

Simultaneity constancy

Agnieszka Kopinska, Laurence R Harris

Centre for Vision Research, York University, Toronto, Ontario M3J 1P3, Canada;

e-mail: kopinska@yorku.ca

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Abstract. Sound and light take different amounts of time to reach their respective receptors, to be transduced, and to be transmitted to the cortex. Their processing times also vary with factors such as intensity and retinal eccentricity. We assessed the capability of subjects to perceive simultaneity correctly despite these variations. Temporal asynchronies of up to 200 ms were introduced between the components of sound/light pairs. Using the method of constant stimuli, seven subjects judged which came first. Distance, and hence the times of arrival of paired visual and auditory targets, was varied from 1 to 32 m. Visual intensity was varied by viewing the target through 1.8 dB attenuating glasses, and a retinal eccentricity of 20° was compared to central presentation. Despite large differences in reaction times, which varied in a predictable way with the stimulus parameters, the timing of sound/light pairings judged as simultaneous corresponded to when the light and sound left the source simultaneously. Almost complete compensation was found in all conditions tested, showing that these substantial but predictable variations in timing can be taken into account in creating simultaneity constancy.

1 Introduction

The process of judging the time at which things happen is not straightforward. There is always a delay between an external event and the first moment at which any neurons in the cortex can respond. The main sources of delay are: the time it takes the energy from the event to reach the neural sensors; the time for the transduction process; and the neural transmission time for the information to pass from the transducers to the central nervous system. Many factors can influence the timing of each of these steps and any two simultaneous stimuli will often differ in the timing of all three. The processing times of even the different parts of a single event might differ in the timing of these stages. Reconstructing the actual timing of an event, or its timing relative to another event, therefore involves making some allowance for these variable delays.

The differences in the three delays can be particularly pronounced if the comparison is between different senses. When looking at something that makes a noise, the sound and light take different times to reach the sensors (sound takes longer), have different transduction times (sound, being a mechanical stimulus, takes less time) and the information takes a different amount of time to reach the brain (the auditory nerve is physically shorter, Woolsey et al 2003). If observers are to identify correctly the timing of bimodal events, happening simultaneously in the world, they need to allow for all of these factors. Detecting simultaneity is an important task, as it indicates whether or not information should be bound together as an individual event (Vroomen et al 2001). In fact, we suggest that this is such a central feature of perception that mechanisms of perceptual constancy comparable to other constancies such as those that exist for size and colour (Walsh and Kulikowski 1998) have evolved. A perceptual constancy maintains some percepts as constant despite huge variations in the sensory information arriving at the receptors. We propose that one such mechanism exists to support simultaneity constancy, in which simultaneity is correctly perceived, despite huge variation in the timing of various aspects of the sensory process.

Light and sound have been reported to appear simultaneous, despite variations in their time of arrival at the receptors (Engel and Dougherty 1971; Sugita and Suzuki 2003). Perhaps the delay of sound transmission in the air fortuitously balances its speedier transduction and transmission. Or perhaps the phenomenon merely reflects insensitivity to a difference in the time of arrival. The former could only work for one distance and given the exquisite sensitivity of the auditory system to timing differences, the tolerance explanation seems unlikely. Having a large acceptance window for simultaneity would lead to an inability to distinguish between any pair of stimuli that happen to occur within that period. Therefore we postulate that the perception of simultaneity represents a form of perceptual constancy. Comparable to the way that invariant size is deduced from retinal information of varying dimensions, simultaneity constancy is deduced from varying temporal information. Achieving cross-modal simultaneity constancy, however, requires processing a formidable amount of information, including knowledge of physical constants such as the speed of sound.

To measure the extent of cross-modal simultaneity constancy, we presented subjects with sound/light pairs and introduced variable delays between the sound and light components. We varied the relative time for the sound and light to reach the sensors by presenting the stimuli at different distances, which affected only the time-of-arrival of the sound. We altered the relative neural processing times by dimming the visual stimulus or by viewing it eccentrically.

2 Methods

2.1 Participants

Seven subjects (two males, five females, 22–49 years old) participated in all the experiments. Two of them knew the scientific background of the study. The others were given only general information about the purpose of the study and were paid for their participation. All experiments were conducted in accordance with the ethics procedures of York University.

