

Libet's Temporal Anomalies: A Reassessment of the Data

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Benjamin Libet compared the perceived time of direct brain stimulation to the perceived time of skin stimulation. His results are among the most controversial experiments at the interface between psychology and philosophy. The new element that I bring to this discussion is a reanalysis of Libet's raw data. Libet's original data were difficult to interpret because of the manner in which they were presented in tables. Plotting the data as psychometric functions shows that the observers have great uncertainty about the relative timing of events, as seen the shallow psychometric slopes. A second indication of uncertainty comes from Libet's use of three response categories, A first; B first; and A and B simultaneous. The large number of "perceptually simultaneous" responses provides a further measure of the difficulty of the judgment. There are thus a very broad range of stimulus delays in which the subject is unable to make an accurate ordering response. These points provide evidence that there is no compelling reason to invent exotic or ad hoc mechanisms to account for Libet's data since the uncertainty window is large enough to allow simple mechanism such as memory shifts. Libet argued that his data provide evidence for a backward referral in time. I argue that even though Libet's own data are weak, there are good arguments for a backward referral mechanism to help the subject make sense out of the tangled chaos of asynchronous information associated with experienced events. © 2002

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1. INTRODUCTION

Over the past three and a half decades Benjamin Libet (1965, 1993) has measured neural activity in patients undergoing brain surgery. Through a large number of difficult and clever experiments he has produced unique sets of data connecting brain activity to sensory awareness and volition. In the studies to be considered here, Libet (Libet, Wright, Feinstein, & Pearl, 1979) compared the time of subjective awareness produced by cortical or thalamic stimulation while patients were undergoing neurosurgery, to the subjective event time produced by visual or skin stimulation. He concluded that a backward referral in time (to be clarified) was needed. The present article argues: (a) a reanalysis of Libet's data shows that the raw data are weak and do not imply exotic mechanisms since simple physiological mechanisms can account for the data, (b) even though Libet's data are weak, and even though there are multiple physiologically plausible mechanisms to account for his data, backward referral in time is a sound idea and useful for an organism to implement and can be achieved without exotic mechanisms.

Although Libet himself has been somewhat careful in avoiding overstating the data's implications, a number of others have been less modest. For example, Penrose's three popular books (1989, 1994, 1997) involving physics and mind feature

Libet's experiments on time anomalies. Penrose and, more recently, Wolf (1998) argue that quantum mechanisms are needed for consciousness and Libet's data are the only data cited. Popper and Eccles (1977, p. 364) comment that "the antedating procedure does not seem to be explicable by any neurophysiological process." A number of prominent philosophers (Churchland, 1981a, 1981b; Dennett, 1991; Dennett & Kinsbourne, 1992) have pointed out how Libet's data are not surprising and can be explained quite simply in terms of standard neural mechanisms. Thus it is interesting to ask why is there still such a commotion over Libet's findings. I think that part of the answer is that Libet's data on time anomalies are hard to grasp conceptually and the resulting confusion produces misunderstandings. One of the goals of the present article is to present Libet's data graphically, in the form that is most commonly found in the perception and psychophysics literature. I believe that with this form of data presentation it will be easier to grasp whether exotic models are needed. My conclusion is that they are not needed.

2. LIBET'S EXPERIMENT ON BACKWARD REFERRAL

The critical findings of Libet's experiments on time anomalies can be summarized as follows:

(i) A cortical or thalamic stimulus require a duration of more than 250 ms to be felt, whereas a skin stimulus of 20 ms is adequate. The stimulus duration needed to generate a feeling is called the "neuronal adequacy" time (NA). It can differ from the perceived time of the feeling. Libet is often quoted as saying that $NA = 500$ ms is needed for brain stimulation, but that is only for very weak stimuli near threshold. In the backward referral experiments medium strength stimuli are used giving $NA \approx 250$ ms. With these stronger stimuli Libet gets useful data that are able to avoid several critiques (Churchland, 1981a, 1981b).

(ii) A cortical stimulus whose onset arrives within 250 ms after a skin stimulus can suppress or enhance the skin response or the memory of that response, if it has an overlapping felt location. Libet uses this data to argue that the skin stimulus has a 250-ms (or more) delay before becoming conscious. However, a much shorter skin delay is possible if it is a memory of the skin response that is suppressed (Dennett, 1991; Pockett, 2002).

(iii) For a skin stimulus to be felt as synchronous with a nonoverlapping brain stimulus, the skin stimulus must be delayed about 250 ms relative to a cortical stimulus or delayed about zero ms relative to a thalamic stimulus (Section 5 presents these raw data and explores the uncertainty of the synchrony judgments).

(iv) Both the skin and the thalamic stimulation generate an evoked potential (E) shortly after stimulus onset. The cortical stimulus does not generate this potential.

Items (i), (ii), and (iv) are summarized in Fig. 1A. The XX in connection with the skin stimulation indicates the upper limit for when the skin feeling can be canceled by a cortical stimulus (item (ii)). Item (iii) is summarized in Figs. 1B or 1C by the circled Q's that indicate the timing of the qualia. The thalamic, skin, and cortical stimuli are taken to have the same onsets.

Libet argues that his data on cortical stimulation imply a backward referral in time of the skin stimulation qualia since item (ii) seems to imply that the skin stimulation

