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RESEARCH ARTICLE

Vanessa Harrar · Laurence R. Harris

Simultaneity constancy: detecting events with touch and vision

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Abstract What are the consequences of visual and tactile neural processing time differences when combining multisensory information about an event on the body's surface? Visual information about such events reaches the brain at a time that is independent of the location of the event. However, tactile information about such events takes different amounts of time to be processed depending on the distance between the stimulated surface and the brain. To investigate the consequences of these differences, we measured reaction times to touches and lights on different parts of the body and the perceived subjective simultaneity (PSS) for various combinations. The PSSs for pairs of stimuli were predicted by the differences in reaction times. When lights and touches were on different body parts (i.e. the hand and foot) a trend towards compensation for any processing time differences was found, such that simultaneity was veridically perceived. When stimuli were both on the foot, subjects perceived simultaneity when the light came on significantly earlier than the touch, despite similar processing times for these stimuli. When the stimuli were both on the hand, however, there was complete compensation for the significant processing time differences between the light and touch such that simultaneity was correctly perceived, a form of simultaneity constancy. To identify if there was a single simultaneity constancy mechanism or multiple parallel mechanisms, we altered the PSS of an auditory-visual stimulus pair and looked for effects on the PSS of a visual-touch pair. After repeated exposure to a light/sound pair with a fixed time lag between them, there was no effect on the PSS of a touch-light pair, suggesting multiple parallel simultaneity constancy mechanisms.

Keywords Neural processing delays · Touch · Tactile
Vision · Simultaneity · Temporal order judgments
Simultaneity constancy · Timing perception
Multisensory integration in time · Perceived subjective simultaneity (PSS)

Introduction

How is it possible to know the time of an external event when the senses take an often highly variable amount of time to process information about that event? Different energy types, for example, light and sound, even when they originate from the same event, for example, someone speaking, can take different amounts of time to reach the appropriate sense organs, and to be transduced and transmitted to the central nervous system. The fact that these processes take any time at all means that perceiving the actual time at which something happens must involve a reconstructive process (see Dennett and Kinsbourne 1992). Nowhere are these constraints more likely to be consequential than when seeing and feeling the position of an object in one's hand (Blake et al. 2004; Pears and Jackson 2004).

The perceived timing of sensory events is not determined exclusively by the physical properties of the sensory systems, such as the transduction mechanism or the length of the nerves. Attention, for example, can alter the processing time of sensory stimuli and allow perceptual processes some flexibility within their biological constraints (see Spence et al. 2001 for a comprehensive review). The brain can use this flexibility to compensate for some temporal differences between sensory processes (Stone et al. 2001; Spence and Squire 2003) and accurately decide whether they originated from a single event. This perception of true simultaneity, despite dif-

V. Harrar · L. R. Harris
Centre for Vision Research, York University,
Toronto, Ontario, M3J 1P3, Canada

L. R. Harris (✉)
Department Psychology, York University,
Toronto, Ontario, M3J 1P3, Canada
E-mail: harris@yorku.ca
Tel.: +1-416-7362100
Fax: +1-416-7365857

ferences in the corresponding neural activity, is a form of perceptual constancy called ''simultaneity constancy'' (Kopinska and Harris 2004).

Some timing differences that might usefully be compensated for by simultaneity constancy arise from the fact that touches delivered to different parts of the body take different amounts of time to reach the brain. Given a typical conduction velocity of 55 m/s (Macefield et al. 1989), tactile information about a touch to the face should precede information from a touch to the foot by some 30 ms. However, complete simultaneity constancy has not been found for touches delivered to different parts of the body (Von Békésy 1963; Bergenheim et al. 1996). This may be because of the type of stimulation used. Von Békésy (1963) used electrical stimulation, while Bergenheim et al. (1996) used mechanical taps of only 2 ms duration. Neither of these stimuli seems comparable to normal touches.

Since the processing times to touches vary with body location while the processing times to lights do not, also raises a challenge for a simultaneity constancy mechanism.

Therefore, we investigated the perception of the relative timing of touches and lights at different points on the skin using stimuli of 50 ms duration. We used temporal order judgements to assess the timing between two stimuli needed for them to be regarded as simultaneous (perceived subjective simultaneity, PSS). We compared subjects' PSS with actual simultaneity to see which pairs of stimuli, if any, were subject to simultaneity constancy and how this varied over the body. If simultaneity constancy only applies to multimodal stimuli that are likely to arise from single events then we expect to see simultaneity constancy only when the component stimuli are in the same location.

General methods

Subjects

Subjects were volunteers from the graduate and undergraduate pool at York University. There were six subjects in the unimodal experiments (touch–touch and light–light) (experiments 1 and 2), 14 subjects in the multimodal touch–light experiments (experiments 1 and 2), and five subjects in the adaptation experiment (experiment 3). The age range for subjects was 20–50 years. Some subjects were paid at York standard rates. All experiments were approved by the York Ethics Board.

