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## The effects of subthreshold synchrony on the perception of simultaneity

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**Abstract** We aimed to examine the effects of subthreshold synchrony and asynchrony on the perception of simultaneity. We rendered simultaneous or asynchronous luminance changes below detection thresholds by embedding them in a sequence of rapidly onsetting flankers. Still, simultaneity of subthreshold luminance changes can influence decisions concerning the simultaneity of clearly visible changes in luminance: across a range of very brief target SOAs, subthreshold synchrony was found to increase the tendency to report 'simultaneity', although simultaneity thresholds themselves remained largely uninfluenced. These effects are discussed in terms of the early synchronization of sensory mechanisms and the extent to which this pattern of synchronization influences the perception of relations between events in time.

to be simultaneous for inter-flash intervals within the range 1–5 ms and only subsequently yield the perception of successiveness (in this case of apparent motion, see Sweet, 1953; Westheimer & McKee, 1977; Wehrhahn & Rapf, 1992). Other estimates suggest maximum intervals for the perception of simultaneity and, by extension, minimum time differences in temporal order discrimination (with attendant motion perception) for intervals of up to 17 and 44 ms (Exner, 1875). Considering invariances, a common measure that extends across sensory modalities seems to be the minimum time required for temporal order discrimination following the successive presentation of more than two stimuli. For tactile and visual stimuli and irrespective of the precise structure of the visual stimuli concerned, simultaneity thresholds have been determined with remarkably little variation: Brecher (1932) showed what he referred to as units of 'subjective time' corresponded to average periods of 55.3 ms for tactile stimulation and periods of 56.9 ms for visual stimulation, with standard deviations of no greater than 1.4 ms.

### Introduction

Even though two stimuli are presented at different times for very brief intervals they may appear to be presented simultaneously. Minimum estimates of simultaneity perception concern spatially separate flashes or lines presented in close spatial proximity. These are perceived

We sought to investigate how exposure to stimuli, for which simultaneous or asynchronous changes were not detected by observers, influences a subsequent judgment of simultaneity for stimuli presented either simultaneously or with small stimulus-onset asynchronies (SOAs). Our investigations were premised on two sets of previous discoveries. First, that subthreshold stimuli can activate responses directly and without mediation via conscious perception has been shown by a series of masked priming studies (e.g., Klotz & Neumann, 1999; Vorberg, Mattler, Heinecke, Schmidt, & Schwarzbach, 2003). A second set of studies has shown perception to be influenced directly by the timing of subthreshold stimuli. More specifically, these findings have shown that the coding of spatial grouping is expedited following the prior presentation of rapidly repeating premask elements in the same phase of a multi-element and multiphase presentation matrix (Elliott & Müller, 1998, 2000, 2001). In these studies, the premask elements, which were divided across a number of presentation

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phases, were presented repeatedly and at high frequency such that the precise temporal relations between the elements could not be determined by observers (Elliott & Müller, 1998, Experiment 2). Reaction times (RTs) to subsequently presented target groupings were faster if target elements were preceded at their locations by temporally synchronized premask elements relative to identical targets preceded by premask elements that were divided across two or more presentation phases. These studies lead us to believe that it is, in principle, possible to assess the extent to which judgments of the simultaneity or asynchrony of fully visible stimuli are influenced by the synchrony or asynchrony of stimuli presented below detection thresholds. The particular question we sought to address was whether subthreshold synchrony ( $SB_S$ ) or asynchronies ( $SB_A$ ) would bring about a shift in the threshold for perceptual simultaneity.

In the first of two experiments, we established the simultaneity thresholds for a pair of vertical bars presented to observers either simultaneously or with very small SOAs. These data provided a benchmark for the data collected in a second experiment within which two vertical bars again increased in luminance either simultaneously or over a small range of SOAs but with luminance increments rendered below detection thresholds by the serialized presentation of a number of flanking bars. In Experiment 2, the subthreshold luminance change was followed by a second change in luminance to which observers reported whether the two bars changed luminance simultaneously or with an asynchrony. Relative to the first experiment within which simultaneity thresholds were found at around 36 ms, in the second experiment, simultaneity thresholds were increased and, irrespective of the presentation of  $SB_S$  or  $SB_A$ , were near identical at 59 and 63 ms. However, simultaneity reports were increased in frequency for targets preceded by  $SB_S$  relative to  $SB_A$  but only across a small range of SOAs between 0 and 28 ms. Simultaneity reports deviated from an optimum reportage for pure simultaneity between 0 and (14–21) ms.