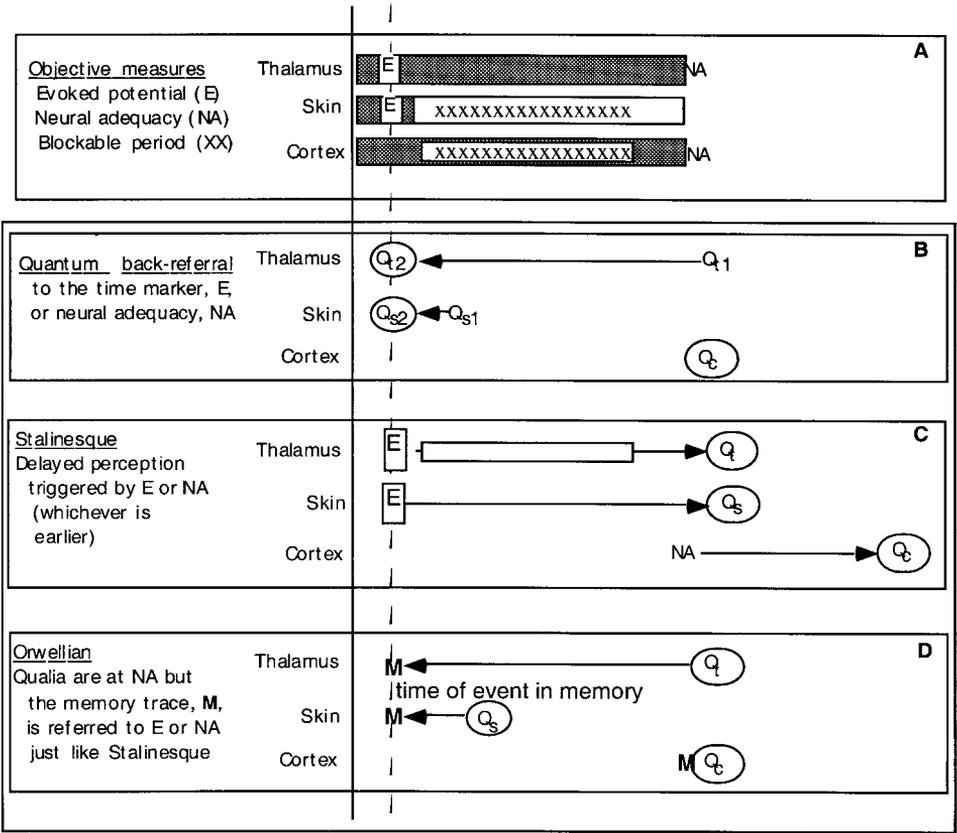


FIG. 1. (A) Summary of Libet's data. NA, neuronal adequacy duration, indicated by the cross-hatched bar, representing the duration of brain stimulation needed to become conscious. In these backward referral experiments strength of electrical stimulation was above the threshold level and NA was about 250 ms. E, evoked potential elicited by skin and thalamic, but not cortical stimulation. (B–D) Possible explanations of Libet's data. Q surrounded by a circle represents the time of the felt qualia. Subscripts t, s, c indicate whether the qualia came from thalamic, skin, or cortical stimulation. (B) Back-action whereby the original qualia at the time of NA are shifted in time back to the time marker (E for thalamic or skin stimulation and NA for cortical stimulation). This back-action requires an exotic mechanism involving a revision of the present laws of quantum mechanics such as proposed by Penrose (1989). (C) Stalinesque case where the qualia occur at a fixed delay from the time marker. (D) All qualia occurring at a fixed time from the time of neuronal adequacy, as was the case of the original qualia in (B), but the memory marker is placed at the time marker. The Darwinian survival advantage of this option is taken up in the Discussion.

does not become conscious for about 250 ms so that it could be canceled by the cortical masker. Backward referral is then needed to account for the combination of items (ii) and (iii).

The backward referral argument is easier to justify in the thalamic case since there is a decoupling between the duration for neuronal sufficiency and the time of subjective equality of skin vs the thalamic stimulation. That is, for thalamic stimulation it

seems that conscious awareness comes before there is sufficient stimulation to produce the awareness. Libet argues that since the thalamic sensation does not reach neuronal adequacy until 250 ms after the pulse train begins (item i), a back referral mechanism is needed with thalamic stimulation to produce the synchrony sensation (item iii) that is perceived. Referring to this argument, Pockett (2002) says, "At first sight Libet's logic seems inescapable." On second sight Pockett (2002) discusses the possibility of facilitation that reduces the neuronal adequacy time for brain stimulation from about 250 ms to a time that is comparable with the brief skin delay. However, Pockett (2002) did not present data or refer to data indicating that the facilitation could dramatically cut the neuronal adequacy time (NA) in half, as would be required to match the time for the skin stimulus to reach consciousness. Pockett's suggestion has the advantage that it is testable by reproducing Libet's experiment and measuring the NA following a period of stimulation. However, until clear evidence is found for this dramatic reduction in NA, it seems reasonable to continue with the assumption that there is not a large decrease in NA due to facilitation.

3. MULTIPLE EXPLANATIONS OF LIBET'S DATA

A number of physiologically plausible (nonquantum) explanations have been proposed for Libet's data (Churchland, 1981a, 1981b; Honderich, 1984; Glynn, 1990; Libet vs Glynn, 1991; Dennett, 1991; Dennett & Kinsbourne, 1992; Gomes, 1998). I especially recommend the Dennett and Kinsbourne (1992) *Behavioral and Brain Sciences* (BBS) article plus 28 peer commentaries by many of the top thinkers in this area (including Libet), and the responses by Dennett and Kinsbourne. Much of that discussion is about alternative interpretations of Libet's data. The give and take of the BBS format makes for exciting reading. The recent article by Gomes (1998) is also first class. Gomes examines numerous alternative explanations of most of Libet's many experiments. For a more chatty discussion of Libet's experiment I recommend Dennett (1991) because of his picturesque language, which makes the alternative explanations easy to recall. The Dennett (1991) and Dennett and Kinsbourne (1992) analyses of Libet make sense even if one disagrees with Dennett's critique of the meaningfulness of qualia.

Dennett points out that our brain has adopted numerous tricks to make sense of its tumultuous neural activity. He calls some of these tricks Orwellian and some Stalinesque. A Stalinesque account involves hallucinating (misperceiving, seeing illusions) whereby the brain generates images not in agreement with the input information (similar to Stalin's staged trials). An Orwellian account involves rewriting history (now called false memories). For example, item (ii) could be caused by brain stimulation erasing the memory of a conscious skin touch, an Orwellian mechanism. Dennett spends the main part of his Chapter 6 ("Time and Experience") on Libet's experiments. Further clarification on the application of the Stalinesque vs Orwellian means of dealing with Libet's time anomalies can be found in Libet's (1993) article in the CIBA Foundation Symposium volume. At the end of that article is a discussion by a number of philosophers including Dennett and Searle together with Libet's responses and several counterresponses.

Three explanations of the subjective data are shown diagrammatically in Figs. 1B–

1D. These explanations make use of Libet's finding an early evoked potential following skin and thalamic stimulation but not cortical stimulation. The time marker used for backward referral would be either the evoked potential, E, or the point of neuronal adequacy, NA, whichever is earlier.