Touch stimulators

Touch stimulators were made from small solenoids mounted in wooden cups (Fig. 1). When the solenoid was powered, a central pin was pushed out. The pin extended about 1 mm from the edge of the cup, and hit the skin surface with a force of a light tap spread over a surface area of about 1 mm^2. Solenoids were controlled by appropriately amplified 5-V signals from a CED1401 interface box controlled by a PC. The solenoids took 5 ms both to extend and to retract back into the wooden cups as measured by a carefully positioned photocell. Two touch stimulators could be worn by the subject at any one time. They were taped to the forehead, lip, neck,

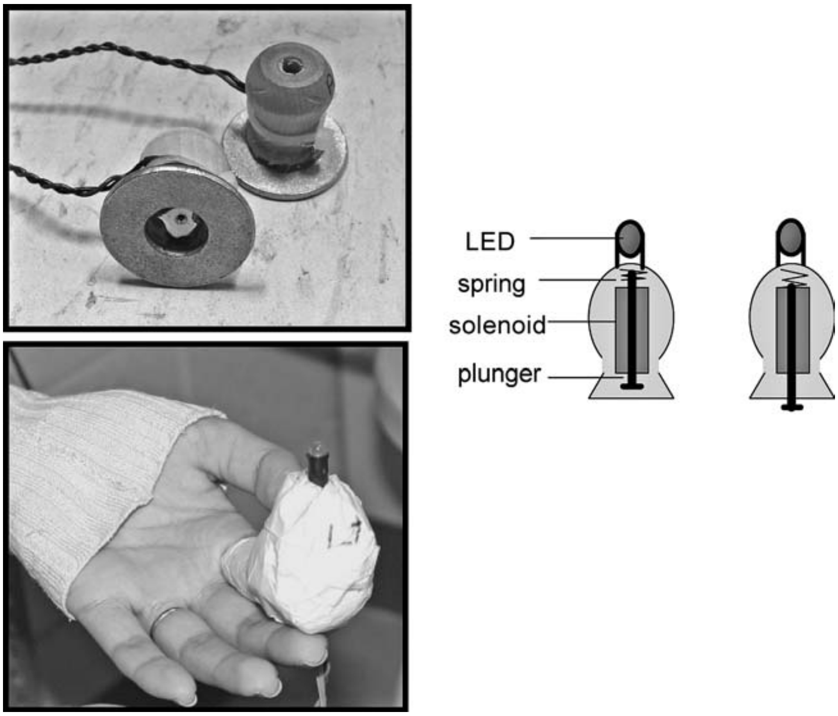

Fig. 1 The touch stimuli used in this experiment were plungers moved by solenoids. When current was applied to the solenoid, the plunger, with a blunted tip, was pushed out and returned by a small spring. Also mounted on the device was a green LED

index finger, or to the sole of the foot (the foot rested on the subject's opposite knee). Subjects adjusted the position of each solenoid until they were felt to be of comparable intensity.

Visual stimulation

Visual stimulation was provided by green LEDs mounted on top of the wooden cups that contained the solenoids (see Fig. 1). They were controlled directly by 5-V signals from a CED1401 interface box controlled by a PC.

Experiment 1

Measuring reaction times

The difference between the reaction times to lights and touches presented alone provides a crude estimate of their relative processing times. If, in fact, there is no compensation for the difference in processing times, then reaction times can predict the delay time between a pair of stimuli needed for them to appear simultaneous. We therefore measured reaction times to individual stimuli on different parts of the body in order to compare pairs of these measurements with the actual delay time required for that particular pair of stimuli to be perceived as simultaneous.

Methods

The stimuli to be used in a given session were first demonstrated to the subjects. They then rested their chosen response finger (from the hand opposite the stimulation) on a response key. Light and touch stimuli (see General methods) at multiple locations were randomly interleaved with a variable time period between trials of between 1 and 4 s. Each stimulus was presented 30 times, and each session took about 15 min. Subjects were instructed to respond as quickly as possible as soon they detected any stimuli. Stimuli stayed on until the subject reacted. Subjects repeated these reaction time tests both before and after the temporal order judgement tests (see experiment 2 below). Reaction times faster than 100 ms or slower than 500 ms were automatically discarded and the trial repeated. Gaussian curves were fitted to histograms of the distributions of reaction times. The peak was taken as the subject's mean reaction time for a given stimulus.

Results

The reaction times to touches provided by the solenoid stimulators mounted on various parts of the body are shown in Fig. 2a, plotted as a function of distance from the geometric centre of the head. There is a linear relationship between distance and reaction time ($\mathrm{rt} = 182 + \mathrm{distance} \times 45$ ms; $r^2 = 0.94$). The intercept of 182 ms is an estimate of the time needed for internal processing and response generation; the slope of 45 ms/m is an estimate of the conduction velocity.

