

Temporal Analysis of Cortical Mechanisms for Pain Relief by Tactile Stimuli in Humans

Koji Inui, Takeshi Tsuji and Ryusuke Kakigi

Department of Integrative Physiology, National Institute for Physiological Sciences, Myodaiji, Okazaki 444-8585, Japan

The mechanisms by which vibrotactile stimuli relieve pain are not well understood, especially in humans. We recorded cortical magnetic responses to paired noxious (intra-epidermal electrical stimulation, IES) and innocuous (transcutaneous electrical stimulation, TS) stimuli applied to the back at a conditioning-test interval (CTI) of -500 to 500 ms. Results showed that IES-induced responses were remarkably attenuated when TS was applied 20-60 ms later and 0-500 ms earlier than IES (CTI = -60 to 500 ms). Since the signals evoked by IES reached the spinal cord (CTI = -60 to -20 ms conditions) and the cortex (-60 and -40 ms condition) earlier than those evoked by TS, the present results indicate that cortical responses to noxious stimuli can be inhibited by innocuous tactile stimuli at the cortical level, with minimal contribution at the spinal level.

Keywords: intra-epidermal electrical stimulation, magnetoencephalogram, pain relief, transcutaneous electrical stimulation, vibrotactile stimuli

Introduction

Pain relief by vibrotactile stimuli is a well-known phenomenon. Although vibrotactile stimuli actually reduce experimental pain in animals (Woolf *et al.*, 1977) and humans (Wall and Cronly-Dillon, 1960), and pathological pain in patients (Wall and Sweet, 1967; Meyer and Fields, 1972), the underlying mechanisms of this inhibition are still largely unknown. Notably, whether such an inhibition of nociception occurs at the cortical level has not been investigated at all. Many previous studies have considered the dorsal horn of the spinal cord as an important site for this phenomenon where large myelinated fiber inputs are said to affect the central transmission of signals from nociceptors (Melzack and Wall, 1965). In the present study, we demonstrate that cortical responses to noxious stimuli can be substantially inhibited by innocuous tactile stimuli with minimal contribution at the periphery or spinal cord.

Materials and Methods

Nine healthy male volunteers aged 24-40 (mean 31.1) years participated in this study. The study was approved in advance by the Ethical Committee of the National Institute for Physiological Sciences and written consent was obtained from all the subjects. Experiments were conducted according to the Declaration of Helsinki.

Stimulation

For a test noxious stimulation, we used an intra-epidermal electrical stimulation (IES) method that we recently developed (Inui *et al.*, 2002a) for the selective stimulation of cutaneous A-delta fibers. However, the original method was modified slightly to provide high selectivity for the activation of nociceptors at a stronger intensity of stimulation than that used in previous studies (Inui *et al.*, 2002a,b, 2003a,b). We used a stainless steel concentric bipolar needle electrode (patent pending) for IES. The anode was an outer ring 1.2 mm in

diameter and the cathode was an inner needle that protruded 0.2 mm from the outer ring. By pressing the electrode against the skin gently, the needle tip was inserted in the epidermis and superficial part of the dermis where nociceptors are located, while the outer ring was attached to the skin surface. Two electrodes 5 mm apart were used for augmentation of the response. The two electrodes were placed in parallel with the midline of the back. The electrical stimulus was current constant double pulses at 100 Hz with a 0.5 ms duration, and was applied to the right side of the back 4 cm lateral to the ninth thoracic vertebral spinous process. We chose this point since (i) the area around the back's midline is suitable for minimizing the conduction distance from the point of stimulation to the spinal cord; (ii) we wanted to stimulate the peripheral nerve of one side; and (iii) a lower point than the Th9 level would mean a longer conduction distance to the spinal cord while a higher point caused magnetic noise related to thoracic movements, that is, the stimulation electrode attached to the back moved with respiration and produced magnetic noise. The current intensity was at a level producing a definite pain sensation of ~40-60 in the visual analogue scale (VAS, 0-100) in each subject, where 0 represented no painful sensation and 100 represented an imaginary intolerable pain sensation. The mean stimulus intensity was 0.3 ± 0.08 mA. IES did not cause flare reactions around the electrode, an indication of C-fiber activation, like in our previous study (Inui *et al.*, 2002a).