2.2 Stimuli

Visual and auditory stimuli were produced with a personal computer. The visual stimulus was a 4 cm diameter bright disc (77.9 cd m^{-2}) displayed on a black background (5.4 cd m^{-2}) for 50 ms on a VGA monitor. Sounds were unwrapped tone bursts of 3 kHz, of amplitude 67 dB measured at 1 m, and a duration of 50 ms presented through the computer's inbuilt speaker. The stimuli were always the same for all the conditions used in this study. No attempt was made to adjust the stimuli for different distances of viewing. For the simultaneity-judgment experiments, the delays of the sound relative to the light ranged from -200 ms to 200 ms in 25 ms steps. There were 16 repetitions for each time delay. The participants were seated in a well-illuminated corridor (ambient illumination: 110.9 m cd ; see figure 1) and viewed the monitor screen at 1, 4, 8, 16, 24, or 32 m. A chin-rest ensured their heads were pointing directly at the centre of the monitor. Participants were instructed to look either straight-ahead or at a marker on the wall at 20° to the right. Under some conditions, participants viewed the screen through red-tinted glasses that reduced light level by 1.8 dB. They removed the glasses approximately every 30 s to maintain normal light adaptation.

2.3 Procedure

To measure reaction times, subjects clicked a mouse button connected to the computer through a line driver, as soon as they detected either a sound or a light. Thirty sounds and lights were presented for each condition in a random order. Rather than using the highly subjective measure of asking people whether the stimuli components appeared simultaneous (Stone et al 2001) the point of simultaneity was inferred from temporal-order judgments which were collected by the method of constant stimuli. Sound/light



Figure 1. Photograph of the experimental setup. Subject sat with his/her head restrained, a known distance from the stimulus, in a corridor with textured floor, ceiling, and walls. The stimulus was presented on a computer screen and through the computer speaker that was positioned within a few inches of the screen.

pairings were presented with a delay between them. Participants indicated whether the sound or the light stimulus was first by pressing either the left or the right mouse button. For each subject the point of subjective equality was obtained from a psychometric function fitted to the number of times the sound was judged first in response to sound/light pairs with 1 of 11 delays between the onset of the flash and the onset of the sound. Delays varied in 25 ms steps from the light leading the sound by 200 ms to the sound leading the light by the same amount. All of these functions for the 32 m presentations are given in figure 5.

There were 272 trials (17 time delays with 16 repetitions for each delay). It took approximately 15 h for each subject to complete all the experiments. The experimental sessions were scheduled so as not to exceed 1 h and were run over several days. The experiments were presented in random order.

3 Results

3.1 *Variations with distance: reaction times*

The reaction times to a 3 kHz, 67 dB, 50 ms sound burst and a 50 ms flash of a 4 cm diameter, 78 cd m⁻² circle are shown in figure 2a as a function of the viewing distance. The increase in the reaction time to sound with distance can be largely attributed to the speed of sound. The increase expected from the time it took the sound to travel down the corridor is illustrated by the dashed line in figure 2a, which has a slope of 3 ms m⁻¹, the inverse of the speed of sound (343 m s⁻¹). The regression line through the data has a slope significantly steeper (4.1 ms m⁻¹, $t_{40} = 3.69$, $p < 0.001$). The reaction time to the 4 cm flashed circle also increased slightly with distance, although the function was not linear. As the distance increased from 1 to 32 m the reaction time to the flashed circle increased by about 30 ms. Visual and auditory reaction-time

functions crossed at the distance at which the reaction times to the two stimuli were equal. The point of equality for these particular stimuli occurred at 16 m (figure 2a).

3.2 Variations with distance: simultaneity

Simultaneity was inferred from temporal-order judgments of sound/light pairs with a variable delay between the light and the sound. The delay between the light and sound components of the sound/light pairs at which subjects could not tell which came first is shown as a function of viewing distance in figure 2b. Each point in the graph is an average of the judgments of the seven subjects.

