 response [Bacar-Eroglu et al., 1996; Tallon-Baudry et al., 1996, 1997]).

The choice of target object and of the detection paradigm was based on three related findings: The simple form conjunctions defining Kanizsa figures are represented prior to attentional allocation, and in parallel across the visual field (Donnelly et al., 1991); the process of Kanizsa figure perception is associated with both diffuse and local cortical gamma band (30-40 Hz) EEG activity (Tallon et al., 1995); and discerning a target amongst distracters is associated with early (95 ms post-stimulus) phase-locked EEG activity (35 Hz at occipital sites) (Tallon-Baudry et al., 1997). Accordingly, we presented Kanizsa squares as target figures within a matrix of corner junctions that were arranged to preclude any incidental figural grouping and, thus, functioned as distracters. The ‘goodness’ of the Kanizsa figure was weakened, by reducing the length of the inducers, in order to encourage a response based on the temporally coded, synchronous, prime. The reduction in inducer element size produced a Kanizsa square which, according to recent formulations (Shipley & Kelman, 1992), represents a ‘good square’ with less than .1 probability. It was anticipated that the synchronous premask, oscillating under conditions comparable to those engaged during neural feature binding processes, would facilitate the co-activation of task-relevant feature-coding neurons. In this way, by virtue of oscillation frequency, the synchronous premask would effectively prime the same neural system subsequently engaged during the representation of the target display, providing a basis for figural grouping and further response-related processes.

Experiment 1

In experiment 1, 21 practiced observers (nine male, including both authors; mean age 27.6 years; all with normal or corrected-to-normal vision) performed 2240 trials presented over 4 sessions, each consisting of 10 blocks of 56 trials (with the first 2 trials in each block serving as unrecorded warm-up trials). The target (absent vs. present), synchronicity (synchronous vs. random), and oscillation frequency conditions (Fig. 1) were varied randomly within each trial block, while premask presentation time was kept constant within a given block but varied randomly across blocks. Observers responded as rapidly and accurately as possible to the presence or absence of a target. Their RT (in ms) and error status were recorded, with erroneous responses signaled to observers by computer generated tone. [Footnote 2]

Figure 2 about here

Figure 2 presents the mean correct RTs (and their associated standard errors, SE Mean) as a function of premask oscillation frequency, separately for the synchronicity (synchronous, random) x target (present, absent) conditions. Figure 2 suggests that there are synchronicity effects which are, however, confined to target-present responses under 25 and 40 Hz conditions. RTs were examined by means of a four-way analysis of variance (ANOVA) with main terms for synchronicity (synchronous, random), target (present, absent), premask oscillation frequency (25, 29, 33, 40, 50, 67, 100 Hz), and premask presentation time (300, 600, 1200, 2400, 4800 ms). Besides a significant main effect of target ($F(1,20) = 89.64, p < .001$), this ANOVA revealed significant main effects of premask frequency ($F(6,120) = 7.23, p$

< .001) and presentation time ($F(1,20) = 47.21, p < .001$), as well as interactions between synchronicity and target ($F(1,20) = 9.42, p < .006$) and synchronicity and frequency ($F(6,120) = 3.99, p < .001$). The synchronicity main effect was not significant ($F(1,20) = 1.48$), nor were there any other interactions involving synchronicity.

Target-absent RTs were slower than target-present RTs (660 vs. 593 ms), which reflects additional display search under target-absent conditions. The synchronous condition produced faster RTs than the random condition on target-present trials (590 vs. 596 ms), but not on target-absent trials (661 vs. 659 ms) (synchronicity x target interaction). Furthermore, synchronicity effects were dependent on premask oscillation frequency (synchronicity x frequency interaction): A significant RT advantage for synchronous relative to random conditions was found only with 40 Hz premask presentation (simple main effect, $F(1,120) = 4.21, p < .05$; mean RT enhancement: 10 ms). There was also a tendency for an advantage with 25 Hz (simple main effect, $F(1,120) = 3.09, p < .10$; 8 ms), but not with any of the frequencies intermediate between 25 and 40 Hz and frequencies greater than 40 Hz.