For a conditioning tactile stimulation, similar cutaneous sites were stimulated using a bipolar felt tip electrode (NM-420S, NihonKoden, Tokyo), 0.9 mm in diameter with a distance of 23 mm between the anode and cathode (transcutaneous electrical stimulation, TS). The felt tip electrode was placed just lateral to the concentric electrodes, and the center of them was 1 cm apart. The stimulus was double pulses at 100 Hz with 0.5 ms duration and the stimulus intensity was three times that of the sensory threshold (1.4 ± 0.2 mA) in each subject. Clear tactile sensations were elicited without any painful sensations using these stimulus parameters.

There were 13 stimulus conditions: control TS (conditioning stimulus alone), control IES (test stimulus alone) and 11 paired stimulus (IES + TS) conditions. In the eleven IES + TS conditions, paired stimuli were delivered with conditioning-test intervals (CTIs) of -500, -300, -100, -60, -40, -20, 0, 50, 100, 300 and 500 ms. Since the distance between the stimulus point and the corresponding level of the spinal cord is ~10 cm, it takes 1.7 ms for signals evoked by TS to reach the spinal cord at a conduction velocity of 60 m/s (A-beta fiber), while it takes 6.7 ms for signals due to ES at 15 m/s (A-delta fiber) (Inui *et al.*, 2002a,b). Therefore, in the IES + TS -500 to -20 ms conditions, signals caused by IES are expected to reach the spinal cord earlier than those due to TS. Signals conveyed through peripheral A-beta and A-delta fibers also ascend in the spinal cord at different conduction velocities: A-beta fiber signals at 50-60 m/s and A-delta fiber signals at 8-10 m/s (Kakigi and Shibasaki, 1991). Given that the respective velocity is 60 and 9 m/s and the length of the spinal cord between C1 and T9 is 30 cm, the conduction time through the spinal cord in this study is 5 ms for TS and 33.3 ms for IES. Given the conduction time in the periphery and spinal cord, the difference in response latency at the cortex for TS and IES is expected to be ~33 ms. This means that in the IES + TS -500 to -40 ms conditions, signals due to IES reach the cortex earlier than those due to TS.

Pain Rating

First, we compared pain ratings among the control (IES) and 11 IES + TS conditions to examine whether and how the conditioning tactile stimuli affect the intensity of the perceived pain sensation. The stimuli of twelve conditions were presented randomly at an interval of ~5 s and subjects assessed the intensity of the pain of each stimulus based on VAS (0–100). Ten trials were performed for each condition and the mean value was used for the analysis.

MEG Recording and Analysis

Because of the long experiment time, the MEG experiment was separated into two sessions. IES + TS conditions with CTIs of –40 to 500 ms were examined in the first session, and IES + TS conditions with CTIs of –500 to –60 ms in the second session. Therefore, there were nine conditions in the first session: control IES, control TS and seven IES + TS conditions with CTIs of –40, –20, 0, 50, 100, 300 and 500 ms. In the second session, there were six conditions: control IES, control TS and four IES + TS conditions with CTIs of –500, –300, –100 and –60 ms. The two sessions were performed on different days. Somatosensory evoked magnetic fields (SEFs) were recorded using a dual 37-channel axial-type first-order biomagnetometer (Magnes, Biomagnetic Technologies, San Diego, CA) as described previously (Kakigi *et al.*, 2000). The probes were centered on the C3 and C4 positions as based on the International 10/20 System. The SEFs were recorded with a filter of 0.1–200 Hz at a sampling rate of 1048 Hz, and then filtered offline with a bandpass of 0.5–150 Hz. Sweeps were triggered by the conditioning stimulus (TS) in the first session and by the test stimulus (IES) in the second session. The window of analysis was from 150 ms before to 800 ms after the conditioning stimulus, and the prestimulus period was used as the DC baseline. The stimuli of various conditions were presented randomly at an interval of 3–5 s. For each condition, 50 artifact-free trials were collected. Throughout the MEG experiment, subjects were instructed to look at a fixation point presented 1m in front of them.