Figure 1B shows an exotic backward causation explanation, whereby the stimulus is perceived before thalamic neuronal adequacy is reached. The perception is transferred back to the time of the evoked potential (E) if an evoked potential is present. Note that since all the time markers and qualia *follow* stimulus onset there is no violation of physical causality in the objective data. However, the exotic quantum mechanism proposed by Penrose (1989, 1994) seems to violate causality in the link between consciousness and neural processing since the awareness of thalamic stimulation comes before there is enough time for the stimulus to become conscious. A nonexotic variant of this explanation is Pockett's suggestion that after repeated stimulation of the thalamus a facilitative mechanism reduces the time of neuronal adequacy such that the qualia evoked by thalamic stimulation occurs at about the same time as that evoked by skin stimulation. As discussed earlier, until support for this facilitation hypothesis is found, it would be prudent to assume that facilitation is not strong enough to account for the large backward referral shift.

Figure 1C depicts a Stalinesque explanation (Dennett, 1991), whereby the time of the sensation occurs at a fixed delay from the time marker. This is also Churchland's (1981a, 1981b) and Glynn's (1990) account. The best recent discussion of this particular analysis is given by Gomes (1998). All paradoxical results are removed by having the delay based on the evoked potential rather than the time of neuronal adequacy in the case of thalamic and skin stimulation.

Figure 1D reveals an Orwellian explanation (Dennett, 1991), whereby the qualia for any stimulus are delayed, but the timing of those perceptions is not recorded. What gets into memory is based on the time marker information. This explanation actually involves backward referral of memories laid down later, pointing to the time markers. Neither of these last two mechanisms needs exotic physics.

Libet found that for normal stimulation of the skin there is an evoked potential, about 70 ms after the stimulation itself (Libet et al., 1979). When the event is laid down in memory it makes sense for the memory to be associated with the time set by the evoked potential time marker. This would produce a backward referral sensation. Libet also found that a similar evoked potential time marker was present for thalamic stimulation but not for cortical stimulation (Fig. 1A). Since the cortical stimulation has no evoked potential time marker the memory would have to be associated with the later event of neuronal adequacy, the Orwellian explanation of Libet's data. Gomes (1998) raises the point that the evoked potential cannot be a perfect marker. He says (Gomes, 1998, p. 581), "Two simultaneous stimuli can lead to sensations that are not simultaneous. The attended stimulus is experienced as coming before the unattended one, although the primary evoked potentials they produce are certainly simultaneous." We will come back to attentional shifts in synchrony judgments in the Discussion (Section 6).

A few physicists find the Stalinesque and Orwellian explanations to be ad hoc and distasteful. Gomes (1998) shows that these explanations are quite plausible. In any case, psychologists and biologists are quite familiar with the inelegant contrivances

that evolution invents again and again. Section 5 of this article offers a reanalysis of Libet's data in terms of psychometric functions and shows that the temporal shifts are relatively small relative to the uncertainties in the observers' judgments. Therefore, the contrivances or ad hoc assumptions needed to account for Libet's data are quite modest compared to the exotic mechanisms that are invented to account for many standard visual illusions.

4. STANDARD PSYCHOPHYSICAL ANALYSIS

This section provides an introduction to the topic of psychometric functions as applied to temporal asynchrony judgments. Consider the task of comparing the subjective time of a skin touch relative to a light flash. The subject is shown the pair of stimuli with a variety of asynchronies. The percentage of times that the skin appears later will have a shape such as that shown in the top panel of Fig. 2. This curve,

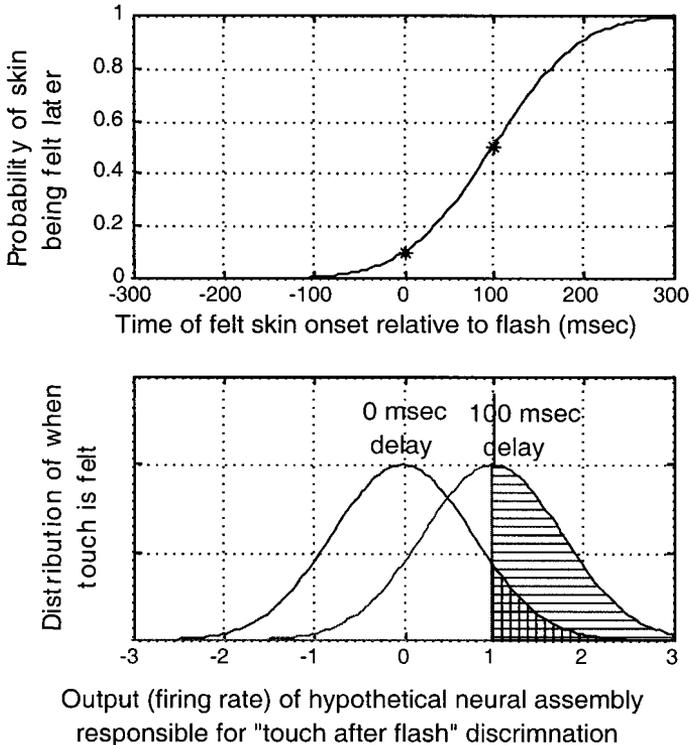


FIG. 2. Top panel shows a cumulative normal psychometric function used as an illustration. The abscissa is the objective time of a tactile stimulus relative to a flashed stimulus. The ordinate is the probability that the tactile stimulus is felt after the flash. When the touch comes 100 ms after the flash they are perceived to be simultaneous, indicated by the asterisk on the curve at the 50% point. The 100-ms delay corresponding to the 50% point on the ordinate is called the point of subjective equality (PSE). Bottom panel shows left and right Gaussians representing the probability distribution for stimulus asynchronies of 0 and 100 ms, respectively. The vertical line is the criterion the subject uses in making the responses shown in the upper panel.

relating an objective quantity (the objective stimulus asynchrony in this case) to a subjective quantity (the percentage of time one stimulus appears earlier than the second), is called the psychometric function. The psychometric function is characterized by two numbers: (i) the stimulus strength corresponding to the 50% response point, called the point of subjective equality (PSE); (ii) the slope of the function which is inversely related to the discrimination threshold.

For the psychometric function in Fig. 2, when the touch and flash are synchronous the subject says the touch appears later 10% of the time. When the touch is applied 100 ms after the flash then it appears later 50% of the time. One might have thought that the subject would have said 50% for the zero stimulus asynchrony but it is common in these types of experiments to find subjective biases. In this example there is a bias of 100 ms (PSE = 100 ms). There are two general reasons for finding a displaced PSE. First, there might be offsets due to sensory processing. Klein (1999) discusses the example of the Muller-Lyer size illusion (a comparison of two lines with arrowheads pointing inward vs outward) for which there are several sensory processing explanations. The second possibility for nonzero PSEs are response biases in which the PSE shift is produced at a late (response) rather than an early (sensory) stage. Klein (1998) discussed this possibility in detail in connection with blindsight individuals. Rather than being blind these individuals may have shifted their "seeing" PSE to be very conservative (the stimulus needs to be super visible before they say they see it). Further details on interpreting psychometric functions and bias problems are discussed by Klein (2001).