Although the synchronicity x target x frequency interaction was not significant ($F(6,120) = 0.87$), follow-on ANOVAs conducted separately for the target-present and absent RTs revealed a significant synchronicity x frequency interaction only for target-present trials ($F(6,120) = 4.28, p < .001$; target-absent trials, $F(6,120) = 1.20$), with a significant synchronicity enhancement of target-present RTs at 40 Hz only (simple main effect, $F(1,20) = 4.37, p = 0.05$; mean RT enhancement: 17 ms). At 25 Hz, the small (13 ms) target-present RT advantage for synchronous relative to random trials was not even borderline-significant (simple main effect, $F(1,20) = 2.07, p >$

0.10), so that the tendency for a 25 Hz synchronicity enhancement in the overall ANOVA cannot be solely attributed to target-present RTs.

Experiment 1 showed no evidence of synchronicity effects at frequencies intermediate between 25 and 40 Hz, as well as frequencies greater than 40 Hz, so that the hypothesis of synchronicity effects across the entire gamma bandwidth can be rejected. The synchronicity enhancement at 40 Hz is consistent with the theory that mid-gamma band frequencies are instrumental for perceptual organization, though the unexpected finding of a small synchronicity enhancement at 25 Hz would be at odds with this. However, there are grounds for suggesting that the enhancement effects at 25 and 40 Hz are qualitatively different: (i) Relative to the 40 Hz effect, the 25 Hz effect was weaker overall and did not differ reliably between target-present and absent trials; (ii) it may have involved the use of response strategies based upon phenomenal awareness of the temporal premask structure.

Concerning point (i), although we made no specific prediction concerning a synchronicity effect on target-absent trials, at least three different hypotheses could logically be assumed. Hypothesis 1 is based on the assumption that synchronous premask elements in one quadrant engage spatial attention, acting similar to abrupt-onset cues (e.g., Yantis & Jonides, 1984). Accordingly, on target-absent trials, presentation of synchronous premask at one location would result in an additional RT cost, due to the need to disengage attention from the synchronous-premask location prior to search of other quadrants of the target display (e.g., Posner & Petersen, 1990). Alternatively, one could adopt the opposite Hypothesis 2, that presentation of a synchronous premask at one location would permit this location to be rejected more rapidly as containing a target, expediting search of the other locations. Consequently, there should be synchronicity enhancement for target-absent trials (though the effect

would be expected to be reduced/obscured relative to target-present trials since absent responses require elimination of target presence in all display quadrants). This hypothesis cannot be ruled out for the 25 Hz condition, in which there may indeed be some synchronicity enhancement of target-absent responses. Hypothesis 3 conceives of the synchronicity enhancement as a figural priming effect, i.e., an effect that is realized only if the neural system entrained by the synchronous premask is subsequently engaged in the coding of a good, target, figure. Thus, in the absence of a target following a synchronous premask in one quadrant, no priming would be realized, and all quadrants would be processed with equal efficiency. This hypothesis is completely consistent with the pattern of results obtained under 40 Hz conditions.

Taken together, the findings of experiment 1 suggest that, at 40 Hz, the synchronicity enhancement is target-specific, consistent with our hypothesis of frequency-specific priming (entrainment) of object-coding neural systems. In contrast, caution should be exercised in interpreting the 25 Hz enhancement effect as resulting (exclusively) from frequency-specific priming. One alternative explanation of the 25 Hz effect is that it is mediated by phenomenal awareness of the premask structure. Consistent with this, the 25 Hz enhancement took 300-600 ms premask presentation time to become apparent, whereas the 40 Hz enhancement was manifest at the shortest times (though this differential effect was not statistically significant). Thus, it appears that the premask has to cycle for some time at 25 Hz for its synchronous structure to become phenomenally available and strategically usable.

Experiment 2

Experiment 2 was designed to examine the potential role of phenomenal awareness of premask structure in the 25 Hz condition as opposed to the 40 Hz condition, by determining observers' sensitivity for discerning the presence/absence of synchronous elements in premask oscillating at either 25 or 40 Hz. Ten practiced observers (5 male; mean age 26.8 years; all with normal or corrected-to-normal vision) performed 480 trials in one experimental session. The stimulus displays were similar to those presented in the threshold determination experiment (see Footnote 1), except that only 25 and 40 Hz premask conditions were used and the premask presentation time was fixed at 2400 ms. Premask oscillation frequency was kept constant during blocks of 48 trials and varied randomly across blocks, while the synchronicity (synchronous vs. random) conditions were varied randomly within a given block. After the final display frame (non-grouping 90° corner junctions), observers had to indicate, with confidence, whether the premask display contained a quadrant of synchronous crosses or not (response alternatives: certain-present, uncertain-present, uncertain-absent, certain-absent).