Since magnetic fields recorded in the IES + TS conditions were a mixture of TS- and IES-evoked responses, we subtracted the control TS-induced response from the response recorded in the IES + TS conditions to obtain the actual IES-evoked response. Then we calculated the root mean square (RMS) across all 74 channels of the subtracted waveform to compare the amplitude of the IES-evoked response among conditions. This method is easy to perform and the results are easy to understand. This method is based on the assumption that the TS-evoked response is not influenced by concomitant IES. However, in some IES + TS conditions, the TS-evoked cortical response was substantially affected by a preceding IES as will be described below. Therefore, we then calculated how the TS- and IES-evoked responses explain the waveforms of the IES + TS conditions using a least squares fit. Since the waveform for a IES + TS condition is the sum of the waveforms of IES and TS with various ratios, it can be expressed as

$$f(\text{IES} + \text{TS}) = a \times f(\text{TS}) + b \times f(\text{IES}), \quad 0 \leq a, b \leq 1$$

where *a* and *b* are coefficients for TS and IES, respectively. The values of *a* and *b* indicate to what extent TS and IES contribute to the activity in the IES + TS conditions. When *a* is much larger than *b*, TS contributes to the waveform much more than IES, and vice versa. To obtain the best explanation of *f*(IES + TS), coefficients *a* and *b* must minimize the sum difference square,

$$\sum_{i=1}^{74} (\text{IES} + \text{TS}_i - a\text{TS}_i - b\text{IES}_i)^2$$

where $\text{IES} + \text{TS}_i$ are values for an IES + TS condition, TS_i are values for TS, and IES_i are values for IES. For example, by applying data at a latency point of 110 ms (peak latency) after TS for the IES + TS –40 ms condition in Figure 7, we obtained the following formula and calculated *a* and *b* to minimize its number:

$$1295212a^2 + 1080948b^2 - 2249122a - 1779640b + 2045030ab + 1060634$$

By solving this problem, we get *a* = 0.86 and *b* = 0.007, which indicate that the IES-evoked response does not contribute to the waveform of

the IES + TS –40 ms condition at this latency point. By using this method, we could assess whether and how the control IES-evoked responses were changed in IES + TS conditions without being affected by changes of the conditioning stimulus-evoked response.

Data were expressed as the mean ± standard deviation. Differences of values among conditions were assessed with a one-way analysis of variance (ANOVA). *P* values of < 0.05 were considered significant.

Results

Pain rating

The mean pain rating for the control condition (IES alone) was 44.3 ± 9.3 . The respective values for 11 paired stimuli conditions (IES + TS) with CTIs of –500, –300, –100, –60, –40, –20, 0, 50, 100, 300 and 500 ms were 43.1 ± 7.7 , 42.5 ± 8.2 , 39.7 ± 8.5 , 37.4 ± 9.5 , 12.7 ± 7.2 , 11.1 ± 6.3 , 13.7 ± 6.8 , 16.8 ± 7.9 , 23.6 ± 9.0 , 29.1 ± 11.3 and 33.4 ± 13.9 . Therefore, the pain rating was highest for the control condition and lowest for the IES + TS –20 ms condition. The difference among the twelve conditions was significant [$F(1,11) = 18.3$, $P < 0.0001$].