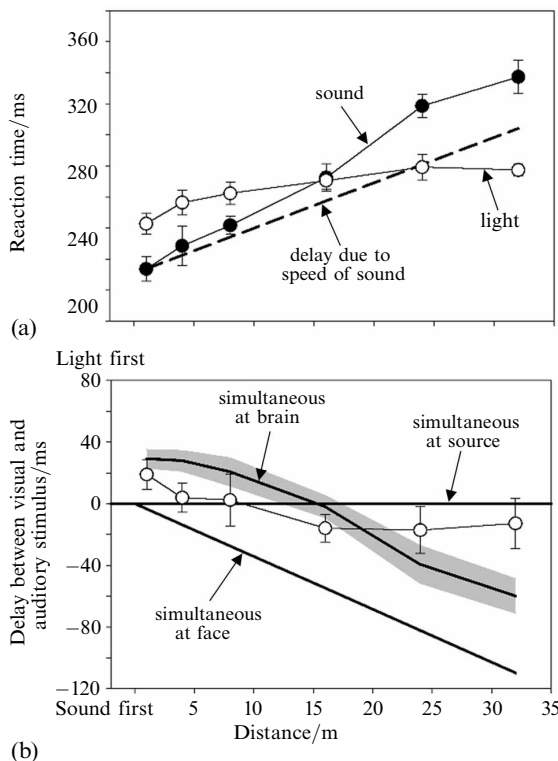


Figure 2. (a) Reaction times for light and sound targets viewed separately at different distances. Open circles are the reaction times to a 50 ms flash of a 4 cm circle; closed circles to a 50 ms beep of 3 kHz sounds. The dashed line indicates the increase in reaction time that would be due to the speed of sound alone. (b) The auditory/visual stimulus onset asynchrony that was perceived as simultaneous (open circles, + means light first) as a function of viewing distance. The thick lines represent three predictions. The line labelled 'simultaneous at face' indicates the amount of lead time a sound would need in order for it to arrive at the end organ simultaneously with light from the same target and is simply determined by the speed of sound. The curve labelled 'simultaneous at brain' is the difference in the two reaction time curves given in (a). The shaded area is derived from the standard errors of each reaction time curve. The line labelled 'simultaneous at source' corresponds to no change in stimulus onset time dependent on distance.

Superimposed on the delays at which subjects could not tell whether the light or sound came first, are three predictions of how such judgments of simultaneity might vary with viewing distance. If the delays needed simply balanced the difference in reaction times, then the curve labelled 'simultaneous at brain' would be followed. This curve is simply the difference in reaction times to the two stimuli presented alone taken from figure 2a. According to this prediction, for the close distances, at which the sound was processed faster than the flashed circle, the light would need to be initiated before the sound to balance the difference in processing times. For distances beyond the equality point of 16 m, at which the reaction times to the sound were longer than those to the flashed circle, the sounds would need to be presented first to give them enough time to pass down the corridor and catch up with the light. This prediction implies no compensation at all by observers who would make their decisions on the basis of independent processing of each stimulus.

A second prediction is that some compensation might take place but only for the internal differences in processing speed. In this model, delays caused by external factors, such as the speed of sound, lead to predictable stagger times being required between the components of the stimulus for them to appear as simultaneous. In the

present case, this prediction expects that the delay between the stimuli would be proportional to the speed of sound. This prediction is shown in figure 2b labelled 'simultaneous at face'.

A third possibility is that all the variables are compensated for, and that simultaneity judgments correctly reflect the stimuli actually being simultaneous at the source. Completely compensated judgments would be accurate and would correspond to zero onset-time differences at all distances. This prediction is shown in figure 2b as the horizontal line labelled 'simultaneous at source'.

The delay between the onset of the light and the onset of the sound shows very little variation with distance with a slope of only -1 ms m^{-1} . This slope is significantly different from the 'simultaneous at brain' prediction ($t_{80} = 3.63$, $p < 0.001$). The data are also significantly different from both the 'simultaneous at source' prediction ($t_{40} = 2.11$, $p < 0.05$) and from the slope (-3.4 ms m^{-1}) of the 'simultaneous at face' prediction ($t_{40} = 9.31$, $p < 0.001$).

3.3 *Variations with intensity: reaction times*

We measured the reaction time to flashes viewed through 1.8 dB attenuating glasses. Comparison of figures 2a and 3a shows that reaction times to the circle were increased by about 36 ms compared to the no-glasses condition ($F_{1,6} = 24.72$, $p < 0.01$). The distance at which the reaction times for light and sound were equal was correspondingly pushed back to about 25 m. The reaction time to sound was unaffected by the glasses.