Table 1 about here

Each observer produced 240 rated synchronous/random-premask judgments for both 25 and 40 Hz conditions, from which the signal detection sensitivity parameter A_z was derived, using the maximum-likelihood estimation procedure for rating method data developed by Dorfman and Alf (1969) (A_z is a measure of signal detection sensitivity equivalent to the area under the receiver operating characteristic

curve, ranging between 0.5, chance performance, and 1.0, perfect performance). Table 1 gives the A_z parameters for each observer, along with their associated variabilities estimated by the maximum likelihood procedure. A planned t-test revealed sensitivity to premask structure to be significantly greater in the 25 Hz condition than in the 40 Hz condition ($t(9) = 6.06$, $p < .001$), with mean sensitivity above chance when premask oscillated at 25 Hz ($A_z = .687$, $SE = .034$), but approximately at chance for 40 Hz ($A_z = .528$, $SE = .018$). The 95%, 99% and 99.9% confidence intervals were calculated for all observer scores (based on the variability estimates), to examine whether individual observers' A_z values were significantly above chance (see Table 1 for significant values). For 8 of the 10 observers, synchronous premask detection was significantly better than chance when premask oscillated at 25 Hz (with five observers detecting synchronous premask on the majority of trials). In contrast, at 40 Hz, sensitivity was above chance for only 2 of the 10 observers. These differential signal detection effects support the hypothesis that, in experiment 1, task performance may have been influenced by the explicit perceptual availability of synchronous premask structure at 25 Hz, but not at 40 Hz. In other words, the 25 Hz RT enhancement effect may result from strategic processes involving the allocation of spatial attention. In contrast, the lack of phenomenal awareness under 40 Hz conditions proscribes interpretation in these terms and supports the hypothesis that the 40 Hz synchronicity effect is a specific measure of preattentive binding operations.

Experiment 3

Experiment 3 was designed to test the spatial-attention account of synchronicity enhancement (see Hypothesis 1, Experiment 1, above) under 25 and 40 Hz frequency conditions. Frequency was a between-subject factor to preclude carry-over of response strategies (criterion contents) developed in one frequency condition to the other condition. Experiment 3 employed an RT paradigm similar to that used in experiment 1, except that synchronous premask crosses could also appear in a non-identical quadrant to that of the subsequent Kanizsa square; this condition will be referred to as ‘mislocated-synchronous’ condition. According to the spatial-attention account, if attention is oriented to a nontarget quadrant in the mislocated-synchronous condition, this should produce an RT cost relative to the random premask condition, reflecting the need to redeploy attention from the nontarget to the target quadrant in order to discern the presence of the Kanizsa square. A group of 20 practiced observers participated in the 40 Hz condition (9 male; mean age 25.4 years), and a group of 17 observers in the 25 Hz condition (7 male; mean age 26.2 years) (all with normal or corrected-to-normal vision). The 40 Hz group performed 2560 trials over four separate sessions of 640 trials each. The 25 Hz group performed 1600 trials over four sessions of 400 trials (the trial number was reduced by reducing the number of random premask oscillation trials relative to the 40 Hz sessions). The stimulus parameters were identical to those used in experiment 1, except that premask presentation time varied between 300 and 2400 ms. The crucial difference to experiment 1 was that, in experiment 3, the synchronous premask quadrant was systematically varied relative to the target quadrant: quadrants were either identical (synchronous condition) or non-identical (mislocated-synchronous condition). A

random premask condition was also included as a baseline. Premask presentation time was kept constant during 40 trial blocks and varied randomly across blocks, while the target (absent, present) and spatio-temporal premask arrangement (present trials: synchronous, mislocated-synchronous, random) conditions were varied randomly within each block.