MEG Experiment

The mean onset latency of TS-induced magnetic fields (control TS) was 51.4 ± 7.2 ms for the first session and 49.2 ± 6.2 ms for the second session. The mean onset latency of IES-induced magnetic fields was 89.5 ± 15.4 ms for the first session and 87.5 ± 10.6 ms for the second session. The mean difference in onset latency between TS and IES was 38.1 ms (ranging from 16.2 to 59.5 ms) for the first session and 38.3 ms (from 18.2 to 54.8) in the second session. In all subjects, the field distribution of the waveform recorded from the left hemisphere (contralateral to the stimulus) following IES at the peak latency showed a single dipole pattern originating from the upper bank or bottom of the sylvian fissure corresponding to the secondary somatosensory cortex (SII)/insula region, or a two-dipole pattern originating from SII/insula and the primary somatosensory cortex (SI), similar to the results in our previous study following stimulation of the hand (Inui *et al.*, 2002b). In the right hemisphere (ipsilateral to the stimulus), clear magnetic fields were recorded in six subjects and the field distribution showed a single dipole pattern generated by activity from the SII/insula region. Figure 1 shows representative results in the first session. The nine traces in Figure 1A show recorded waveforms in each condition, and the seven traces in Figure 1B show the waveforms obtained by a subtraction of the control TS waveform from the waveform for each of the seven IES + TS conditions. The result of the subtraction clearly showed that cortical responses to IES were markedly attenuated when TS was applied at CTIs of –40, –20, 0 and 50 ms, moderately attenuated at 100 ms and slightly attenuated at 300 and 500 ms. Figures 2 and 3 show the mean time course of the amplitude of the recorded and subtracted waveforms represented as the root mean square (RMS) of all subjects. The mean peak amplitudes of the subtracted waveform of the IES + TS –500, –300, –100, –60, –40, –20, 0, 50, 100, 300 and 500 ms conditions were 100.3 ± 7.1 , 100.0 ± 12.2 , 99.9 ± 12.8 , 76.8 ± 21.4 , 34.5 ± 19.6 , 20.2 ± 12.7 , 23.4 ± 11.3 , 35.9 ± 16.5 , 45.0 ± 27.2 , 68.6 ± 27.0 and $71.0 \pm 26.5\%$ of the control response, respectively. The difference among the 11 conditions was significant [$F(1,11) = 27.4$, $P < 0.0001$]. There was a significant linear correlation between the peak amplitude and pain rating (Fig. 4, $r = 0.76$, $P < 0.0001$).