In addition to the PSE, the psychometric function is characterized by its slope. The top panel of Fig. 2 indicates that the transition from touch first to flash first is not abrupt. The psychometric slope can be specified by noting that it takes 200 ms to go from 10 to 90% "touch first" judgments. In this article, we will define the discrimination threshold to be the change in stimulus asynchrony needed to produce the 10 to 90% shift, so in this example the asynchrony threshold is 200 ms. This broad distribution (shallow slope) means that the temporal ordering judgment is noisy. The noise can be represented by the broad Gaussian distribution shown in the bottom panel of Fig. 2. The abscissa represents the activity of an imaginary neuronal cell assembly whose output is the neural correlate of the subjective asynchrony. The leftmost Gaussian distribution represents the probability of a particular judged asynchrony for the case when the two stimuli are presented simultaneously. The units on the abscissa are arbitrary. For convenience we centered the Gaussian at zero because the stimuli were simultaneous. The breadth of the Gaussian indicates that there is about a 200-ms spread of uncertainty of the timing of the touch relative to the flash. The rightmost Gaussian is for the case of the touch coming 100 ms after the flash. Because the touch comes later, the neural activity is greater (shifted rightward).

The connection between the neural activity represented in the lower panel and the psychometric function in the upper panel is made when the neural activity is forwarded to a decision stage. The decision stage maintains a criterion, shown by the vertical line in the lower panel. If the neural activity is above the criterion then the subject says the touch comes later. The likelihood for this to happen is indicated by the area of the vertical crosshatching in the lower panel. When the touch stimulus follows the flash by 100 ms, the probability of the subject's response is increased,

as indicated by the horizontal crosshatching. The vertical and horizontal cross-hatching covers 10 and 50% of the Gaussian's area, directly corresponding to the data points in the upper panel. In this example the criterion in the bottom panel was not located at the zero point, but rather was shifted rightward. The rightward shift is called a response bias (Klein, 1998). Observers often exhibit response biases for no good reason. It is like a subject liking to say "heads" more often than "tails" in a coin flip prediction. The relevance of this discussion to the Libet data is taken up next.

5. A REANALYSIS OF LIBET'S RAW DATA

This section shows that the slopes of Libet's psychometric functions are sufficiently shallow and the criterion uncertainties are sufficiently large, that the timing shifts between skin and brain stimulation do not need special mechanisms. Libet presents his data in tables. His main data comparing thalamic vs skin stimulation is presented in his Table 2A (Libet, 1979). The data for subject GS are shown in the top three rows of Table 1, where I have combined Sessions B and C. The thalamus was stimulated on the right side corresponding to the left hand. The skin was stimulated on the right hand. The rightmost column of Table 1 is for the case where the thalamic stimulation occurs 200 ms after the skin stimulation. GS responded 16, 2, and 2 times that the thalamic stimulus was perceived as coming last, simultaneous, and first, respectively. The fourth row gives the fraction of times that the thalamic stimulus (left hand) is felt after the skin stimulus (right hand). For the +200-ms delay the thalamic stimulus was perceived to come later 16/20, or 80% of the time. For the looser criterion, where the simultaneous judgment is included with the "thalamus last" judgment, there were 18/20 responses or 90% of the time.

It is difficult to gain a quick impression of the meaning of the data by looking at a table of numbers. A plot is easier to use, so the data from Table 2A of Libet (1979) are plotted in Fig. 3. The data from Table 1 are plotted in the lower right panel. The ordinate is the percentage of occurrences that the left hand (thalamic stimulation) was perceived to be later than the right hand (skin stimulation). The abscissa is the time delay of the thalamic and skin stimulation; a positive number means thalamic

TABLE 1
Table of Events (Number of Observations/Total Number) for Lower Right Panel of Fig. 3

Thalamic onset relative to skin onset for GS	-200 ms	-100 ms	0 ms	100 ms	200 ms
Thalamic stimulation perceived last	0	0	6	10	16
Thalamic and skin stimulation tied	6	16	8	5	2
Thalamic stimulation perceived first	12	2	5	2	2
Thalamic stimulation last (asterisks)	0/18 = 0	0/16 = 0	6/19 = 0.32	10/17 = 0.59	16/20 = 0.8
Thalamic stimulation last or tied (diamonds)	6/18 = 0.33	16/18 = 0.89	14/19 = 0.74	15/17 = 0.88	18/20 = 0.9