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## Experiment 1

### Methods

The purpose of Experiment 1 was to estimate the simultaneity threshold for two vertical bars presented simultaneously or in rapid succession.

### Observers

Fourteen observers (12 females, mean age 29.9 years) participated in the experiment. All observers had normal or corrected-to-normal vision. Participants were provided with written instructions and were paid €8.00 per hour or received course credit.

### Apparatus and stimuli

All stimuli and the experimental procedure were produced by custom software driving a Cambridge Research Systems VSG 2/3 graphics card, installed in an IBM-compatible PC running Windows 98. Stimuli were presented on a Sony GDM-F520 (21 in.) monitor with the refresh rate set to 140 Hz. Stimuli consisted of two vertical gray bars which increased in luminance for 40 ms and then decreased to background luminance in the following 40 ms. Luminance changes were Gaussian-enveloped to remove stimulus transients and ranged from a background of  $0.06 \text{ cd/m}^2$  to a peak luminance of  $14.4 \text{ cd/m}^2$ . The two bars were presented at various SOAs in the range 0 ms (i.e., simultaneously) to 99.96 ms and were separated by  $13^\circ$  of visual angle at a viewing distance of 100 cm. Each bar subtended  $3^\circ \times 10^\circ$  of visual angle. Stimulus presentation occurred in an environment of low intensity, ambient light ( $0.1 \text{ cd/m}^2$ ) to reduce the impact of onscreen persistence.

### Design and procedure

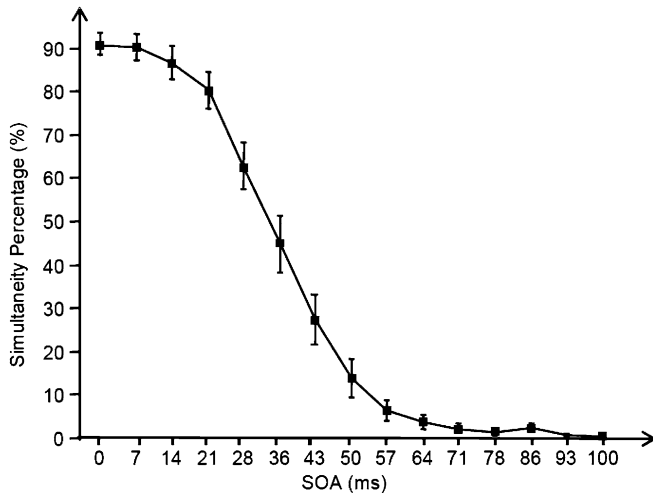
The apparent simultaneity of the bars was measured by means of two-alternative forced-choice task in which observers were asked to indicate whether the ‘two bars appeared simultaneously’ or whether the ‘two bars appeared asynchronously’. Observers were asked to fixate on the centrally located fixation cross and to avoid eye movements or blinks during the experimental trials. In each trial, the stimulus was preceded with a 500 ms fixation cross followed by a random interval of 50–150 ms. After this interval, the first bar was presented (either to the left or right with location counterbalanced in pseudo-randomized sequences) followed by the presentation of the second bar at an SOA of 0–99.96 ms. (Naturally if the second bar appeared at an SOA of 0 ms both bars were presented at the same time.) Observers were asked to make their response using a two-key keypad as accurately as possible following the disappearance of the two bars. The trials were separated by a 2 s inter-trial interval. Participants completed one 60-trial practice block and 15 experimental blocks of 60 trials per block.