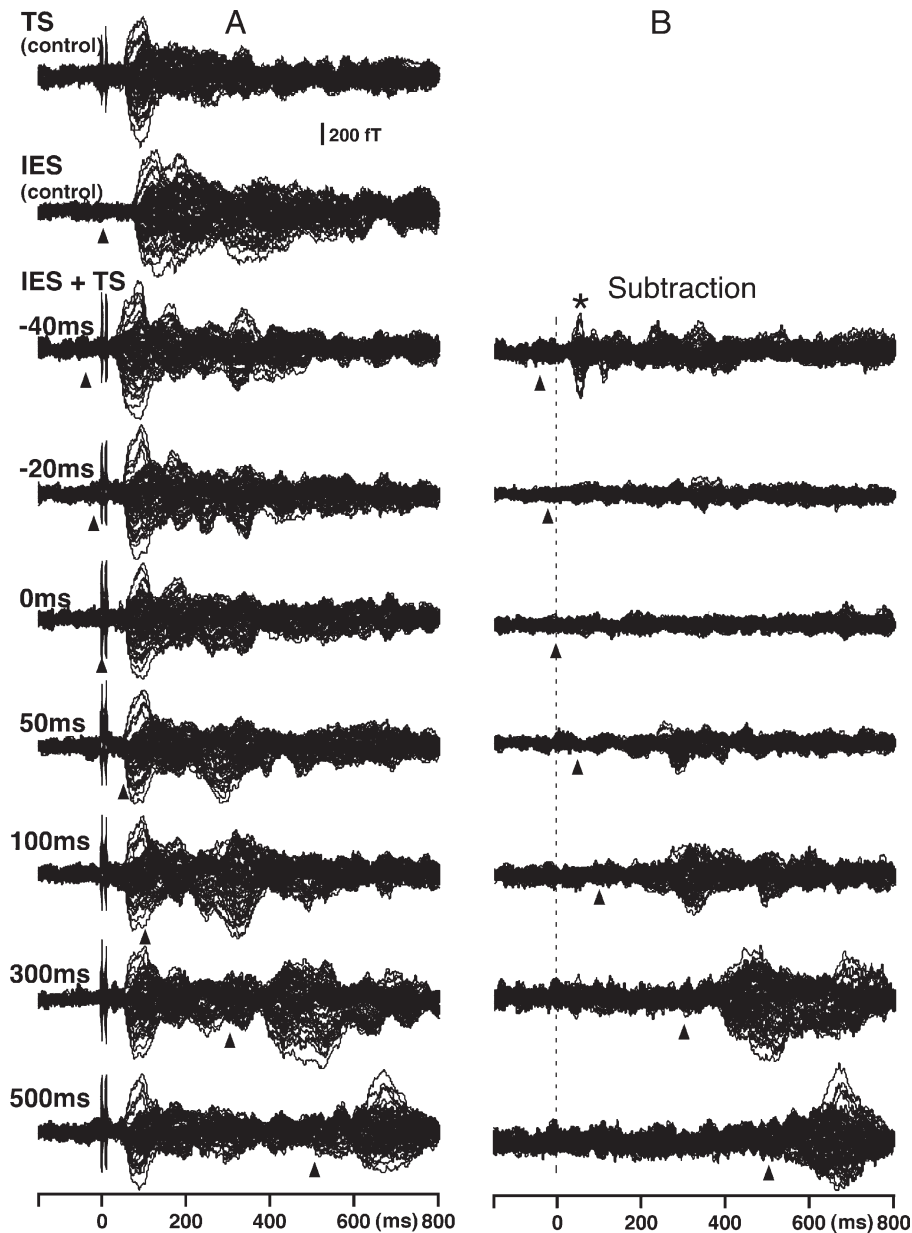


Figure 1. Effects of innocuous somatosensory stimulation on magnetic fields evoked by noxious stimulation. (A) Recorded magnetic fields evoked by innocuous stimulation alone (control TS), noxious stimulation alone (control IES) and paired innocuous and noxious stimulations (IES + TS) applied to the back at various CTIs in a single subject (subject 1). Traces are superimposed waveforms recorded from 74 channels. (B) Waveforms obtained by subtraction of the control TS-evoked response from the recorded waveforms in each condition. Filled triangles indicate timing of IES. A sharp component in the subtracted waveform shown by an asterisk indicates that the IES-evoked response occurs earlier than the TS-evoked response in this condition.

Since signals evoked by TS reach the spinal cord ~5 ms earlier than signals evoked by IES due to a difference of peripheral conduction velocity between A-beta and A-delta fibers (see Materials and Methods), signals evoked by IES reach the spinal cord earlier than those due to TS in the IES + TS conditions with negative CTIs >20 ms. Therefore, data for these IES + TS conditions are important to establishing the level in the central nervous system at which this inhibition occurs. As Figures 1 and 2 show, cortical responses to IES were almost abolished in the IES + TS -20 ms condition, indicating that the inhibition in this condition occurred at a level higher than the spinal cord. In the IES + TS -40 and -60 ms conditions in Figures 1-3, there was a sharp component 5 ms

after IES shown by an asterisk in the subtracted waveform, which indicated that the IES-induced cortical responses occurred earlier than the TS-induced responses in these conditions, and in addition, large parts of the later IES-evoked responses were almost abolished. Figure 5 shows the difference of waveform in the IES + TS -40 ms condition in detail. The waveform for the IES + TS -40 ms condition was very similar to that of the control TS, suggesting that the cortical response to TS changed little even when signals due to IES reached the cortex slightly early, and that on the other hand, IES-evoked responses were remarkably attenuated by later arriving TS-evoked signals. In Figure 6, waveforms in the IES + TS -40 ms condition of all subjects are shown.