The reaction time to the LEDs (shown as a horizontal band in Fig. 2) was 266 ± 1.1 (SE) ms, regardless of where they were mounted. This value is comparable to the reaction time to touches on the foot.

Discussion

The reaction times to touches on different sites along the body varied proportionally with distance from the brain (Fig. 2). The slope of the relationship between distance from the brain and the reaction times showed an increase in reaction time of 45 ms/m; that is a conduction velocity of 22 m/s. This is rather slower than conduction velocities measured using physiological techniques (Macefield et al. 1989).

The differences in reaction times for stimuli at different sites predict that for stimuli to be perceived as simultaneous, they actually need to be presented at staggered times with the slower one being presented before the faster one, unless there is a compensation for the timing difference. The amount of stagger predicted is simply the reaction time difference between the stimuli. However, this means that truly simultaneous stimuli would not be perceived as being simultaneous and therefore may be identified as separate events. Therefore, when multiple stimuli occur at the same time, neural processing time difference may incorrectly indicate that

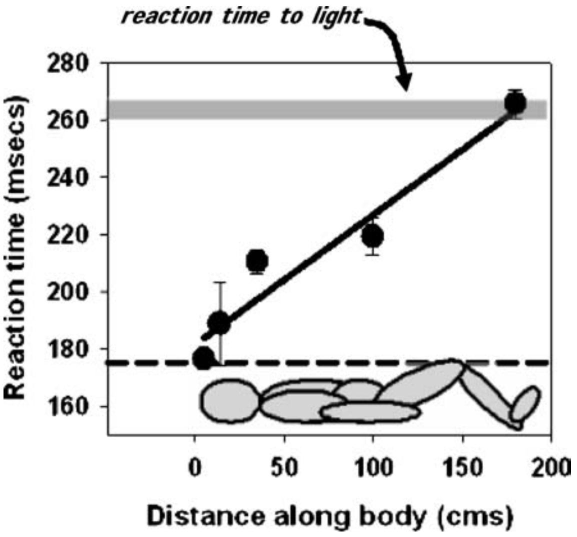

Fig. 2 Reaction times to touches and lights. The average reaction times (with standard error bars) to touches on various parts of the body (forehead, lip, neck, hand and foot) are plotted as a function of distance to the centre of the head. Also shown is the average reaction time to lights on any part of the body as a bar of width ± 1 SE

they are different events. Therefore, in many circumstances, compensation for this timing difference is required for accurate integration of information concerning single events. Does this occur for combinations of touches and lights on the body's surface?

Experiment 2

Temporal order judgements

We extrapolated subjects' perceived simultaneity from their temporal order judgments (TOJs) concerning stimuli presented with different onset times. When subjects could not tell which was first, we took this as an indication that they perceived them as happening at the same time. These points of perceived subjective simultaneity (PSS) were then compared to the predictions, based on the differences of the reaction times to those stimuli (obtained in experiment 1), to look for evidence of compensation.

Methods

TOJs were obtained by presenting pairs of stimuli (duration 50 ms) with stimulus onset asynchronies (SOAs) of 0–200 ms, and asking subjects to press one of two coloured buttons to indicate which stimulus appeared to come first. There were typically 21 SOAs, and each was presented 10 times. The probability of choosing one member of the pair was plotted as a function of the SOA and a sigmoid was fitted to the data. The point at which subjects were equally likely to choose either stimulus (50%) was taken as the PSS. Each session took about 30 min. Stimuli tested were pairs of unimodal and bimodal stimuli. Unimodal touch pairs were made up of combinations of touches to the lip, hand and foot. The unimodal light pair had lights on the hand and foot. Bimodal pairs were made up of all four light-touch combinations on the hand and foot.

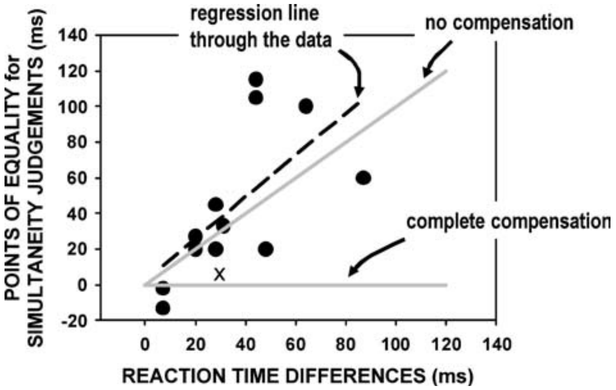

Fig. 3 The PSS as a function of reaction time differences between pairs of touches. The two predictions are plotted: "no compensation" in which the PSS is directly predicted from the reaction time differences, and "complete compensation" in which the PSS is unaffected by reaction time differences. The regression through the data has a slope of 1.2, closely fitting the "no compensation" model. The x is from touches to the hand and foot specifically—actual data shown in Fig. 4a "touch"