Figure 3 about here

The data of experiment 3 were examined in two stages: analysis of target-present data only (three-way ANOVA with main terms of frequency [25, 40 Hz], synchronicity [synchronous, mislocated-synchronous, random], and premask presentation time [300, 600, 1200, 2400 ms]), and analysis of corresponding target-present and absent data (four-way ANOVA with an additional main term for target [present, absent], excluding the mislocated-synchronous condition which was logically impossible for target-absent trials).

Figure 3a graphs target-present RT as a function of synchronicity, separately for the 25 and 40 Hz conditions. The ANOVA of the target-present data revealed the main effect of synchronicity to be significant ($F(2,70) = 20.72, p < .001$), but not the synchronicity x frequency interaction ($F(2,70) = .03$) (further, there was a significant main effect of presentation time, $F(3,105) = 27.32, p < .001$). In both frequency conditions, RTs were significantly enhanced for synchronous trials relative to both mislocated-synchronous and random trials (planned t-tests conducted separately for the 25 and 40 Hz conditions: 25 Hz, $t(16) = 5.75$ and $4.70, p < .001$; 40 Hz, $t(19) = 7.08$ and $5.79, p < .001$). However, for neither frequency condition were the mislocated-synchronous condition RTs slower than the random condition RTs (25 Hz,

480 vs. 479 ms; 40 Hz, 531 vs. 530 ms). Experiment 3, thus, confirms the existence of synchronicity enhancement effects at 40 Hz and at 25 Hz (replicating experiment 1). Furthermore, the absence of mislocation costs (relative to the random conditions) in experiment 3 provides evidence against the synchronicity enhancement being due to synchronous premask elements in a display quadrant engaging spatial attention, in either frequency condition.

Figure 3b graphs target-present and absent RTs as a function of premask oscillation frequency, separately for the synchronicity (synchronous, random) conditions. Besides a significant synchronicity main effect ($F(1,35) = 24.20$, $p < 0.001$), the second ANOVA revealed the synchronicity x target interaction to be significant ($F(1,35) = 13.54$, $p < 0.001$) (furthermore, there were significant main effects of target, $F(1,35) = 34.69$, $p < 0.001$, and of presentation time, $F(3,105) = 34.69$, $p < 0.001$). Although the synchronicity x frequency x target interaction was not significant ($F(1,35) = 0.99$), there was evidence of differential synchronicity enhancement effects on target-present and absent trials between the two frequency conditions, as already observed in experiment 1. In the 40 Hz condition, enhancement was manifest only on target-present trials (a separate ANOVA of the 40 Hz condition revealed the synchronicity x target interaction to be significant, $F(1,19) = 23.23$, $p < 0.0005$). In contrast, the 25 Hz condition showed evidence of enhancement on both target-present and absent trials (15 and 5 ms, respectively), with no reliable difference between the target-present and absent effects (an ANOVA failed to reveal a significant synchronicity x target interaction, $F(1,16) = 2.11$, $p > 0.10$). Thus, experiment 3 replicates the results of experiment 1, which also exhibited differential synchronicity x target interactions between the 40 and 25 Hz conditions (40 Hz, $F(1,20) = 7.14$, $p < 0.015$; 25 Hz, $F(1,20) = 3.03$, $p > 0.08$).

The finding of a small enhancement for target-absent RTs under the 25 Hz condition (experiments 1 and 3), together with above-chance sensitivity to the temporal premask structure (experiment 2), is consistent with the idea that strategic deployment of processing resources (attention) plays a role in producing the synchronicity at 25 Hz (though without the resource deployment involving the engagement, disengagement, and shifting of spatial attention). Preferential resource deployment to the quadrant of the synchronous elements may facilitate rejection of this quadrant as not containing a target, thereby speeding up target-absent responses under synchronous relative to random conditions, in line with Hypothesis 2 above. In contrast, the 40 Hz data are consistent with Hypothesis 3 above, according to which the synchronicity enhancement is a priming effect reflecting the entrainment of object coding mechanisms that are engaged only when the prime is followed by a target figure.

Discussion

In summary, we have demonstrated that (i) the visual system is sensitive to the presence of externally modulated, synchronous information within a premask display, but that (ii) the temporal premask patterning has a facilitatory effect on preattentive target detection only under specific 40 Hz conditions. Under 40 Hz conditions, there is no confounding phenomenal awareness of the premask structure (experiment 2) and no evidence of a role for strategic allocation of processing resources (experiments 1 and 3). By implication, we propose that the RT advantage for synchronous 40 Hz premask presentation results from the frequency-specific priming of neural mechanisms in early stages of visual processing.