3.4 *Variation with intensity: simultaneity*

The change in reaction time to the light caused the 'simultaneous at brain' prediction line to be shifted. The reaction-time-difference prediction without the glasses (open circles, from figure 2) is compared with the prediction with the glasses in figure 3 (filled circles). The shift of the no-shades curve is significant ($F_{1,6} = 67.67$, $p < 0.001$). The other predictions were not affected. The delays associated with subjective equality when wearing the glasses (figure 3d, filled circles), however, were not different for data obtained without wearing them (open circles). The data are compared with the predictions in figure 3b.

3.5 *Variation with eccentricity: reaction times*

Experiments were repeated with eccentric viewing. Subjects fixated spots on the wall that were carefully positioned so that the visual stimulus was at 20° . Figure 4a shows the reaction times to the eccentrically viewed visual stimulus. The reaction times to the circle were increased by about 35 ms compared to central viewing ($F_{1,6} = 17.79$, $p < 0.01$). Reaction times to sound were unaffected. The distance at which the two lines crossed was consequently pushed well beyond our operating range: now sounds from all the distances tested were processed faster than light, even allowing for their time of passage down the corridor.

3.6 *Variation with eccentricity: simultaneity*

The longer reaction times with eccentric viewing caused the prediction line based on the auditory/visual reaction time difference (figure 4c, filled circles) to be significantly shifted compared to foveal viewing (figure 4c, open circles, $F_{1,6} = 48.57$, $p < 0.001$). The other predictions were not affected. The delays associated with subjective equality with eccentric viewing (figure 4d, filled circles), however, were not different for data obtained with central viewing (figure 4d, open circles). The data are compared with the predictions in figure 4b.