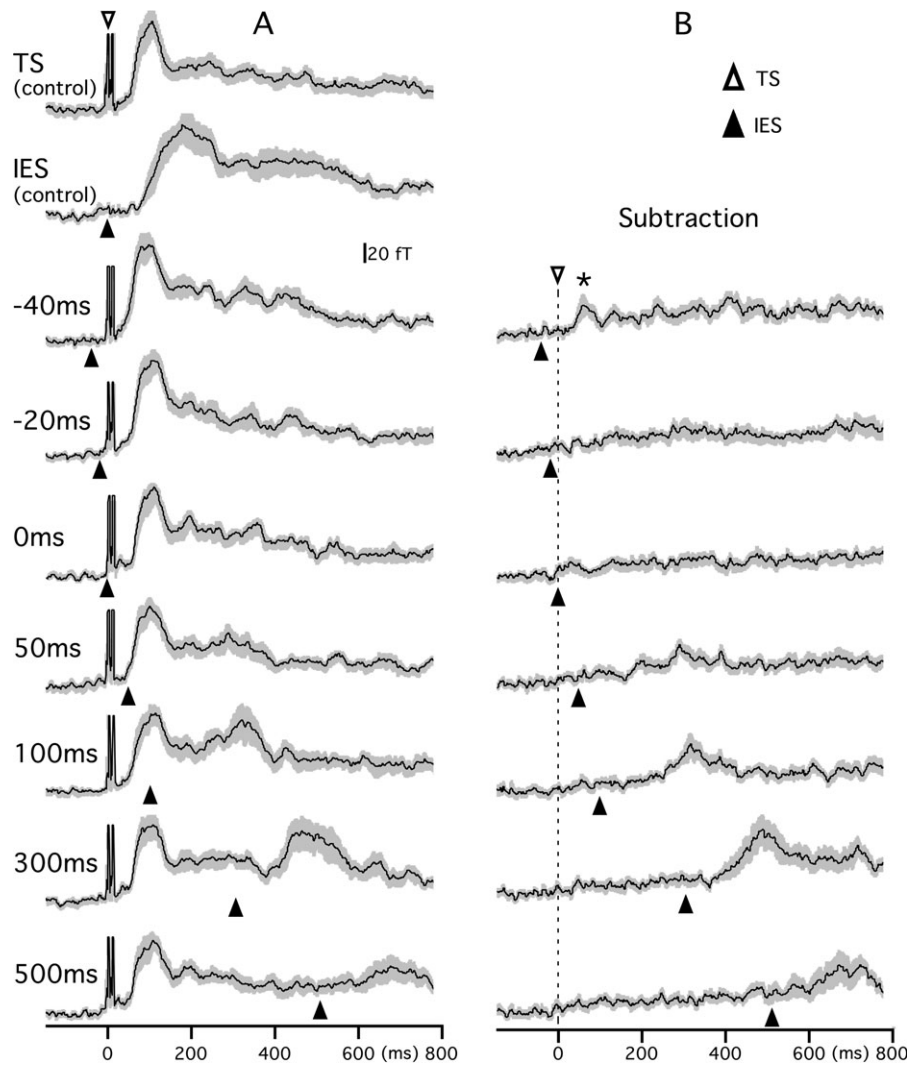


Figure 2. Group-averaged waveforms of the root mean square in the first session with seven IES + TS conditions at a CTI of -40 to 500 ms. Traces are the group-averaged time course of the amplitude of recorded (A) and subtracted (B) waveforms represented as the root mean square across 74 channels. In this and the next figure, shaded areas indicate ± 1 SE width.