An important question concerns how the synchronicity advantage observed in the present study is actually generated. There are two possibilities (which are not mutually exclusive): featural or figural priming. According to the first possibility, the four premask crosses, oscillating in synchrony at 40 Hz, locally entrain the feature-coding mechanisms responsible for detection of the subsequently presented Kanizsa square. Detection of the target figure requires the collinearity grouping of local inducer elements (Donnelly et al., 1991), for which synchronization of aligned feature detectors is presumed to be important. Given both the specificity and homogeneity of external stimulus oscillations and internal oscillatory activity, the 40 Hz synchronicity enhancement may be taken to reflect the fact that relevant feature-coding mechanisms become temporally co-activated and, thus, primed for subsequent Kanizsa figure detection.

Alternatively, since it is the whole premask display, rather than simply the synchronous premask quadrant, which is presented at 40 Hz, synchronicity priming may reflect the operation of preattentive processes that segment the synchronous-elements (quadrant) from the remainder of the premask display as a function of 40 Hz entrainment. This is consistent with the notion of temporal-binding as advocated by von der Malsburg (1981), who linked synchronized neural oscillations with the low-level (preattentive) organization of the perceptual field by figure-ground segmentation processes. Accordingly, since the local, oscillatory neural activity entrained by the temporal premask structure becomes globally synchronized across the four simultaneous crosses, the synchronicity effect may be best described in terms of the priming of processes that segment the target from background elements. The results of experiments 1 and 3 characterize the 40 Hz synchronicity priming as conditional in the sense that it produces a facilitatory effect only on trials on which a target appears

in the final display. This suggests that the pattern of activity generated by a synchronous prime itself possesses weak, if any, figural definition. Instead, it subsequently expedites target figure formation and later object-recognition processes (e.g. Fujita et al., 1992; Chelazzi et al., 1993).

In conclusion, our experiments demonstrate more efficient perceptual organization through the co-activation of preattentive binding mechanisms, achieved through specific entrainment under 40 Hz oscillation conditions.

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Tables

Table 1

Individual Observers' A_z Sensitivity Scores (and their associated variance) for each Presentation Frequency Condition in Experiment 2

Observer	25 Hz		40 Hz	
	A_z	var(A_z)	A_z	var(A_z)
Mae	0.738***	0.00124	0.542	0.00155
Jcw	0.562	0.00149	0.485	0.00155
Rog	0.689***	0.00169	0.521	0.00152
Jxk	0.808***	0.00084	0.540	0.00153
Tfw	0.772***	0.00099	0.477	0.00154
Myp	0.794***	0.00090	0.628***	0.00139
Amd	0.538	0.00200	0.505	0.00196
Sak	0.783***	0.00096	0.590*	0.00157
Vac	0.567*	0.00096	0.428	0.00155
Amc	0.616*	0.00223	0.543	0.00257

Note: A_z scores significantly above chance performance are marked by * ($p < 0.05$) or *** ($p < 0.001$)

Footnotes

Note 1. Pilot experiment: For 16 practiced observers (8 male; mean age 25.6 years; all with normal or corrected-to-normal vision; informed consent given), the 75%-threshold for discerning the presence of a synchronous premask within the oscillating premask matrix was determined using an adaptive staircase procedure (Findlay, 1978). The oscillating premask crosses were presented for a fixed time of 1200 ms and then reduced to a final display frame of non-grouping 90° corner junctions (corresponding to a target-absent display in experiment 1). Observers had to indicate, as accurately as possible, whether the premask matrix contained synchronous elements (in one quadrant) or random elements. The starting premask oscillation frequency, from which parameter estimation proceeded, was set at 4 Hz. At this frequency, all observers reported phenomenal awareness of the synchronous premask. For each observer, independent threshold estimates were obtained on two separate days and found to be stable across sessions.

