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

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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 stimulus-onset asynchronies, 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.

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 to be simultaneous for inter-flash intervals within the range 1-5 milliseconds (ms) and only subsequently yield the perception of successiveness (in this case of apparent motion, see Sweet, 1953; Westheimer & McKee, 1977). 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 ms 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 to 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.

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). 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. Full details of this study are given in Elliott, Shi & Sürer (2006).

### Methods

Observers: Fourteen observers (12 female, mean age: 29.9) participated in the experiment. All observers had normal or corrected to normal vision. Participants were provided with written instructions and were paid €(EURO) 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”) monitor which the refresh rate set to 140 Hz.

The target stimuli consisted of two vertical gray bars separated by  $13^\circ$  of visual angle at a viewing distance of 100 cm at which each bar subtended  $3^\circ \times 10^\circ$  of visual angle. Target bars increased luminance twice: The first increase (ranging from a background of  $0.06 \text{ cd/m}^2$  to a peak luminance of  $14.4 \text{ cd/m}^2$ ) was masked to render it below detection thresholds, while the second increase (ranging from  $14.4 \text{ cd/m}^2$  to  $29.8 \text{ cd/m}^2$ ) occurred in the absence of masking flankers. It was to the second increase that observers made their judgment of the simultaneity or asynchrony of the luminance increases between bars. Stimulus presentation occurred in an environment of low intensity, ambient light ( $0.1 \text{ cd/m}^2$ ) to reduce the impact of onscreen persistence. The mask took the form of 4 flanker bars of identical dimensions to the target bars separated by  $20^\circ$  of visual angle and arranged to surround and appear 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. The masking bars onset in pseudo-random order and temporally interleaved with the first change in target-bar luminance. The first change in target bar luminance occurred in two conditions; subthreshold synchrony ( $SB_S$ ) or asynchrony ( $SB_A$ ). In  $SB_S$  the two bars started to change luminance at the same time. In  $SB_A$  the two bars proceeded to change luminance at SOAs no lower than a previously determined simultaneity threshold for two bars presented in isolation and no higher than a previously determined simultaneity threshold in the presence of flankers. 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 detection threshold (given flankers).

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, for the second increase in luminance, the ‘two bars appeared simultaneously’ or whether ‘two bars appeared asynchronously’. No instructions or information was given concerning the first increase. 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 target display was preceded with a 500 ms fixation cross followed by a random interval of between 50 to 150 ms. After this interval, either a flanker or the first bar was presented (either to the left or right with location counterbalanced in pseudo-randomized sequences) followed by presentation of the second bar at an SOA of between 0 ms to 99.96 ms. (Naturally if the second bar appeared at an SOA of 0 ms both bars were presented at the same time). 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 of estimates of the minimum duration of a perception (137 ms discussed in Efron, 1970a 1970b) and is thus designed to avoid any retroactive inheritance of a perceptual code upon concurrently active mechanisms maintaining  $SB_S$  or  $SB_A$ . 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 seconds 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 experiment required 2 sessions of 11 blocks comprising 64 trials per block. Presentation orders were fully pseudo randomized on a session by session basis taking into account the levels of target SOA (each level was presented on 88 occasions), the values over the range of SOAs employed for the  $SB_A$  condition and the  $SB_S$  condition.

## Results

Psychometric functions (PFs) were calculated individually and are presented for the ‘simultaneity’ response only 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:

$$P_{adj}(x) = \frac{P(x)}{P(0)} \quad (1)$$

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

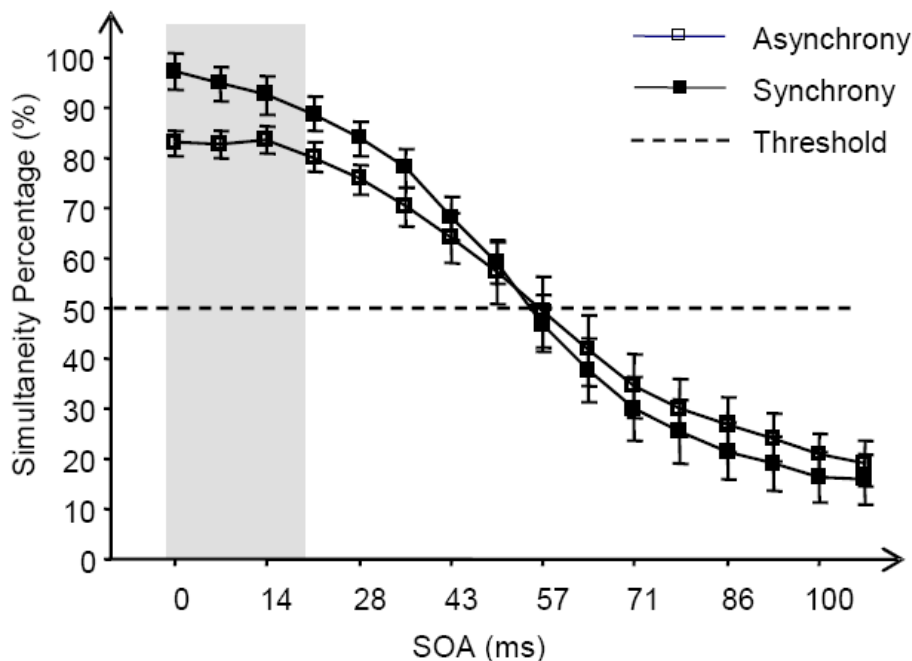


Figure: The mean psychometric functions for ‘simultaneity’ responses. The curve with filled squares represents subthreshold simultaneity condition, while the curve with unfilled squares represents subthreshold temporal asynchrony condition. The dashed line denotes threshold. The filled region denotes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

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 ( $t(11)=-1.21$ ,  $p>0.1$ ). From the Figure it can be seen that  $SB_S$  and  $SB_A$  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 ( $t=3.05, 2.91, 1.80, 1.96, 2.09$  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 the Figure). Pair-wise  $t$ -tests revealed simultaneity reports to differ significantly from the optimum at between (7 – 14) – 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  $t \geq -3.23$  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.

## Discussion

This experiment 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 the experiment used a design in which stimuli were repeatedly presented, in analogy with the conditions employed by Brecher to obtain his estimates of subjective time. When considered alongside the values reported by Brecher, the thresholds reported here are suggestive of a top-down influence on the perception of simultaneity. This conclusion arises chiefly because the thresholds reported by Brecher were approximately equivalent irrespective to 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.

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 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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