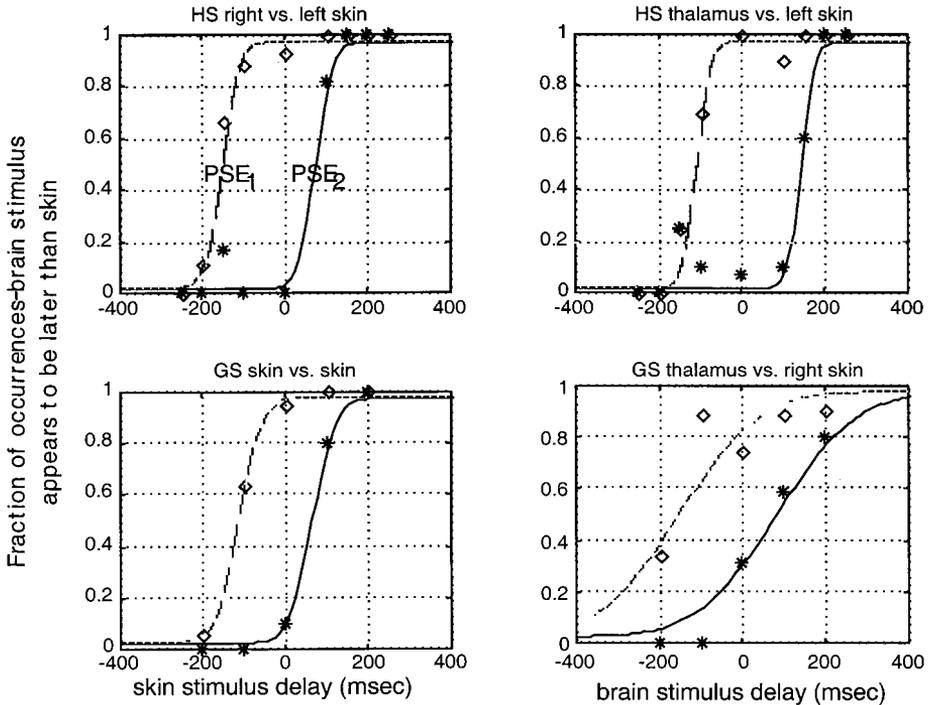


FIG. 3. Data from Table 2A of Libet (1979). The right panels compare the perceived timing of a thalamic stimulus relative to a reference skin stimulus. The left panels compare a skin stimulus to the same reference that was used in the right panels. The upper and lower panels are for two observers. The abscissa is the time of the thalamic stimulation relative to the skin stimulation. The ordinate is the fraction of occurrences that the thalamic stimulation is felt to occur after the skin stimulation. The observers used three categories for judgments: thalamus first, simultaneous, and thalamus last. The asterisks and the solid curve are for the “thalamus last” judgments. The diamonds and dashed line are for the looser criterion where the “thalamus last” and the “simultaneous” judgments are grouped together. The curves are fit to the data using cumulative normal function (probit analysis) with a 2.5% lapse rate. The gap between the two curves shows the fraction of time that the observer felt the two stimuli were simultaneous. This large gap indicates the difficulty of the asynchrony judgment and provides a measure of the uncertainty of the results. The average of the two plots shows that the judged asynchrony between skin and thalamic stimulation is small.

stimulation was later. The asterisks are for the stricter criterion where the “simultaneous” judgments are not grouped with the “thalamic later” judgments. The diamonds are the looser criterion where the “simultaneous” and “thalamic later” judgments are grouped together. The lower left panel is for a control experiment in which the skin was stimulated for both the right and the left hand (Session A of Libet’s Table 2A for patient GS). The two upper plots are similar data for subject HS, with hands switched (left hand skin stimulation was reference and left thalamus was stimulated). I hope the figures make Libet’s data unambiguous. I originally had trouble sorting out the sign of the time differences, which accounts for errors in plotting a preliminary version of this data analysis (Klein, 1999).

The two continuous curves in each panel are the best fits to the data. The fitting function is

$$\text{prob}_i(d) = g + (1 - 2g) \Phi((d - \text{PSE}_i)/\sigma). \quad (1)$$

$\Phi(z)$ is the standard cumulative normal distribution given by

$$\Phi(z) = (2\pi)^{-0.5} \int_{-\infty}^z \exp(-x^2/2) dx, \quad (2)$$

and where d is the interstimulus interval, PSE_1 and PSE_2 are the points of subjective equality for the two criteria. The slopes of the two curves in each panel are constrained to be equal and specified by σ , the standard deviation of the underlying Gaussian. The stimulus threshold, defined as the stimulus range for 10 to 90% correct, is 2.6σ . A guessing parameter, g , is commonly included (Klein, 2001) to allow for the possibility of making absent-minded errors even when the stimulus delay is large; g was constrained to equal 0.025. If g were set to zero the chi-square goodness of fit and the thresholds are found to be greatly elevated. Three free parameters were used to fit the data for each panel: two criteria, labeled PSE_i , (with $i = 1$ or 2) to locate the horizontal position of each curve, and one parameter, σ , to determine the slopes (threshold) of the curves. The two curves were assumed to have the same slopes.

The optimal parameter values were obtained by minimizing chi-square (Levi et al., 1984; Press et al., 1992),

$$\chi^2 = \sum_i \frac{(O_i - E_i)^2}{E_i}, \quad (3)$$

where O_i are the observed raw data (the upper three rows of Table 1) and $E_i = N_i \text{prob}(z_i)$ are the corresponding expected values based on the fitted curve. Results of the fit are summarized in our Table 2.

The optimal chi-square value is given in the last column of Table 2. For HS there are nine stimuli, at delays of ± 250 , ± 200 , ± 150 , ± 100 , and 0 ms. For GS the stimuli are at ± 200 , ± 100 , and 0 ms. Thus the summation is over $9 \times 3 = 27$ cells for HS and $5 \times 3 = 15$ cells for GS. The degrees of freedom (number of independent data

TABLE 2
Parameter Estimates and Standard Errors for the Psychometric Function Fits in Fig. 3

Subject and condition	PSE_1 (ms)	PSE_2 (ms)	10–90 threshold (ms)	Deg. free.	Chi-square
HS, skin–skin	-153 ± 13	69 ± 18	87 ± 26	15	8.9
HS, thalamus–skin	-111 ± 13	139 ± 13	68 ± 30	15	16.6
HS PSE shift	+41	+70			
GS, skin–skin	-115 ± 12	60 ± 13	117 ± 25	7	2.9
GS, thalamus–skin	-156 ± 56	78 ± 47	395 ± 127	7	17.9
GS PSE shift	-39	+18			

minus number of parameters) are $9 * (3 - 1) - 3 = 15$ and $5 * (3 - 1) - 3 = 7$ respectively, so the chi-square values are reasonable (chi-square is expected to be approximately equal to the degrees of freedom with a variance equal to twice the degrees of freedom).

The shifts in the average PSE shift between thalamus vs skin and skin vs skin are $(41 + 70)/2 = +56$ and $(-39 + 18)/2 = -11$ ms for HS and GS, respectively. Libet's average shift from his Table 2B (his A&C vs B&D) are $(42-18)/2 = 12$ and $(10-30)/2 = 20$ ms, respectively. The 30- to 40-ms discrepancies between our calculations and Libet's are due to our different methods of fitting the data. Our method (Levi et al., 1984), based on minimizing Eq. (3), is the standard method for fitting this type of data. In any case, the discrepancy between the two PSE calculations is small when compared to the 10-90% threshold. The approximate equality of perceived time of thalamic and skin stimulation shows up in Fig. 1 as follows: Panel B—the equality of timing of qualia (quantum back-referral explanation); Panel C—equality of delayed perceptions (Stalinesque explanation); and Panel D—equality of altered memory (Orwellian explanation).

Before further analysis of Fig. 3 and Table 2, it is useful to present the data from Libet's Table 3a comparing touch and visual stimulation with cortical rather than thalamic stimulation. As with the case of thalamic stimulation, the pulse train intensity was chosen to be sufficiently large so that the train duration needed for conscious awareness was between 200 and 300 ms. The actual pulse train that was delivered was between 500 and 700 ms.