Results

Perceived subjective simultaneity of two touches on different parts of the body

The PSSs of all combinations of body parts tested are plotted against the relevant reaction time differences in Fig. 3. Figure 3 compares the simultaneity constancy hypothesis with the no-compensation hypothesis for two touches. Simultaneity constancy requires that true simultaneity is correctly perceived ($PSS = 0$), despite variations in neural processing times. No compensation predicts that the PSS will depend entirely on neural processing times, and that PSS should be equal to the reaction time differences and result in a slope of 1. The regression line had a slope of 1.2 and a regression coefficient of 0.42 ($P = 0.023$). Comparing each of the six subjects' PSS with the difference in reaction times to the same pair of stimuli indicated no significant difference [$F(1,11) = 0.823$, $P = 0.38$]. There was no indication of compensation for differences in processing times of tactile stimuli.

Perceived subjective simultaneity of multimodal light/touch pairs and unimodal controls

TOJs for pairs of stimuli in the same modality (lights or touches) presented on different parts of the body are shown in Fig. 4a. TOJs for multimodal touch/light pairs with the light and touch on different body parts are shown in Fig. 4b. Figure 4c shows the multimodal judgements when the light and touch were on the same body part. The PSS is compared to the corresponding reaction time based prediction for those stimuli.

Paired t-tests show that the PSS for unimodal stimulus pairs on different body parts (Fig. 4a) were not significantly different from their respective reaction time based predictions [paired t-tests, $P(\text{vision}) = 0.31$, $P(\text{touch}) = 0.26$]. For vision, neither the prediction nor the PSS was significantly different from zero (one-sample t-test, $P = 0.13$, $P = 0.71$, respectively). For touch, the reaction time difference was significantly different from zero (one-sample t-test, $t = -7.96$, $P = 0.001$, $df = 5$), but the PSS was not (one-sample t-test, $P = 0.71$), suggesting partial compensation.

Paired t-tests show that the PSS for multimodal stimulus pairs on different parts of the body (Fig. 4b) were not significantly different from the reaction time based predictions [paired t-test, $P(\text{hand light/foot touch}) = 0.79$, $P(\text{hand touch/foot light}) = 0.64$]. Neither the hand light/foot touch prediction nor the PSS for this pair was different from zero (one-sample t-test, $P = 0.10$, $P = 0.32$, respectively). The hand touch/foot