Fifteen levels of SOA were examined at a resolution defined by the monitor refresh rate. This gave SOAs across the range  $1\text{--}15 \times 7.14 \text{ ms}$ . Each level of SOA was tested on 60 occasions with presentation order pseudo-randomized in advance of each session and on a session-wise basis.

### Results

The grand average of simultaneity reports yielded the psychometric function shown in Fig. 1.

Figure 1 reveals a less than perfect detection of simultaneity (the psychometric function never achieved



**Fig. 1** Mean psychometric function for 'simultaneity' responses across 15 levels of SOA in Experiment 1

a probability of 1.0 at the level of physical simultaneity). The commensurate reduction in accuracy at this point suggested a guess rate of around 9.2%. The simultaneity threshold was measured with the so-called "correction for guessing transformation" (see, e.g., Klein, 2001). Using this method the simultaneity threshold was located at an SOA of 36 ms with a standard deviation of 9 ms.

## Experiment 2

### Methods

Experiment 2 was conducted with the aim of examining whether or not subthreshold synchrony ( $SB_S$ ) and/or subthreshold asynchrony ( $SB_A$ ) influences judgments of perceptual simultaneity or asynchrony.

### Observers

Fourteen observers (12 females, mean age 29.9 years) participated in Experiment 2. Of these 14 observers, 13 were participants in Experiment 1. Participants were provided with written instructions and were paid €8.00 per hour or received course credit.

### Apparatus and stimuli

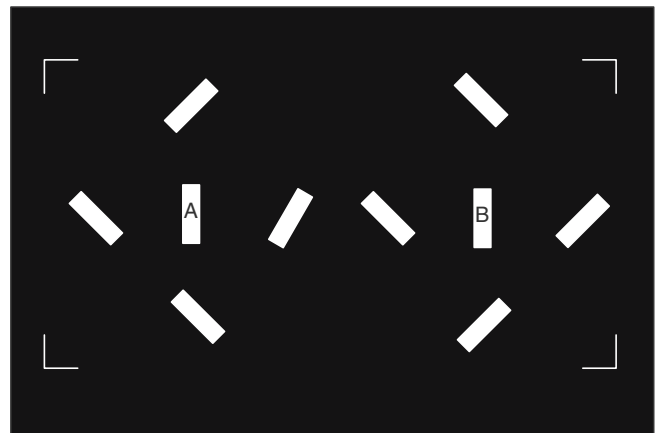
The apparatus was as used in Experiment 1 and the stimuli were almost identical. As in Experiment 1, two target bars were presented flanking the center of the monitor although in this case the targets did not switch on and then off but were present from trial onset and increased luminance twice during the trial. The first increase in luminance was masked to render it below detection thresholds while the second increase was akin

to the change in luminance in Experiment 1. It was to this second change that observers made their judgment of simultaneity or asynchrony. The major difference between Experiments 1 and 2 was the presence of an additional eight flanking bars (hereafter flankers) in Experiment 2. Each of the targets had a four-flanker mask designed to mask the first change in luminance. The flankers were separated by  $20^\circ$  of visual angle and were arranged to surround the two targets, appearing at horizontal angles of  $0^\circ$ ,  $90^\circ$ ,  $180^\circ$  and  $270^\circ$  relative to the targets. Each flanker was of the same size as the target but was oriented pseudo-randomly  $45^\circ$  to the left or right of the vertical meridian.

### Design and procedure

Experiment 2 was carried out in two parts. The first part was intended to determine the lower and upper simultaneity thresholds for increasing luminance (1) when flankers were absent (lower threshold) and (2) with presentation of the flankers (upper threshold). These thresholds were then used to circumscribe a range of subthreshold asynchronies in the second part of the experiment. All observers undertook both parts of Experiment 2 (Fig. 2).