Figure 4 shows the psychometric functions for three observers, JW, CJ, and MT. These are the three observers that Libet considered to be his best examples for illustrating backward referral. The bottom pair of panels is for observer MT, who had a slightly different stimulus; a visual flash was paired either with a skin stimulus or a cortical stimulus. The results of the chi-square minimization fit are shown in Table 3.

Standard errors are undefined in several conditions because of scanty data. The column labeled "No. good data" is a count of the number of data points that lie on the sloping part of the psychometric function rather than at either of the two asymptotic levels, 0 and 100%. For the skin-skin data of JW there is only a single data point on each of the psychometric functions. Thus the slope of the functions is indeterminate. For the skin-skin data of JW and CJ there was only a single point on the psychometric function between 0 and 100%, so the computer was unable to estimate the slope and threshold errors (indicated by "??"). Crude estimates of the PSE and threshold are given (and indicated by "?" because the slope is not well estimated). For the skin-cortex data of CJ there were no trials in which the observer responded that the cortex stimulus was first, so the search program was unable to produce a standard error estimate for the right-most criterion. Even though there are not many points on the sloping region of the psychometric function, Fig. 4 shows that except for the cortex-skin delay of CJ's PSE₁ the parameters are fairly well constrained.

The scanty data also produced abnormally low chi-square values (right-hand column). The expected chi-square is approximately the number of independent data minus 3 (the number of fitting parameters). With three free parameters one can nearly perfectly fit data that have at most three points between 0 and 100%. Only the lower

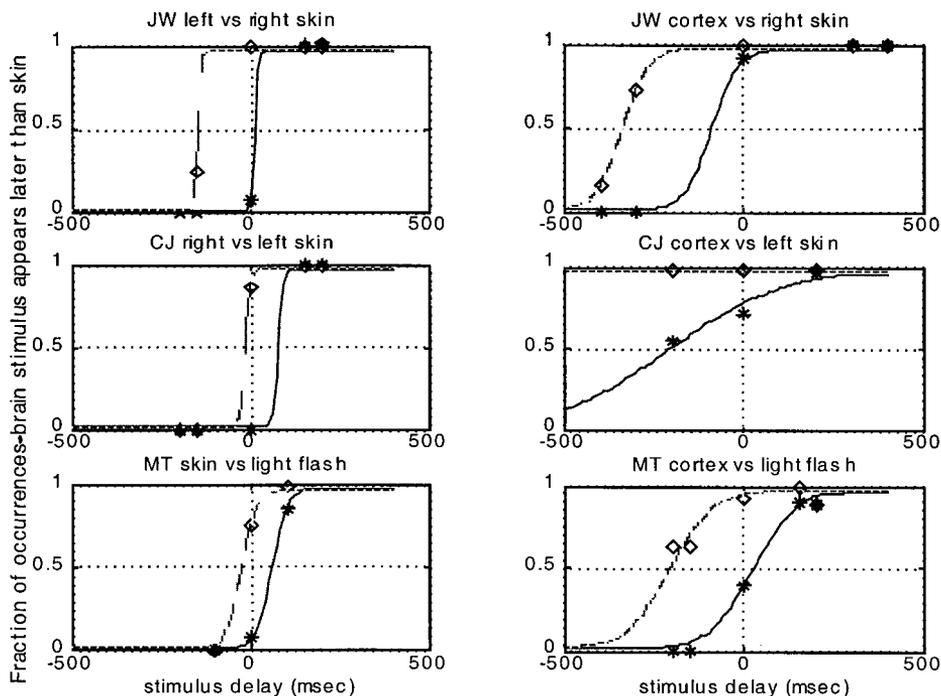


FIG. 4. Data from Table 3A of Libet (1979). The right panels compare the perceived timing of a cortical stimulus relative to a reference skin stimulus (or a visual flash for MT). The left panels compare a skin stimulus to the same reference. Results for three observers are shown. See the legends for Fig. 3 for details of the plots, with “cortical” replacing “thalamic” stimulation. The average of the two plots show that the curves for cortical stimulation are shifted leftward corresponding to cortical stimulation judged as being later than skin stimulation when both stimuli begin at the same time. For the cortical stimulation, the large gap between the two criteria curves and the shallow slopes indicate that the shift in PSE is not large enough to warrant exotic explanations.

TABLE 3

Parameter Estimates and Standard Errors for the Psychometric Function Fits in Fig. 3

Subject and condition	PSE ₁ (ms)	PSE ₂ (ms)	10–90% threshold	No. “good” data	Degrees of freedom	Chi-square
JW skin–skin	–144? ± ??	+11? ± ??	19? ± ??	2	7	1.5
JW cortex–skin	–338 ± 22	–91 ± 60	154 ± 74	3	7	1.2
JW PSE shift	–194	–102				
CJ skin–skin	–13? ± ??	+74? ± ??	28? ± ??	1	3	1.3
CJ cortex–skin	<–400? ± ??	–213 ± 246	639 ± 452	2	3	1.6
CJ PSE shift	<–400	–287				
MT skin–flash	–25 ± 17	+58 ± 17	89 ± 29	3	3	0.9
MT cortex–flash	–208 ± 31	+22 ± 29	249 ± 78	6	7	5.6
MT PSE shift	–183	–36				

right panel of Fig. 4 has more than three points away from the asymptotic region. See Klein (2001) for a discussion of bias in the chi-square distribution when there are a low number of trials in the cells.

Table 3 shows that for the cortical stimulus to be perceived either last or tied 50% of the time (the definition of PSE_1), the cortical stimulus needs to be given -194 , < -400 and -183 ms before the skin (or flash) stimulus for subjects JW, CJ, and MT. For the cortical stimulus to be perceived last 50% of the time (definition of PSE_2) the cortical stimulus needs to be given -102 , -287 , and -36 ms before the skin (or flash) stimulus. The negative values of PSE indicates that the perceived time of the cortical stimulation has an extra delay of between 36 and 400 ms, as indicated in the delays of qualia or memory in Fig. 1 for the cortex vs skin comparison.

Three problems with Libet's data, revealed by examining Figs. 3 and 4 and Tables 2 and 3, are now examined.

(1) Klein (1999) discusses that in order for a PSE shift to be noteworthy it should be substantially greater than threshold. When the PSE shift is less than about two times threshold, one worries that the PSE shift could be accounted for in terms of bias or attention factors. For a PSE shift to be called a true illusion the shift must be large compared to threshold. Further comments on attentional effects when comparing multisensory stimuli will be considered in the Discussion.