Note 2. For each experiment, stimulus image frames were generated by an IBM-PC compatible computer and stored in an 8 Mb point-plotter buffer. Image frames were presented on a Tektronix 608 oscilloscope monitor equipped with a very fast-decay P15 phosphor. All frame elements were arranged around the center of the screen, and observers viewed the monitor at a distance of 57 cm (maintained via a chin rest). Experiments were conducted in a dimly lit room (mean screen surround luminance 0.078 cd/m²), with stimulus luminance maintained at 0.3 cd/m² upon a background field of 0.075 cd/m².

Figure captions

Figure 1. (a) Example sequences of the four pre-mask subset frames in the synchronous and random conditions. Premask oscillation frequencies (25, 29, 33, 40, 50, 67 and 100 Hz) were defined as the frequency of occurrence of pre-mask subsets per second. For example, in the 40 Hz condition, the entire premask matrix was presented as 10 times the 4 pre-mask subsets per 1000 milliseconds (ms), with a constant subset exposure duration of 25 ms and < 1 ms inter-subset interval. In this way and for all conditions, the premask sequence was continually ‘recycled’ during the lead time to target display onset. This produced the effect of a flickering display of nine crosses (b). The 3 x 3 matrix of premask elements subtended $7^{\circ}51'$ x $7^{\circ}51'$ of visual angle. Premask elements were crosses of size $51'$ and were separated from their nearest horizontal and vertical neighbors by $2^{\circ}39'$. Junction elements in the target display subtended $26'$ of visual angle and were separated horizontally and vertically by between $2^{\circ}39'$ - $3^{\circ}30'$.

Figure 2. Mean correct target-present and absent RTs (\pm SE Mean) for the synchronous and random premask conditions as a function of premask oscillation frequency (data collapsed across premask presentation times). Square and triangle symbols represent target-present and absent conditions, respectively; unfilled and filled symbols represent synchronous and random premask conditions, respectively.

Figure 3. (a) Mean correct target-present RTs (\pm SE Mean) for 25 Hz and 40 Hz premask oscillation frequency as a function of synchronicity. The symbols “S”, “M” and “R” represent synchronous, mislocated synchronous and random premask

conditions respectively. (b) Mean correct RTs (\pm SE Mean) for 25 Hz and 40 Hz premask oscillation frequency as a function of premask presentation frequency. Square and triangle symbols represent target-present and absent conditions, respectively; unfilled and filled symbols represent synchronous and random premask conditions, respectively.

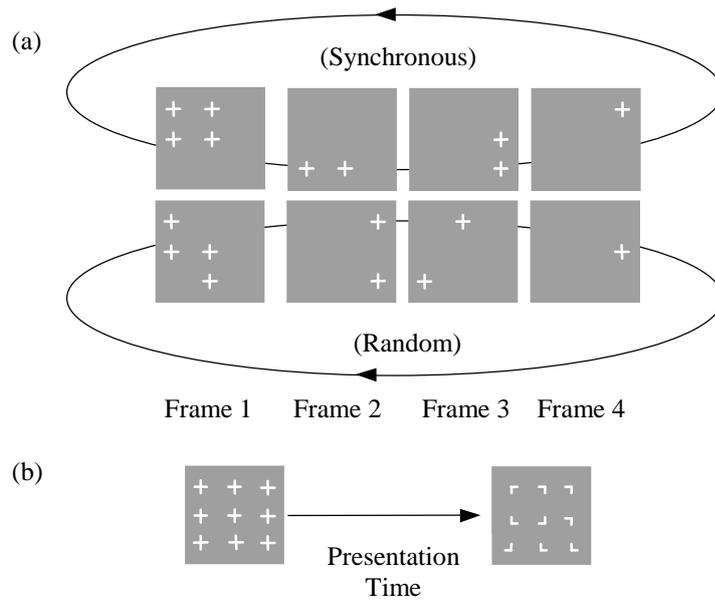


Figure 1.