The second part of Experiment 2 aimed to examine the effects of  $SB_S$  and  $SB_A$  on perceptual simultaneity/asynchrony. A stochastic approximation adaptive procedure was used to determine both lower and upper simultaneity thresholds after Treutwein (1995). Using



**Fig. 2** Schematic presentation display in Experiment 2. The task display is preceded by a dynamic version of the display illustrated here, to which the subjects do not respond. In the dynamic display the two central bars (here marked as 'A' and 'B'—there are no letters inside the bars in the experiment proper) change luminance amidst the serial on- and offset of eight flankers (bars rotated at  $45^\circ$  to the left or right of the vertical meridian) which surround the target bars. During the on- and offset of the flankers, the change in luminance of the target bars was rendered below detection thresholds. After the disappearance of the flankers the target bars increased luminance a second time at various SOAs. Observers were asked to report whether they perceive the second increase as a simultaneity or if the bars appeared to be asynchronous

this method, for each condition (i.e., with or without flankers) the adaptive procedure started with an initial threshold value which was assumed either from Experiment 1 (if the observer concerned was a subject in Experiment 1) or otherwise as a value of 40 ms. Following response and on a trial by trial basis a new target–target SOA was calculated using the following formula:

$$SOA_{n+1} = SOA_n \pm \frac{C}{T_n}, \quad (1)$$

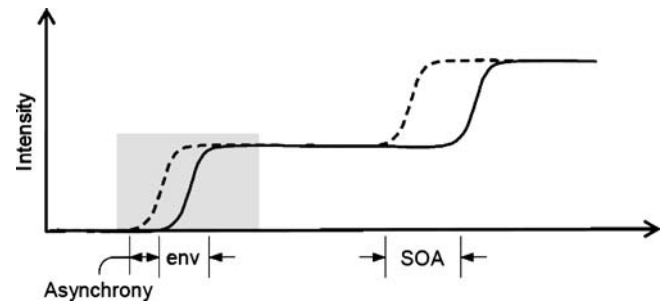
where  $C$  was a constant set as 20 ms and  $T_n$  was the number of reversals (i.e., the number of changes in response in the response sequence). When SOA reduced to below a single frame, i.e.,  $< 7.14$  ms, or when the number of reversals was greater than six the adaptive procedure stopped and the final SOA was taken as the estimated threshold.

To determine the lower simultaneity threshold, the task was identical to that in Experiment 1 except the increase in luminance was not accompanied by a corresponding decrease. Target luminance was modified by a 40 ms Gaussian envelope and increased from 0.06 to 14.4  $\text{cd}/\text{m}^2$ . Following this increase in luminance the targets remained on display at the same luminance for 2 s.

To determine the upper simultaneity threshold, the same procedure was employed with an identical task to that used in Experiment 1. The major change in this instance was that the targets were presented within the display of flankers described above. The presence of flankers was (correctly) assumed to increase simultaneity thresholds relative to the presentation of the target pair in isolation. In this design, stimulus presentation was initiated by presentation of a fixation frame for 500 ms. This consisted of four corner junctions and served to delimit a  $47^\circ \times 9^\circ$  rectangular region at the center of the monitor within which the experimental stimuli were presented. Following presentation of the fixation frame, a brief (500 ms) audio cue and then a randomly generated delay of 50–150 ms, two rapid sequences of four flankers were presented (the precise presentation order pseudo-randomly determined). As with the target stimuli in Experiment 1, the flankers increased luminance nonlinearly from a background luminance of 0.06  $\text{cd}/\text{m}^2$  to a peak luminance of 14.4  $\text{cd}/\text{m}^2$  and then decreased to background luminance within 80 ms. During the presentation of the flankers and within the center of each of the two flanker displays the luminance of the two targets was also increased nonlinearly from 0.06 to 14.4  $\text{cd}/\text{m}^2$  within a 40 ms interval. After increasing in luminance the targets did not decrease luminance and remained fully visible until the end of the trial. The targets were presented semi-independently of the sequences of flankers and at a pseudo-randomly determined interval of 50–100 ms from the onset of the first flanker to appear. The two targets either changed luminance simultaneously or with an SOA calculated from formula 1 described above.