Next, we calculated how the control TS- and IES-evoked responses explained the waveforms of the IES + TS conditions using a least squares fit. Results from a single subject in Figure 7 showed that the waveform for the IES + TS -40 ms condition was well explained by the TS-evoked response alone except at a latency period ~ 50 ms after TS (90 ms after IES) where the IES-evoked response was dominant as shown by an asterisk. The time course of the coefficient b for the IES-evoked response was very similar to that of the subtracted waveform at a latency of 40 – 300 ms, which indicated the reliability of the subtraction method in this condition. Figure 8 depicts group-averaged values of coefficients a and b as functions of time among all subjects. Among the 11 IES + TS conditions, signals due to IES reach the cortex earlier than those due to TS in the -500 to -40 ms conditions, while signals due to TS reach the cortex earlier in the -20 to 500 ms conditions. Therefore, Figure 8A,B compares the effects of later arriving TS signals on the IES-evoked response and effects of later arriving IES signals on the TS-evoked response. On the other hand, Figure 8C,D compares the effects of preceding TS signals on the IES-evoked response

and effects of preceding IES signals on the TS-evoked response. It is obvious from Figure 8B that later arriving IES signals had almost no effect on the TS-evoked response, while in marked contrast, the IES-evoked responses were strongly inhibited by later arriving TS signals (Fig. 8A). In Figure 8A, waveforms of coefficient b for IES in the -40 , -60 and -100 ms conditions started to deviate from that of the -300 or -500 ms condition, which could be considered as a control, at ~ 110 , 130 and 170 ms after the stimulus, indicating clearly that the IES-evoked responses in these conditions were actively inhibited by later arriving TS signals with a similar timing. In each of the three conditions, the onset latency of the inhibition corresponded approximately to the onset latency of the TS-evoked response plus 20 ms. For example, in the -60 ms condition, the onset latency of the TS-evoked cortical response was expected to be at 110 ms after IES, which was shorter by 20 ms than the latency at which the inhibition started in this condition (130 ms). When the strength of the actual IES-evoked response in each condition was expressed as the area under the curve (AUC, coefficient $b \times$ ms) during 50 – 300 ms, the AUCs for the -300 ,

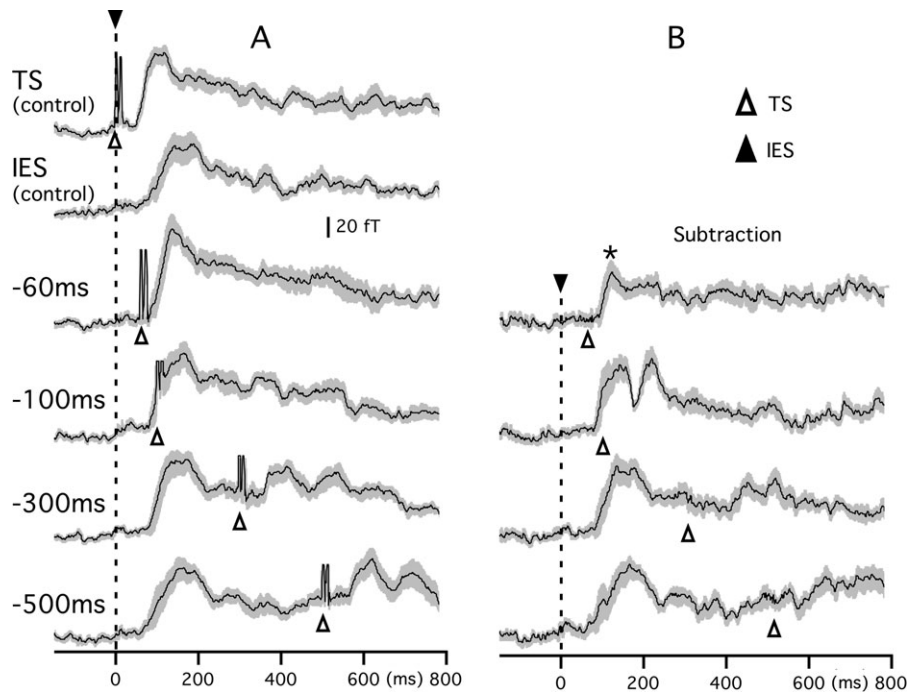


Figure 3. Group-averaged waveforms of the root mean square in the second session with four IES + TS conditions at a CTI of -500 to -60 ms.