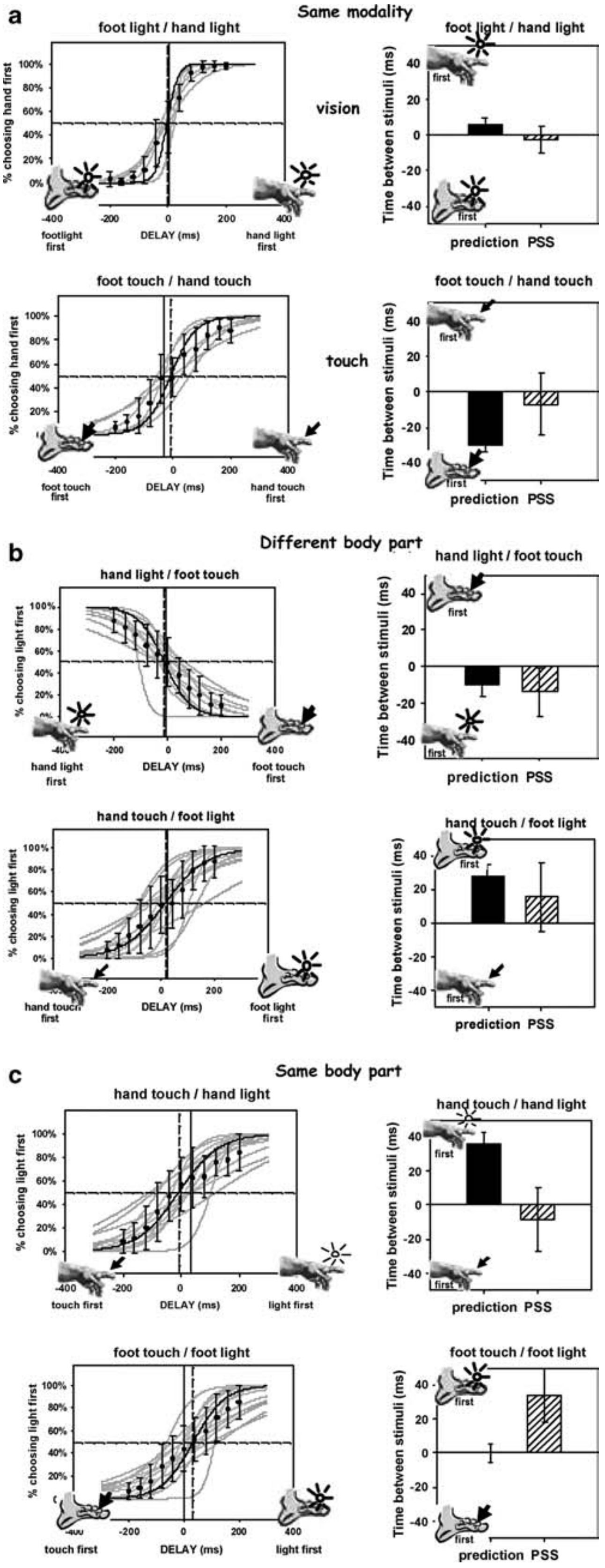

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Fig. 4 Temporal order judgements for touch and light stimuli in various combinations. **a** Pairs of stimuli of the same modality but on different parts of the body. **b** Pairs of stimuli of different modalities and on different parts of the body. **c** Pairs of stimuli of different modalities but on the same part of the body. The format for each of the six combinations illustrated here is the same. The *left part* of the figure shows the temporal order judgements for each pair of stimuli as a function of the delay between the two components of the stimulus pair. *Positive and negative values* on the horizontal axis indicate which of the stimuli was presented first, as shown by the inserted cartoons. The *grey lines* show sigmoid fits through each subject's data and the average data points and standard errors are superimposed on these curves. The *black curve* is a sigmoid reconstructed from the average PSS and standard deviation of all of these curves. The temporal delay at the PSS indicated by the average curve is shown by a *dashed vertical line* and the prediction from the reaction time differences is shown as a *solid vertical line*. In the histograms on the *right*, the reaction time prediction (*black bars*) is compared with the PSS (*shaded bars*). The vertical axis shows the delays between the stimuli as shown by the inserted cartoons. Standard errors are also shown

light prediction was significantly different from zero while the PSS was not (one-sample *t*-test, $t = 3.86$, $P = 0.002$, $df = 13$; $P = 0.46$, respectively). The fact that the perceived simultaneity does not significantly differ from true simultaneity, while the reaction times predict a difference, suggests a trend towards compensation.

For each of our bimodal stimulus pairs on the same parts of the body (hand and foot), the PSS was significantly different from the corresponding reaction time based prediction [paired *t*-test, *P* (hand touch/ hand light) = 0.03, partial $\eta^2 = 0.32$; *P*(foot touch/foot light) = 0.04, partial $\eta^2 = 0.31$]. On the hand, the prediction was different from zero while the PSS was not (one-sample *t*-test, $t = 5.09$, $P < 0.001$, $df = 13$; $P = 0.65$, respectively). On the foot, the prediction was not significantly different from zero while the PSS was ($P = 0.98$; $t = 2.14$, $P = 0.05$, $df = 12$, respectively), showing anti-compensation.

Discussion

A comparison, for each stimulus combination, of the reaction-time-based prediction with the PSS showed four patterns:

Pattern 1: no significant difference between the reaction times to each stimulus presented alone and PSS of zero (foot light/hand light; hand light/foot touch). For this combination, no processing time difference existed, no compensation was required, and none was demonstrated.
Pattern 2: no significant difference between the reaction times to each stimulus presented alone but PSS not equal to zero (foot touch/foot light). This is a puzzling condition since no processing time difference existed but some anti-compensatory mechanism appeared to have shifted the PSS, causing apparently unnecessary errors in determining simultaneity.
Pattern 3: a significant difference between the reaction times to each stimulus presented alone, and PSS equal to

zero, but the reaction time difference and PSS not significantly different from each other (foot touch/hand touch; hand touch/foot light). This pattern indicates a trend towards partial compensation. For the touch/touch pair this observation seems at odds with the data in Fig. 3 and other reports finding no compensation in the tactile system (Bergenheim et al. 1996). The foot touch/hand touch reaction time is plotted against the PSS as an ''x'' in Fig. 3 for comparison.

Pattern 4: a significant difference between the reaction times to each stimulus presented alone, and PSS equal to zero, and the reaction time difference and PSS significantly different from each other (hand touch/hand light). This pattern indicates complete compensation and, out of all the combinations tested in this study, was only found for hand touch/hand light.

To investigate *how* the timing difference between visual and tactile sensory information concerning a single event on the hand was compensated for, we designed an experiment to see if the visual–touch simultaneity mechanism was the same as the auditory–visual simultaneity mechanism.

Experiment 3

Is there a common simultaneity constancy mechanism?