In the second part of Experiment 2, targets changed luminance twice, once within the flanker display and a second time shortly after the flankers had disappeared. For the first luminance change the SOAs between the two targets were set at either 0 ms (i.e.,  $SB_S$ ) or within a range of SOAs ( $SB_A$ ) circumscribed by the lower and upper thresholds that were determined for each observer in the first part of Experiment 2. In this way targets could change luminance at intervals which did not descend below the intervals at which targets would ordinarily be perceived as simultaneous (given no flankers) and at the same time maintained at an upper level which was still below the detection threshold (given flankers). The second change in luminance mimicked the conditions used to determine the lower simultaneity threshold. The second change in luminance followed the first after an interval of 150 ms at which time the flankers had disappeared. The value of 150 ms was chosen because it lies outside the estimates of the minimum duration of perception (137 ms discussed in Efron, 1970a, b) and is thus designed to avoid any retroactive inheritance of a perceptual code upon concurrently active mechanisms maintaining  $SB_S$  or  $SB_A$ . The second luminance change corresponded to the change in luminance during estimation of the lower simultaneity thresholds, except that the target luminance was increased within a 40 ms Gaussian envelope from 14.4 to 29.8  $\text{cd}/\text{m}^2$ . The two target bars were presented with variable SOAs over the range 0 ms (i.e., simultaneously) to 107 ms and, after increasing luminance, remained constant and did not decrease in luminance for 2 s until the end of the trial. Observers were asked to estimate whether the change in luminance between the targets had occurred simultaneously or asynchronously (the procedure is illustrated in Fig. 3).

The second part of Experiment 2 required two sessions of 11 blocks comprising 64 trials per block. Presentation orders were fully pseudo-randomized on a



**Fig. 3** Time line indicating the sequence of target luminance changes in Experiment 2. The *dashed* and *solid* lines represent the luminance of the two target bars. The *gray region* represents the interval of time during which the dynamic presentation of flankers masked the first change in luminance. Following disappearance of the flankers the target bars remained on screen with the same luminance for 150 ms and then increased luminance a second time. Observers were asked to report whether they perceive the second increase as simultaneous or the *bars* as asynchronous

session by session basis taking into account the levels of target SOA (each level was presented on 88 occasions in Experiment 2), the values over the range of SOAs employed for the  $SB_A$  condition and the  $SB_S$  condition.

## Results

For all observers the lower simultaneity thresholds were reliably estimated as below the upper simultaneity thresholds: the range of lower simultaneity thresholds extended from 7.14 to 42.8 ms with the mean located at  $\sim 27$  ms (standard deviation 9 ms), while the upper simultaneity thresholds extended across the range 21.42–85.68 ms with the mean located at 44 ms (19 ms). Note that the  $\sim 9$  ms reduction in the lower simultaneity threshold relative to the threshold determined in Experiment 1 may very well represent a practice effect given that 12 of the 13 subjects had previously undertaken Experiment 1.

For Experiment 2, psychometric functions (PFs) were calculated individually and are presented only for the ‘simultaneity’ response given that there were no significant differences in either thresholds or the slopes of the PFs for asynchronous responses. A preliminary inspection of the data revealed a guess rate of around 20% which recommended correction. On this basis the individual data were submitted to the following probability-based correction:

$$P_{\text{adj}}(x) = \frac{P(x)}{P(0)}, \quad (2)$$

where  $P(0)$  is the percentage of ‘synchrony response’ for ‘subthreshold simultaneity’ (i.e., a subthreshold SOA = 0). The resulting average PF is shown in Fig. 4.

Thresholds were calculated individually by a method of interpolation which revealed average simultaneity thresholds of 63 ms (standard deviation = 19 ms) following exposure to  $SB_S$  and 59 ms (15 ms) following exposure to  $SB_A$ . These values were not significantly different from one another ( $t(11) = -1.21$ ,  $P > 0.1$ ).

Figure 4 reveals  $SB_S$  and  $SB_A$  to produce different patterns of effects only for targets increasing luminance over a very short range of SOAs (including physically simultaneous targets). Taking the data on face value there appears to be a slight increase in the tendency to make simultaneity judgments following exposure to  $SB_S$ , relative to simultaneity judgments following exposure to  $SB_A$ . In addition, and for presentations above threshold, there seems to be a decreasing tendency to report simultaneity when the targets were preceded by  $SB_S$ .