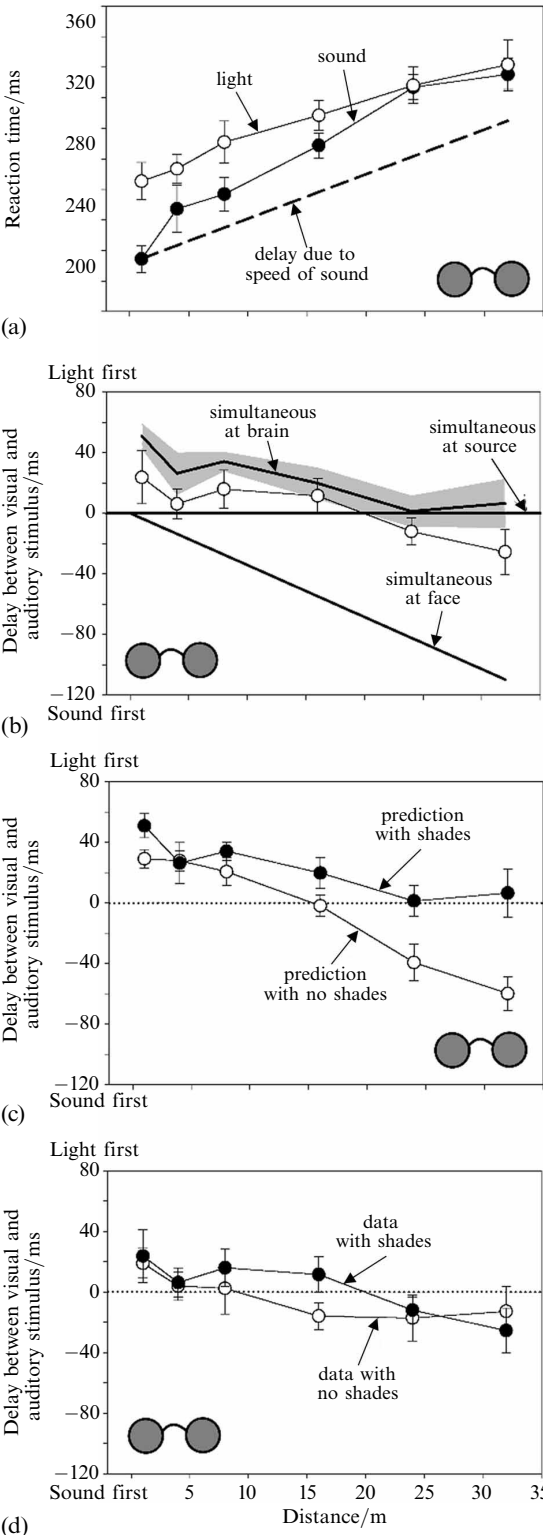


Figure 3. Reaction times (a) and estimates of simultaneity (b) for the same light and sound targets as in figure 2 but viewed through dark glasses that attenuated the image by 1.8 dB. Convention as for figure 2. In (c) the ‘simultaneous-at-brain’ predictions based on reaction time differences for the normal condition (open circles from figure 2a), are compared with the predictions from the reaction times measured while wearing dark glasses (closed circles in figure 3a). The prediction was significantly altered by wearing the glasses. In (d) the judgments with the glasses (closed circles in figure 3b) are compared with judgments without the glasses (open circles in figure 2b). There was no significant change from viewing without glasses.

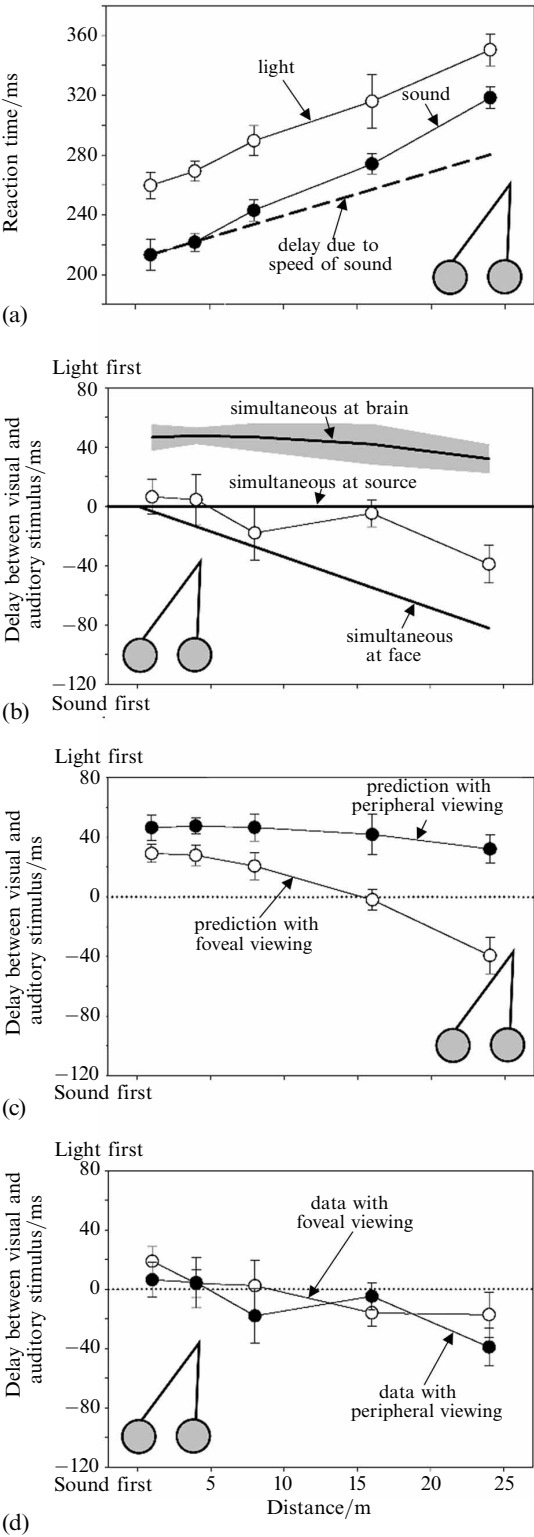


Figure 4. Reaction times (a) and estimates of simultaneity (b) for the same light and sound targets as in figure 2 but viewed 20° eccentrically, taking care that the stimulus did not encroach on the blind-spot of either eye. Convention as for figure 2. In (c) the 'simultaneous-at-brain' predictions based on reaction time differences for the normal condition (open circles in figure 2a) are compared with the predictions from the reaction times measured while viewing was eccentric (closed circles in figure 4a). The prediction was significantly altered by eccentric viewing. In (d) the judgments with eccentric viewing (closed circles in figure 3b) are compared with judgments without eccentric viewing (open circles in figure 2b). There was no significant change from the foveal-viewing condition.