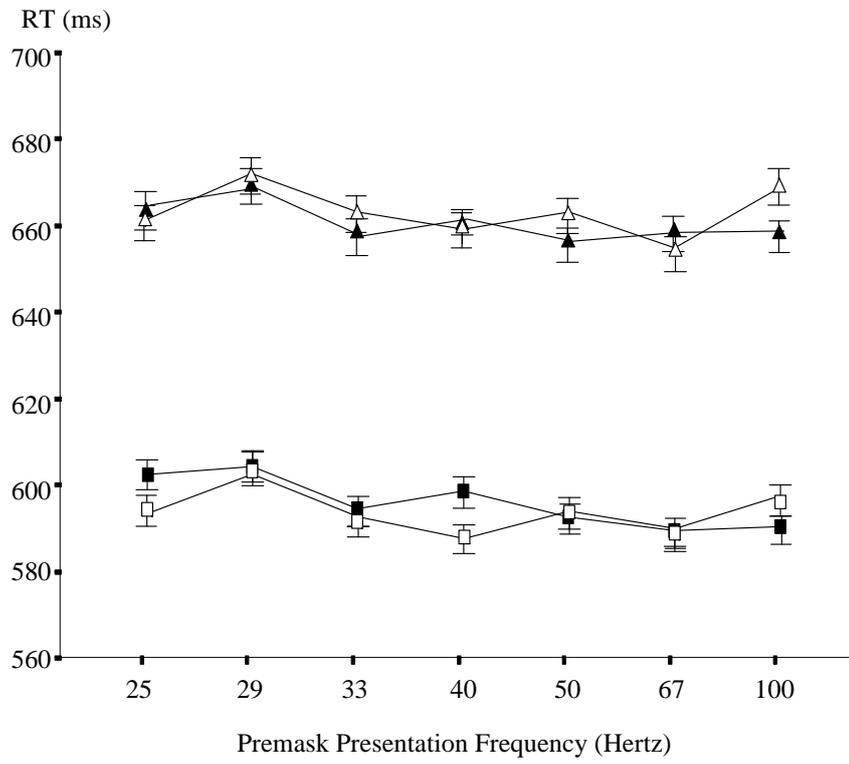


Figure 2.

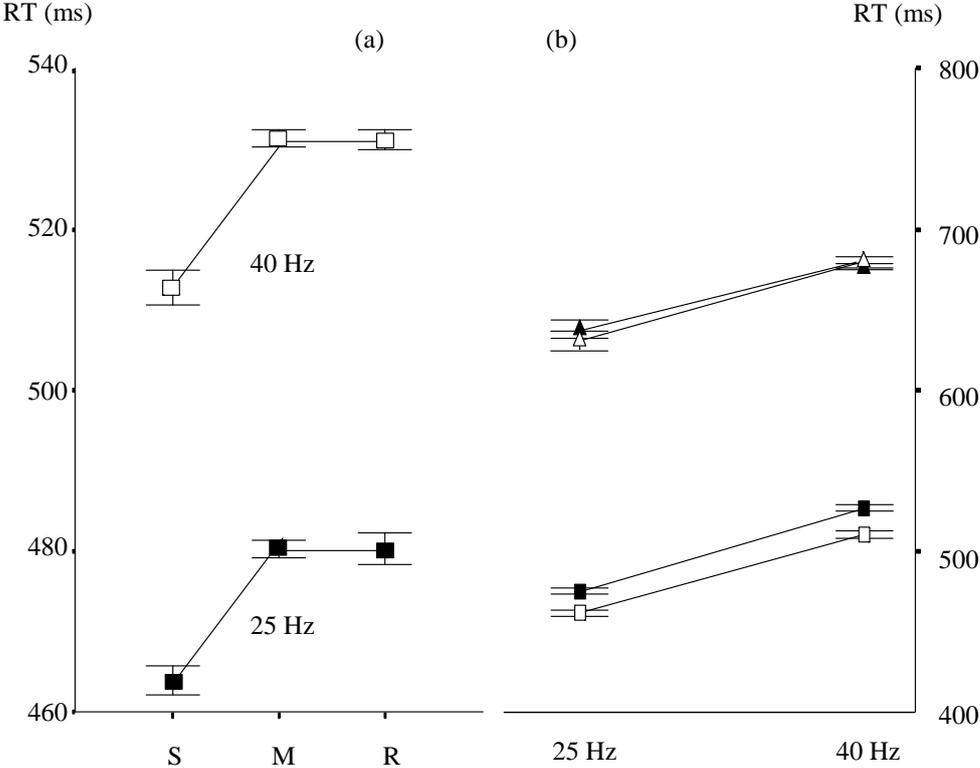


Figure 3.