In order to examine the statistical evidence for these observations the interpolated values on the PFs for ‘simultaneity’ responses were examined for each SOA separately by means of pair-wise  $t$  tests. Values of  $t$  were found to be of some magnitude for brief SOAs in the range 0–28.56 ms ( $t = 3.05, 2.91, 1.80, 1.96, 2.09$  ms for SOAs of 0, 7, 14, 21, 29 ms, respectively) while for the

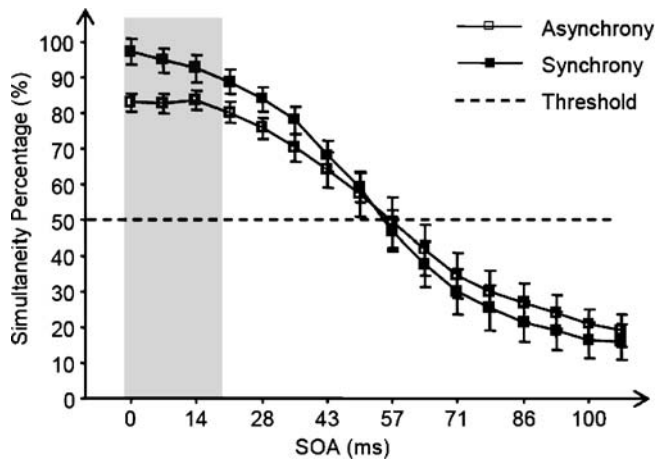
remaining SOAs the values of  $t$  were less than 1 and thus should be considered nonsignificant. In a second analysis the interpolated values on the different PFs following  $SB_S$  and  $SB_A$  were examined for the point of deviation from optimal performance (found in each case at SOAs of 0 ms, see Fig. 4). Pair-wise  $t$  tests revealed simultaneity reports to differ significantly from the optimum between (7–14) and 21 ms for the  $SB_S$  condition (descending values of  $t$  as a function of SOA were  $t = -0.97$  for SOAs of 7 ms,  $t = -1.8$  for SOAs of 14 ms while  $t \geq -2.43$  for SOAs of 21 ms and higher) and in the range 7–21 ms for the  $SB_A$  condition ( $t \leq -1.13$  for SOAs of 7–21 ms and  $t \leq -3.23$  for SOAs of 28 ms and higher). From these analyses it can be concluded that reports of simultaneity may be increased in frequency by prior exposure to  $SB_S$  and subject to a slight reduction in frequency following presentation of  $SB_A$ . This conclusion may be reached in consideration of the fact that the differences between simultaneity reports following  $SB_S$  relative to  $SB_A$  remain quite large for SOAs of up to 28 ms ( $t = 2.09$ ), even though for  $SB_S$ , simultaneity reports markedly reduce in frequency relative to the optimum at SOAs of (14–21) ms and higher.

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## Discussion

Both Experiments 1 and 2 show quite clearly that simultaneity thresholds vary according to precise presentation conditions: on the one hand, and in Experiment 1, a simple target pairing will be judged to onset simultaneously for intervals of up to 36 ms. Similarly, in the first part of Experiment 2 simultaneity thresholds for a single change in luminance (i.e., without a subsequent reduction to background levels) were found at 27 ms. The differences between these values may well represent a practice effect but they nonetheless indicate, in keeping with other findings, that simple simultaneity judgments break down for quite small separations in time. The final part of Experiment 2 reveals an average value for simultaneity thresholds (61 ms) in very close agreement with the value of 55.3 ms originally reported by Brecher (1932), an outcome not altogether surprising when it is considered that Experiment 2 used a design in which stimuli were repeatedly presented, in analogy with the conditions employed by Brecher to obtain his estimates of subjective time. Where the data presented here differ dramatically from that obtained by Brecher are in the standard error of the estimates: Brecher obtained his estimates from both visual and tactile modalities and reported standard errors of less than 2 ms. The errors reported here are of at least an order of magnitude greater than this, although the difference may be due to various unknowns such as differences in the amount of practice undertaken by observers or other experiment-wise effects.