4 Discussion

The results of these experiments show that light and sound pairs are typically judged as simultaneous when they actually are simultaneous, despite large variations in the time at which the stimuli arrive at the transducers and the time it takes to process them. This is a perceptual constancy for simultaneity. The true situation is perceived despite huge, potentially misleading variations in the sensory signals. Just as an object is perceived as having a constant size despite continuous variations in the size of the retinal image, temporal simultaneity is reconstructed from highly variable sensory inputs. The perception of simultaneity is maintained despite changes in illumination or retinal location, both of which have very significant effects on reaction times. Such variations in relative timing are to a great extent compensated for, resulting in almost correct perceptual estimates of simultaneity.

Previous researchers have reported that sound/light pairs can appear simultaneous despite differences in their physical properties (Engel and Dougherty 1971; Sugita and Suzuki 2003; but see Stone et al 2001). We have extended these studies using real sounds at real distances rather than simulated sounds (Sugita and Suzuki 2003). We have varied not only the physical time-of-arrival of the stimuli but also the neural processing times, showing that simultaneity constancy is a sophisticated and comprehensive process.

Making judgments of true simultaneity requires precise information about both internal and external temporal properties. To allow for the time it takes for sound to travel from the source it is necessary to know the distance of the stimulus and the speed of sound. Allowing for the differences in processing time between sound and light requires knowledge of how these vary with the contrast, illumination, and retinal location of visual stimuli, and with the frequency and intensity of the auditory stimulus. Furthermore, attending to one or other component can speed its relative processing time by the law of prior entry (Titchener 1908; Spence et al 2001). The data shown in figures 2b, 3b, and 4b suggest that the brain is largely able to take this information into account, although small effects of distance (systematic errors in perceptual constancy) persist.

4.1 *Variations in reaction time: Do they adequately reflect differences in processing time?*

To find the difference in the processing times of each stimulus, we measured simple reaction times to the lights and sounds presented separately. The reaction times were comprised of several components: the time it took energy to reach the receptors, the transduction and conduction times, the central processing time, and the time it took to plan and execute the motor response. The difference in total reaction times for each stimulus was an indicator of the time difference that needed to be compensated for to achieve simultaneity constancy and for the relative timing to be correctly perceived.

The variations in reaction times with distance that we measured were consistent with these known differences (vision—about 60 ms: Jeffreys and Axford 1972; Lesevre 1982; audition—about 15 ms: Celesia 1976; Liegeois-Chauvel et al 1991). Reducing the illumination of a visual stimulus reduces the transmission speed of a visual signal (Wilson and Anstis 1969) and is thought to be the basis of the well-known Pulfrich effect (Nickalls 1996). Although some aspects of visual processing seem to be faster in the periphery (Carrasco et al 2003), reaction times to a fixed event occurring in the peripheral vision are slower than for the same event occurring at the fovea. The point at which reaction times to lights and reaction times to sounds are the same has been called ‘the horizon of simultaneity’ by Ernst Pöppel (1988). The distance of this point varies with many stimulus parameters.

Although there are many differences between our two tasks of ‘react as fast as you can’ and ‘which came first?’ that make it difficult to know exactly the demands that our

experiments put on the simultaneity constancy system, it is clear that our manipulations affect some aspect of the timing of the stimuli and that this variation was not reflected in the judgments of which stimulus came first.

4.2 Accuracy versus precision

Do the delays (or lack of delays) judged as simultaneous accurately reflect simultaneity, or is there a tolerance for differences such that stimuli that arrive (in the brain or at the receptors) fairly close together in time are accepted as simultaneous? A tolerance for time-of-arrival differences is thought to be the mechanism, for example, for how variation in the accuracy of the synchronisation of a sound track of a movie is tolerated. It is estimated that a desynchronisation of between 260 ms (light first) and 130 ms (sound first) can be tolerated before it is detected (Dixon and Spitz 1980).

Figure 5 shows typical examples of the psychophysical functions on which the data reported here are based. The probability of choosing 'sound first' is plotted against the delay between the auditory and visual components of the stimuli. These data can be well modelled as a sigmoid. The 50% point (when the light and sound have an equal chance of being chosen as first) indicates the point of equality: the delay at which neither component is said to be first. The steepness of the sigmoid is an indicator of the precision with which the task can be done. From the sigmoid, a Gaussian (its mathematical derivative) can be produced that reflects the standard deviation around the central point.