Does the simultaneity constancy found in the touch–light system reflect the working of a common constancy mechanism that adjusts the timing of all sensory information to bring it into synchrony at all times? Or might there be separate mechanisms for each stimulus comparison (see Pick et al. 1969 for example)? To investigate these possibilities, we adapted the sound–light system and looked to see whether this had any effect on the touch–light system. Fujisaki et al. (2004) have recently shown that the PSS can be dramatically shifted even after just a few minutes of repeated exposure to a stimulus pair with a constant time lag between them. If the touch–light and sound–light systems share a common mechanism, then adaptation that affects one's PSS might affect the other's PSS as well.

Method

Subjects were exposed to a 5-min sequence of light/sound pairs with a fixed interval between them of 250 ms, where the light was presented before the sound (see insert to Fig. 5). The light was mounted on the finger, and the sound was delivered through headphones. The pairs were presented with a random interpair interval varying from 0.2 to 1 s and subjects were instructed to pay attention to the pair. Thus subjects were encouraged to believe that the light and sound components originated from single events because of the strong temporal correlation between them. TOJs for interleaved touch/light and sound/light pairs were performed before and immediately following the adaptation. During the TOJ trials that followed the adaptation,

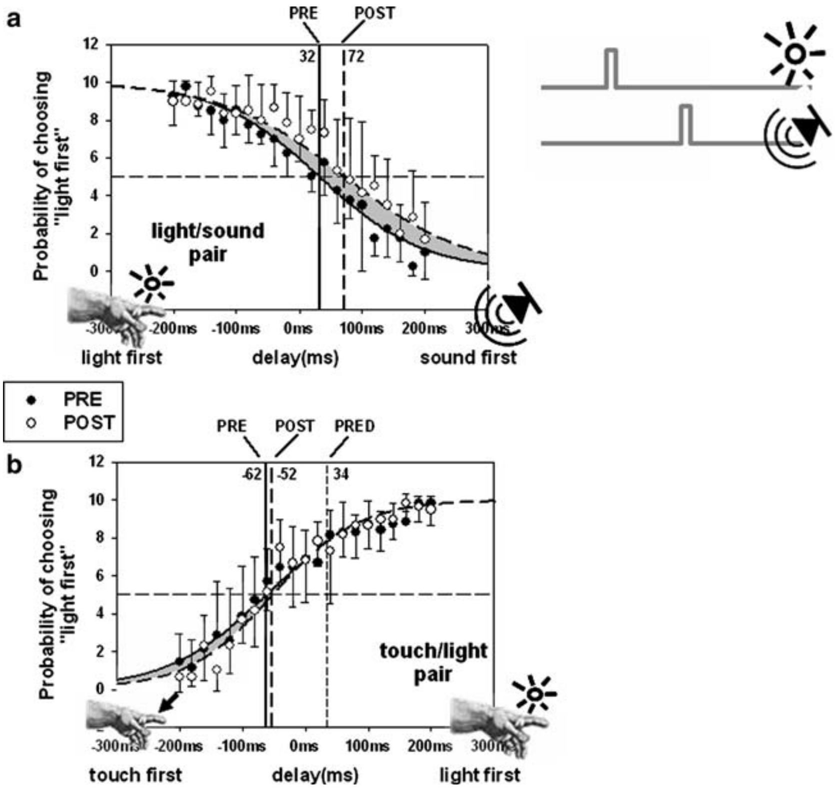

Fig. 5 Effect of adapting to a constant time lag. Subjects were repeatedly exposed to a light/sound pair in which the sound lagged the light (see insert and text). **a** After 5 min of exposure, there was a significant shift in the temporal order judgements between light and sound (before, *filled circles*; after *open circles*; *error bars* over five subjects pooled: see text for details). The *vertical lines* indicate the PSS before (*solid line*) and after (*dashed line*). **b** There was no effect on the temporal order judgements of touch/light (before, *filled circles*; after *open circles*) measured interleaved with the light/sound judgements. The *vertical lines* indicate the PSS before (*solid line*) and after (*long-dashed line*). The *short-dashed line* indicates the reaction-time-based prediction for simultaneity

top-up adaptation sessions of 10 s duration were inserted after every ten judgement trials. The post-adaptation TOJ measurements took about 45 min because of these inserted top-up adaptation periods.

Results

Adapting to a light/sound lag—effect on light/sound TOJs

Figure 5a compares TOJs of the same light/sound pair before and after adaptation with the light presented before the sound. There was a significant shift of the psychometric curve [$F(1,4)-2.85$, $P<0.05$]. The PSS was shifted by +40 ms, such that sound needed to be on 40 ms earlier than it did before adaptation.

Adapting to a light/sound lag—effect on touch/light TOJs

Figure 5b shows the TOJs of a touch/light pair on the finger using the same light as in the adapting pair. There was no significant difference between the before and after psychometric curves [$F(1,4)=-0.4$, $P=0.7$] for the touch/light stimulus pair after effective adaptation to the light first (Fig. 5).