As seen in Fig. 4 and Table 3 the PSE shifts in the cortical data are not large when expressed in threshold units. The entire backward referral enterprise of Penrose is based on the belief that there is a trustworthy substantial shift between the time of cortical awareness vs skin awareness. The shift should be large compared to threshold for the backward referral to be taken seriously as a real "illusion." For observer CJ the 10–90% threshold is 639 ± 452 ms. This is much larger than the measured shift of $213 - (-74) = 287$ ms found for the "cortex last" criterion (PSE_2). PSE_1 was not obtainable from the data, since CJ responded that the cortex stimulus never appeared first for all asynchronies when using the PSE_1 criterion. I placed a " $PSE_1 < -400$ -ms" entry in Table 3 for PSE_1 but the threshold is also large and uncertain, so this very large offset is not that impressive. For observer MT, the threshold is 249 ms, but the cortex-to-skin shift is $22 - 58 = -36$ ms for the "cortex last" criterion (PSE_2) and -183 ms for the "cortex last or equal" criterion (PSE_1). Only for JW is the threshold of 154 ms not larger than one of the criterion shifts, with $PSE_1 = -338 + 144 = -194$ ms and $PSE_2 = -91 - 11 = -102$ ms for "cortex last or tied" and for "cortex last," respectively. Our definition of threshold as going from 10–90% is conservative, but even if we had used a narrower definition, the PSE shifts would not be very large. Glynn (1990) pointed out these problems in a rough, qualitative way without having plotted the data or fitted the data with psychometric functions.

(2) The average cortex-to-skin shift is not large when compared to the uncertainty in the shift itself as measured by the separation between the two criterion PSEs. For JW and MT the difference between the two cortical PSEs were $338 - 91 = 247$ ms and $208 + 22 = 230$ ms. These values are large because the observers made very heavy use of the "tie" category where the two stimuli were perceived to be simultaneous. This heavy use of the tie category undermines any claim of a substantial shift. For CJ the time difference between the two PSEs was too large to measure (as indi-

cated by the question mark in the PSE_1 column for the cortex–skin PSE). The large number of tie responses indicates that the synchrony decision was difficult and not strongly reliable. For the PSE shift to be considered to be substantial it would have been good for the PSE shift to be substantially larger than the PSE uncertainty itself.

(3) Both of the considerations in items 1 and 2 also apply to Fig. 3 and Table 2 comparing the thalamic vs skin stimulation to skin vs skin stimulation. The thalamic data are good to examine because they are more robust than the cortical data. For GS the threshold is large, and for both observers the separation between PSEs is large, again because of heavy use of the tie condition. Thus, the uncertainty in the subjective timings, as evidenced in the raw data, makes it prudent to not develop exotic explanations for the claimed lack of PSE shifts in the thalamic case. The notion that the criterion placement is easily manipulable was also a theme of my Tucson II article on blindsight (Klein, 1998).

6. DISCUSSION

I have argued that Libet's data do not require new laws of nature such as suggested by Penrose (1989). I especially like the Orwellian expansion of Libet's data whereby after all the complex, incoherent neural activity has settled down, a coherent story gets laid down in memory. The story in memory might have slight timing shifts that differ from the order of actual events in the external world. However, there are limits to the magnitude of the timing shifts. For example, if two events are separated by as much as a second, it would be hard to see how an Orwellian rewriting of history would be possible since the occurrence of the first event would have already left a memory trace and it would be hard to reverse the order of events. However, if the two events are close enough in time that it is difficult to discriminate their temporal order, then Orwellian mechanisms should not be difficult to implement. It had not been well appreciated that Libet's subjects exhibited a large uncertainty making asynchrony judgments. Figures 3 and 4 plotted Libet's raw data that he had presented in tables. These plots make it easier to understand Libet's raw data. Tables 2 and 3 show the results of fitting the data with cumulative normal psychometric functions. The results reveal that the temporal uncertainty was about as large as the asynchrony itself. Because of that large uncertainty in judging asynchrony, Orwellian mechanisms that modify the timing of memory traces are quite plausible.

Anomalies in temporal judgments such as those claimed by Libet are not new. Spence, Shore, and Klein (2001) discuss the long history of instability in synchrony judgments across sensory modalities. My favorite of their examples concerns astronomers of the 18th and early 19th century who timed the moment a star crossed the crosshairs of a telescope by listening to the ticks of a clock. Large individual differences across observers were found in judging the star's transit time. Spence et al. (2001) carried out several experiments comparing the synchrony of touch and vision and present their data in plots similar to Figs. 3 and 4. They found that attentional manipulations can produce shifts of more than 100 ms in the perceived time of stimuli arriving through different sensory modalities (like brain and skin in Libet's case). I argued that when the psychometric function is shallow, as in the case of cortical stimulation seen in Fig. 4, one can expect even larger shifts.

The recent flurry of flash-lag experiments initiated by Nijhawan (1994) are also worth mentioning since they show synchrony illusions with PSE shifts substantially larger than synchrony thresholds. The flash-lag experiments measure the location of a moving dot at the instant of a flash. The moving dot is perceived as being ahead of where it really is at the time of the flash. Nijhawan's original explanation involved motion extrapolation. Motion extrapolation would be a convenient mechanism for tasks such as catching a ball where one needs to act on the future position of the ball. In Libet's language, the flash-lag experiments imply a "forward referral" mechanism. Among the alternatives to motion extrapolation that have been proposed, Baldo and Klein (1995) and Baldo, Kihara, Namba, & Klein, (2002) argue that an important component of the PSE shift is due to attentional factors. The flash-lag data are relevant to Libet's experiments in that they show that it is possible to obtain substantial subjective time shifts of up to 100 ms. These time shifts are smaller than those found by Libet. However, the temporal uncertainty in Libet's experiments, as revealed by the shallow psychometric function slopes, indicates that it should be easier to have larger asynchrony shifts.

Libet has received criticism for his notion of "backward referral in time" (Dennett, 1991; Gomes, 1998; Pockett, 2002). In the remainder of the Discussion I will argue that this criticism is unwarranted. Libet compares backward referral in time to the commonly accepted spatial referral in our sense of touch. When we touch something with our finger we refer the "feel" to the tip of our finger, whereas the main neural activity is in our brain. A blind person using a cane refers the "feel" to the tip of the cane. The situation in the temporal domain is similar.