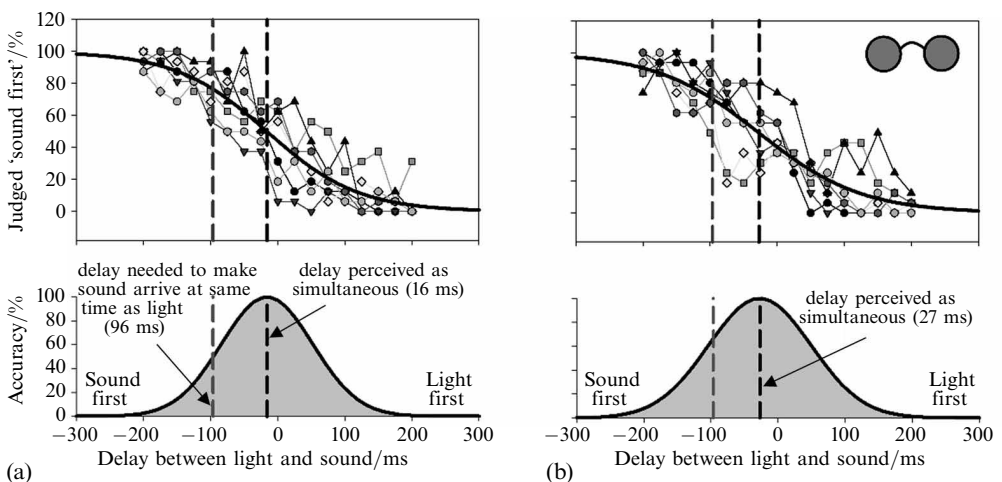


Figure 5. The top graphs show the psychometric functions for the percentage of times 'sound first' was chosen as a function of the temporal gap between the light and sound components (+ means light first). For each graph, each subject, averages and best-fit sigmoid are shown. The grey, vertical dashed line is the delay needed to ensure that the light and sound arrive at the face at the same time after traveling 32 m down the corridor. The black line indicates the midpoint of the psychometric function where the stimuli appeared simultaneous. The lower plot is a Gaussian with the standard deviation of the psychometric function above to indicate the accuracy of the decision. (a) Control data; (b) viewing through attenuating glasses.

The examples shown in figure 5 are taken from the 32 m presentation without (figure 5a) and with (figure 5b) the 1.8 dB glasses. Standard deviations are 68 and 77 ms, respectively, which represent the precision with which the task can be done. Interestingly, the widths of these precision functions are very similar to the typical 'optimal interactive period' for multisensory units in the superior colliculus (Meredith et al 1987) and the temporal window for psychophysically assessed auditory–visual interactions (Shams et al 2002) although narrower than the JNDs for audio/visual temporal order judgments (Hirsh and Sherrick 1961) even when spatial factors are controlled

(Zampini et al 2003). However, the functions are centred close to the actual points of simultaneity and a clear distinction can be made between the responses at actual simultaneity (44% judged sound first) and at the delay corresponding to the physical energy arriving at the face at the same time (76% judged sound first).

4.3 Possible mechanism of simultaneity constancy

When any perceptual event occurs, there is an uncertainty about its timing. This is indicated diagrammatically in figure 6 by the spread in time of the hypothetical activity associated with the visual or auditory event. One model, suggested by Stein and Meredith (Meredith et al 1987; Stein and Meredith 1993), is that these representations are likely to be quite long, perhaps up to 200 ms and therefore will overlap. The point of maximum overlap is then taken as the time of occurrence of the bimodal event (model 1, figure 6). Although this model explains the enhancement of single-unit activity in the superior colliculus, it predicts that a large range of delays would all be perceived as simultaneous. Our data show that, although there is a substantial spread in the psychometric function (figure 5), there is clearly a single timing difference that is best regarded as simultaneous—the temporal order of other pairs is correctly identified despite overlapping sensory representations. In the overlap theory, whenever there was an overlap, a period of enhancement would be created and an illusion of simultaneity would be produced.