Discussion

Auditory–visual temporal compensation, at some level, requires either the more slowly processed information to be speeded up, or the more quickly processed information to be delayed. Our experiments have confirmed Fujisaki et al.'s (2004) demonstration that this process can be altered as the result of experience; the adaptation produces a significant shift in the TOJs between the modalities adapted. However, there was no such shift in the tactile–visual system after effective adaptation in the auditory–visual system.

General discussion

This paper has shown that to provide two touch stimuli such that a subject cannot tell which one came first, requires the introduction of a temporal lag between them. The required duration of that lag can be predicted from differences in the reaction times to each stimulus presented alone. The point of PSS for pairs of touches varies with the location of the stimuli over the body. However, for touches and lights on the same body part, the PSS cannot be predicted in this way. Light/touch pairs on the hand are judged as simultaneous when they are truly simultaneous and not when neural processing times are equal (which would require the light stimulus to come on before the touch by about 36 ms for our stimuli).

The computational effort needed to ascertain whether the sources of multimodal information are co-temporal and therefore define a single event, is most efficiently applied only (1) when these sources are likely to have indeed arisen from a single event, and (2) when the details of the timing of that event are likely to be significant. It is not likely when stimuli occur on different parts of the body (e.g. the lip and foot) that they originate from the same event, but is very likely when they originate from a single body part. Visual and tactile information about single events are particularly likely to involve the hand because one tends to look at things while manipulating them. During such manipulations significant information about single events, such as the contact of a finger with a key on a keyboard, are carried by both visual and tactile systems. Accurate matching of these systems requires compensation for any neural timing differences.

Achieving simultaneity constancy requires calibration and flexibility. A simultaneity constancy mechanism needs to be responsive to changing environmental demands. We were able to exploit this flexibility to see if adapting the PSS of a pair of stimuli that exhibit simultaneity constancy would affect the PSS of other combinations. Shifts in light/sound timing judgements were found after repeated exposure to light/sound stimuli with a lag between them. This shift did not transfer to touch/light judgements compatible with there being multiple independent simultaneity constancy mechanisms.

Touch–light simultaneity constancy

Here we demonstrate that judgements of simultaneity for touch/light pairs on the hand are independent of the differences in their neural processing times. This is an example of simultaneity constancy. Simultaneity constancy has also been previously demonstrated for light/sound pairs (Engel and Dougherty 1971; Sugita and Suzuki 2003; Kopinska and Harris 2004). For light/touch comparisons the situation is not as clear. Spence et al. (2003) found that the visual/tactile PSS was closer to zero when the stimuli were in the same place but did not demonstrate full compensation. Dassonville (1995) asked his subjects to compare the location of touches on a moving arm to that of an earth stationary light. He found no evidence of an internal compensation for the difference in neural processing times between the touch and light but his task was rather more demanding computationally than making a simple temporal order judgement. It is possible that stimuli pairs that are subject to simultaneity constancy differ physically from the stimuli used in studies that do not demonstrate simultaneity constancy. It has been suggested that "higher-order stimuli", such as moving stimuli, may not be affected by simultaneity constancy adjustments, whereas "lower-order stimuli", such as simple light, mechanical touches and tones used here, may be adjusted effectively (Arrighi et al. 2005).

Spence et al. (2001) carried out an extensive series of experiments using touch/light pairs in the same or different locations. They manipulated attention and showed that attending to a stimulus speeds reaction times to it and consequently affects temporal-order judgements: the phenomenon of "prior entry". They found that generally, a light had to be presented some 30 ms before a touch on the hand to be perceived as simultaneous, arguing against a touch/light simultaneity constancy mechanism. However, the lights were not actually presented attached to the hand in these experiments, and, moreover, for some light/touch pairs in the same location—especially on the left—some simultaneity constancy was noted.

The results of Spence et al. (2001) might suggest that apparent simultaneity constancy can arise artefactually if processing times are manipulated by guiding attention appropriately, in this case by attending to the light and, thus, speeding up its slowed response to match that of the touch on the hand. However, the corresponding shifts that such an attention-driven shift would have produced for the other conditions shown in Fig. 4b and c were not found.

Lack of a touch–touch simultaneity mechanism

Despite demonstrating simultaneity constancy between light/touch pairs, and the existence of other examples (light/sound pairs) both between and within modalities (Kopinska et al. 2003), the present study failed to find intramodal simultaneity constancy for two touches on different parts of the body. Bergenheim et al. (1996) also found that PSSs for very brief touches on the foot and arm (foot 11.5 ms before the arm) closely matched the reaction time differences he measured with the same stimuli (13.5 ms). However, they perversely concluded that this demonstrated compensation, since both of these values were too small to be explained by conduction velocities alone, and that some global compensation might have taken place that speeded them all up and separated perceptual processes from their underlying neural events. Using our analysis, a PSS that closely matches the reaction time difference is evidence of "no compensation". By widely separating our stimuli on the body (thus, increasing our reaction-time-based predictions), we found no significant compensation for multiple touches on different parts of the body (Fig. 3.).