It makes evolutionary sense for the perceived time of an event to be synchronous with the actual time. Neural delays would add complexity to understanding events. In order to be concrete it is instructive to do an admittedly crude experiment right now. Use your right forefinger to tap your left hand. Make a judgment of the subjective time of the feeling in the left hand, the feeling in the right hand, the visual moment of touch, and the expected time of impact. When I do it the four judgments feel synchronous. One might say that the synchrony of the tactile and visual events are compatible with a 250-ms delay of consciousness. However, the subjective time of these events are also compatible with the expected time of touch based on the motor commands. For our animal ancestors to survive it seems reasonable that their nervous systems would have had to evolve mechanisms to synchronize the various motor and perceptual systems. For events like touching and being touched a unique temporal point on which to synchronize is the time of the event itself. An Orwellian backward referral mechanism of memory could be used to achieve that synchrony. Without that synchronization our animal ancestors would have had trouble developing a coherent view of the world through the tangle of asynchronous neural activity.

John McCrone (personal communication) argues that my tapping experiment is not surprising because of its similarity to the reafference (or Sperry's corollary discharge) ideas associated with the stability of the world during eye movements. The idea here is that anticipation of an event can generate neural activity whose function is to produce a consistent neural story of the event. The world does not appear to jump when we make a saccade because the brain has figured out a way to use the available neural signals to present a consistent story to our subjective awareness. In

the case of catching a baseball, the consistent story proposed by Nijhawan (1994) would be to have moving objects extrapolated in time (forward referral) to compensate for neural delays. In the case of the finger tap the consistent story is one of synchrony of all the motor and sensory signals. The straightforward method to achieve synchrony is to have the remembered time of the event referred back to the anticipated time of the event. So even though Libet's data might be weak, his notion of backward referral might be strong.

ACKNOWLEDGMENT

The research for this article was partly supported by Grant R01 EY04776 from the National Eye Institute. I thank William Banks and Gilberto Gomes for a number of helpful suggestions.

Note added in proof. Gomes (1998, 2002) points out that a much weaker skin stimulus was used in the thalamus experiment, than in the cortex experiments. Implications are discussed in my commentary (Klein, 2002).

REFERENCES

- Baldo, M. V. C., & Klein, S. A. (1995). Extrapolation or attention shift? *Nature*, **378**, 565–566.
- Baldo, M. V. C., Kihara, A. H., Namba, K., & Klein, S. A., (2002). Evidence for an attentional component of the perceptual misalignment between moving and flashing stimuli. *Perception*, **31**, 17–30.
- Churchland, P. (1981a). On the alleged backwards referral of experiences and its relevance to the mind–body problem. *Philosophy of Science*, **48**, 165–181.
- Churchland, P. (1981b). The timing of sensations: Reply to Libet. *Philosophy of Science*, **48**, 492–497.
- Dennett, D. C. (1991). *Consciousness explained*. Boston: Little Brown.
- Dennett, D. C., & Kinsbourne, M. (1992). Time and the observer: The where and when of consciousness in the brain. *Behavioral and Brain Sciences*, **15**, 183–247.
- Glynn, I. M. (1990). Consciousness and time. *Nature*, **348**, 477–479.
- Gomes, G. (1998). The timing of conscious experience: A critical review and reinterpretation of Libet's research. *Consciousness and Cognition*, **7**, 559–595.
- Gomes, G. (2002). Problems in the timing of conscious experience. *Consciousness and Cognition*, **11**, 221–230.
- Honderich, T. (1984). The time of a conscious sensory experience and mind–brain theories. *J. Theoretical Biology*, **220**, 115–119.
- Klein, S. A. (1998). Double-judgment psychophysics for research on consciousness: Application to blind-sight. In Hameroff, Kazniak, & Scott (Eds.), *Toward a science of consciousness II*, pp. 361–369.
- Klein, S. A. (1999). Do apparent temporal anomalies require nonclassical explanation? In Hameroff, Kazniak, & Chalmers (Eds.), *Toward a science of consciousness III*, pp. 343–357.
- Klein, S. A. (2001). Measuring, estimating, and understanding the psychometric function: A commentary. *Perception & Psychophysics*, **63**, 1421–1455.
- Klein, S. A. (2002). Libet's timing of mental events: Commentary on the commentaries. *Consciousness and Cognition*, **11**, 326–333.
- Levi, D. M., Klein S. A., & Aitsebaomo, P. (1984). Detection and discrimination of motion in central and peripheral vision of normal and amblyopic observers. *Vision Research*, **24**, 789–800.
- Libet, B. (1965). Cortical activation in conscious and unconscious experience. *Perspectives in Biology and Medicine*, **9**, 77–86.
- Libet, B. (1993). The neural time factor in conscious and unconscious events. In *Experimental and theoretical studies of consciousness*, CIBA Foundation Symposium 174, pp. 123–146. Chichester: Wiley.

- Libet, B. vs Glynn, I. M. (1991). Conscious vs. neural time. *Nature*, **352**, 27–28.
- Libet B., Wright, E., Jr, Feinstein, B., & Pearl, D. K. (1979). Subjective referral of the timing for a conscious sensor experience: A functional role for the somatosensory specific projection system in man. *Brain*, **194**, 191–222.
- Nijhawan, R. (1994). Motion extrapolation in catching. *Nature*, **370**, 256–257.
- Penrose, R. (1989). *The emperor's new mind: Concerning computers, minds, and the laws of physics*. Oxford Univ. Press.
- Penrose, R. (1994). *Shadows of the mind: An approach to the missing science of consciousness*. Oxford Univ. Press.
- Penrose, R. (1997). *The large, the small and the human mind*. Cambridge Univ. Press.
- Pockett, S. (2002). On subjective back-referral and how long it takes to become conscious of a stimulus: A reinterpretation of Libet's data. *Consciousness and Cognition*, **11**, 144–161.
- Popper, K. R., & Eccles, J. C. (1977). *The self and its brain*. Springer-Verlag.
- Spence, C., Shore, D. I., & Klein, R. M. (2001). Multisensory prior entry. *Journal of Experimental Psychology: General*, **130**, 799–832.
- Wolf, F. A. (1998). The timing of conscious experience: A causality violating, two-valued, transactional interpretation of subjective antedating and spatial-temporal projection. *Journal of Scientific Exploration*, **12**, 511–542.

Received April 12, 2002