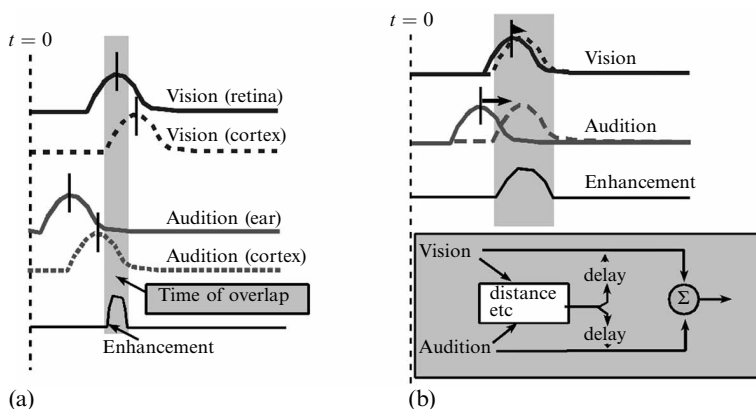


Figure 6. Two possible models for how simultaneity constancy might be achieved. (a) In model 1 the appearance of simultaneity occurs because of the overlap of the internal representations of the light and the sound. (b) Model 2 is more complex and comprehensive; here a variable delay is added to one or the other of the stimuli to compensate for various factors that tend to pull the signals apart (see text) and provide simultaneity constancy.

This model could underlie the phenomenon of temporal ventriloquism (Morein-Zamir et al 2003), but is unlikely to explain our data of the perception of simultaneity. In temporal ventriloquism, the perceived time of occurrence of one stimulus is pulled to the point in time at which another stimulus occurs, in a manner analogous to spatial ventriloquism in which the perceived spatial position of one stimulus is pulled to that of another. Temporal ventriloquism is unlikely to explain the phenomenon we report here. Out of all the time-staggered stimuli, only one was regarded as simultaneous, and others, even quite close in time, were perceived as appearing in a certain order. Temporal ventriloquism would lead to all time-staggered presentations being regarded as simultaneous.

An alternative, but much more complex, model for simultaneity constancy is shown in figure 6b. In this model the internal representation of the faster member of the pair is delayed by an amount precisely tuned to the particular situation. The model looks complex because so many pieces of information need to be factored in to the

delay-generating machinery. It also seems to be logically impossible, since to know what delay is needed requires information about the situation (such as distance, illumination, and retinal location) that can only be obtained from the incoming information itself. However, it is not necessary for this system to work in real time. The system is not providing absolute timing information, but only relative timing. As such, it can take as long as is required working not on the incoming sensory information but on an internal representation or buffer. This model is compatible with our data, since it has the flexibility to introduce delays appropriate for each of our conditions.

4.4 Comparison with other perceptual constancies

Some of the principles of simultaneity constancy are held in common with other perceptual constancies. For example, distance information is required to recover size from the retinal image and allow perceptual size constancy in a similar way as it is needed for simultaneity constancy. Errors in distance perception result in size constancy eventually breaking down. A classic example of this is the moon illusion (Hershenson 1989; Ross and Plug 2002), where differences in distance perception between when the moon is high in the sky compared to when it is close to the horizon result in changes in its apparent size. Interestingly, the fact that these effects can still occur when looking at such distant objects. They are ineffectual in providing an accurate impression of the linear size of the moon, but can still be modulated by changes in the perceived distance, even though the absolute distance is hopelessly wrong. We expect that parallel effects can also be seen for simultaneity constancy. The small delay of a light relative to a distant sound needed for them to appear simultaneous (1 ms m^{-1}) indicates that the mechanism is not perfect. Without this added delay, the sound is heard as following the light, although by a much smaller time than it really does (32 ms compared to 94 ms for a 32 m corridor—figure 2b). For longer distances in the order of hundreds or thousands of metres, we would expect a similar inadequacy (1 s for 1 km, for example, compared to the true value of over 3 s if we can extrapolate from our data), but not necessarily a switching off of the mechanism.

5 Summary

The robust ability to judge simultaneity correctly under the diverse conditions employed in these experiments is remarkable and has interesting and important ramifications. It demonstrates that different parts of a complex scene can be processed according to contextual rules. A single, complex event may have components with images spread across the retina and that might be transduced by more than one sensory system. Contextual rules are thus required to compensate for the different processing times. Applying these rules may involve a substantial memory component in which a trade-off is set up between responding to events as quickly as possible and waiting until all the expected information is received.

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