The inconsistency in results, partial compensation for some touch–touch pairs and no compensation for others, may be because of the unequal intensity of the touches over the body. The touch stimulators could not be perfectly equated since there are multiple ways to do this, each with its own advantages and limitations. The sensitivity imbalance may have affected temporal order judgements by means of prior entry (Spence et al. 2001); attention to the more sensitive skin might cause the PSS to shift towards less sensitive skin areas.

Multiple, independent simultaneity mechanisms

Our adaptation data showed that while the PSS for a pair of stimuli could be altered by adaptation, this shift in PSS did not transfer to other pairs of stimuli. Successful adaptation to light-before-sound requires the processing of sound to be speeded up, or the processing of light to be slowed down, or some combination of the two. The speeding up of sensory processing is subject to biological limitations more than the slowing down of sensory processing, which requires the addition of a delay. However, the slowing down of sensory processing could be dangerous. Therefore, we expected that changes in response to adaptation would involve changes in the processing times of both sound and light. If simultaneity constancy involved a single system, then such changes would cause TOJs for other pairs, e.g. touch/light to be affected. No such shift in the PSS of the touch/light pair was observed. These data could be explained by a single system only if we assume that the sound's (and not the light's) processing rate had been altered by the adaptation—independent of the direction of the adaptation paradigm. However, the presence of a shift in the light/sound PSS with no effect on light/touch PSS is consistent with multiple independent simultaneity mechanisms; such that one can be altered without affecting the others. Such flexible, task-dependent, separate timing mechanisms have been postulated as underlying other aspects of temporal processing (Ivry and Spencer 2004).

The model behind Bergenheim et al.'s (1996) assertion that both reaction times to individual touches experienced alone and the PSS might be less than predicted by a consideration of nerve lengths and conduction velocities, rests on their interpretation of the

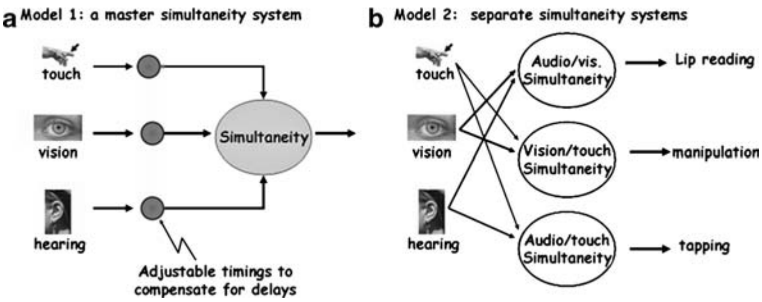

Fig. 6 Two possible mechanisms for the brain to achieve simultaneity constancy. **a** All sensory information is individually adjusted to synchronize to a common standard. **b** Each combination of senses is matched separately with different adjustments available for each match

multiple drafts model of consciousness proposed by (Dennett and Kinsbourne 1992). This model, in common with Libet's model of referred consciousness (Libet et al. 1979; Libet 1991, 2004), solves the problem of knowing when things occur, at least relative to each other, by "tweaking" their timing in the process of constructing consciousness. If individual reaction times are to be subject to this adjustment, then this implies a single simultaneity constancy mechanism in which all inputs are brought into virtual synchrony (Grossberg and Grunewald 1997). This model is illustrated diagrammatically in Fig. 6a.

Here we propose that instead, there are multiple simultaneity constancy mechanisms, which are each involved in very different tasks and subject to different constraints. The model is illustrated in Fig. 6b. In this model, information from a given sense, e.g. vision, is not adjusted as an obligatory part of its processing, to be synchronized with all possible other sensory inputs, as would be required by a central simultaneity mechanism. This would, in any case, be a computationally consuming strategy, since a visual stimulus originating from some distance away could be simultaneous with a sound that might not arrive at the ears for some time. In this case, all sensory processing would need to be delayed in order to be synchronized with the late-arriving sound, thereby seriously compromising the ability to react quickly to dangerous stimuli. Although it might be advantageous to delay visual processing when specifically processing distant bimodal auditory/visual stimuli, it would often be an unacceptable cost to delay visual awareness by more than a minimum amount.

The multiple simultaneity constancy model maintains the flexibility to match vision to sounds when, for example, lip reading (Pandey et al. 1986), but at the same time, use vision for other tasks, such as manipulation, and to remain responsive to other multimodal demands.

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