When considered alongside the values reported by Brecher, the thresholds reported here are suggestive of a top-down influence on the perception of simultaneity.



**Fig. 4** The mean psychometric functions for ‘simultaneity’ responses in Experiment 2. The curve with filled squares represents subthreshold simultaneity condition, while the curve with unfilled squares represents subthreshold temporal asynchrony condition. The dashed line denotes threshold. The filled region denotes the range of SOAs for which the simultaneity response is significantly higher in the frequency following the presentation of a subthreshold synchrony ( $SB_S$ ) relative to the presentation of a subthreshold asynchrony ( $SB_A$ )

This conclusion arises chiefly because the thresholds reported by Brecher were approximately equivalent irrespective of the modality concerned and while it seems possible, it is also quite unlikely that information from visual, haptic (and also auditory) stimulation converges on some central mechanism responsible for order judgments with precisely the same latency. If it is reasonable to assume that sensory magnitudes are generally interpretable as a power function of linear changes in intensity, more complex nonlinearities may represent at least the modulatory effects of local mechanisms, if not that of central mechanisms. A further strand of evidence to suggest the influence of central modulation of sensory information comes from examination of the findings reported by von Békésy (1936).

Békésy, who measured the response to low-frequency sound in the cochlea, demonstrated sharp discontinuities of absolute threshold as a function of frequency. Local invariances, defined as those points in a descending method of limits where the stimulus became noticeable at the same critical frequency, occur for six different levels of intensity when sound periods are integer multiples of a period of 55.6 ms (Geissler & Kompass, 2001). Geissler and Kompass note the equivalence of this value with the values reported by Brecher, noting a qualitative similarity in that the period of  $\sim 55$  ms demarcates a boundary at which the perceived quality changes suddenly. In the case of Békésy’s stimuli the change represented a transition from pulsing stimuli to a pure tone. Clearly, this interpretation of Békésy’s data suggests peripheral mechanisms are modulated at an interval consistent with the centralized quantization of sensory information, and that this has a direct influence on the perceptual qualities attributed to the stimulus.

This then raises the question of how to interpret the modification introduced in this study, namely the outcome of influencing a simultaneity judgment by the prior presentation of  $SB_S$  or  $SB_A$ . On the one hand it would appear that simultaneity thresholds were not at all influenced by either. This would seem to entail that the timing of top-down modulation remains relatively unaffected although interestingly there are significant differences between the simultaneity psychometric functions associated with  $SB_S$  and  $SB_A$ . In addition, both psychometric functions differ quite substantially in shape to that obtained from judgments made to a simple target pairing. Variations in the shape of the psychometric functions suggest variation in the distribution of coding activity over the processes concerned, which may arise as a consequence of the introduction of top-down or recurrent modulation into an otherwise feedforward system. This possibility which cannot be resolved on the strength of the current data may be best addressed using EEG or similar measures. The increased frequency of simultaneous reports in the range 0–28 ms following  $SB_S$  relative to  $SB_A$  seems to represent a mutual divergence of the two functions (i.e., observers increase their frequency of simultaneity reportage following  $SB_S$  and decrease it following  $SB_A$ ). That enhanced simultaneity reportage (following  $SB_S$ ) is maintained for SOAs of 0–(14–21) ms is interesting in that this interval is very close to the maximum separation in time of discharges between synchronized neural activity in visual cortex (see, e.g., Gray, König, Engel, & Singer, 1989 for data and Singer, 1993 for review). It is argued that synchronizing the discharges of distributed neurons increase the probability that their activity crosses threshold at subsequent stages of processing. If it were assumed that corresponding areas of cortex become briefly synchronized by presentation of the subthreshold targets across the range of SOAs corresponding to the maximum intervals separating synchronizing action potentials, the subsequent synchronized assembly may result in an increased likelihood or bias to report simultaneity with no effect upon the processing time or latencies of the systems concerned. This conclusion may help resolve a long-standing issue concerning the relations of externally induced temporal codes and neuronal synchronization.

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