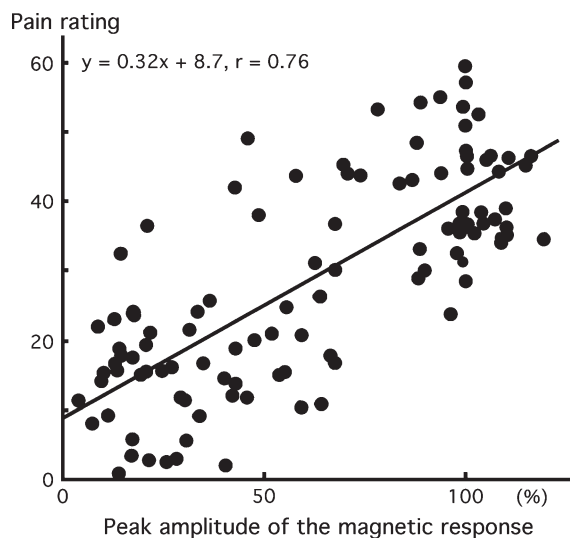


Figure 4. Correlation between the pain rating and peak amplitude of IES-induced cortical response. Data of all stimulus conditions for all subjects are plotted. Amplitudes of magnetic response are represented as a percentage of the control (IES) response. A regression line is indicated.

-100 , -60 and -40 ms conditions were 103.9, 78.1, 46.5 and 22.2% of that in the -500 ms condition, respectively (Fig. 9). In the -500 ms condition, the IES-evoked response during 50–300 ms was not affected by TS at all, and therefore could be considered as a control. The AUCs for the TS-evoked response in the -20 , 0, 50, 100 and 300 ms condition were 99.0, 97.4, 94.1, 103.0 and 93.1% of that in the 500 ms condition (control).

Figure 8C,D shows that preceding TS signals as well as preceding IES signals inhibited the IES- and TS-evoked responses, respectively. The AUCs for the IES-evoked response in the -20 , 0, 50, 100, 300 and 500 ms conditions were 18.3, 15.4,

17.2, 31.6, 40.0 and 30.7% of the control value (-500 ms), suggesting that the inhibition continued up to the CTI 500 ms condition. The AUCs for the TS-evoked response in the -500 , -300 , -100 , -60 and -40 ms conditions were 57.5, 69.0, 57.8, 78.2 and 99.1% of the control value. Therefore, the inhibition of the TS-evoked response was not present when the IES- and TS-evoked signals reached the cortex simultaneously (-40 ms condition), appeared when the IES-evoked signals reached the cortex 20 ms earlier than the TS-evoked signals (-60 ms condition) and was strongest when the IES-evoked signals reached the cortex earlier than those due to TS by 60 ms (-100 ms condition). When the degree of the inhibition in these conditions was compared between the TS- and IES-evoked responses, it was significantly stronger for the TS-induced inhibition of the IES-evoked response than the IES-induced inhibition of the TS-evoked response (t -test, $P < 0.0001$). Like the peak amplitude in the RMS analysis, there was a linear correlation between the pain rating and AUC for IES-evoked responses ($P < 0.0001$, $r = 0.63$). Figure 9 shows the percentage AUC relative to the control for the TS- and IES-evoked response in all conditions.

Discussion

This is the first report to show tactile-induced pain inhibition at the cortical level. A previous paper from our laboratory (Kakigi and Watanabe, 1996) examined effects of tactile stimuli applied to the fingers on vertex potentials evoked by laser beams applied to the dorsum of the same hand. No effects were found when a stroke by a soft wad of tissue paper was used as a tactile stimulus, while laser-evoked potentials were significantly inhibited when continuous vibrotactile stimuli (500 Hz) was used. The results suggest that the timing of the conditioning stimulus is important to its inhibitory effects on pain-evoked brain responses as the present study showed.

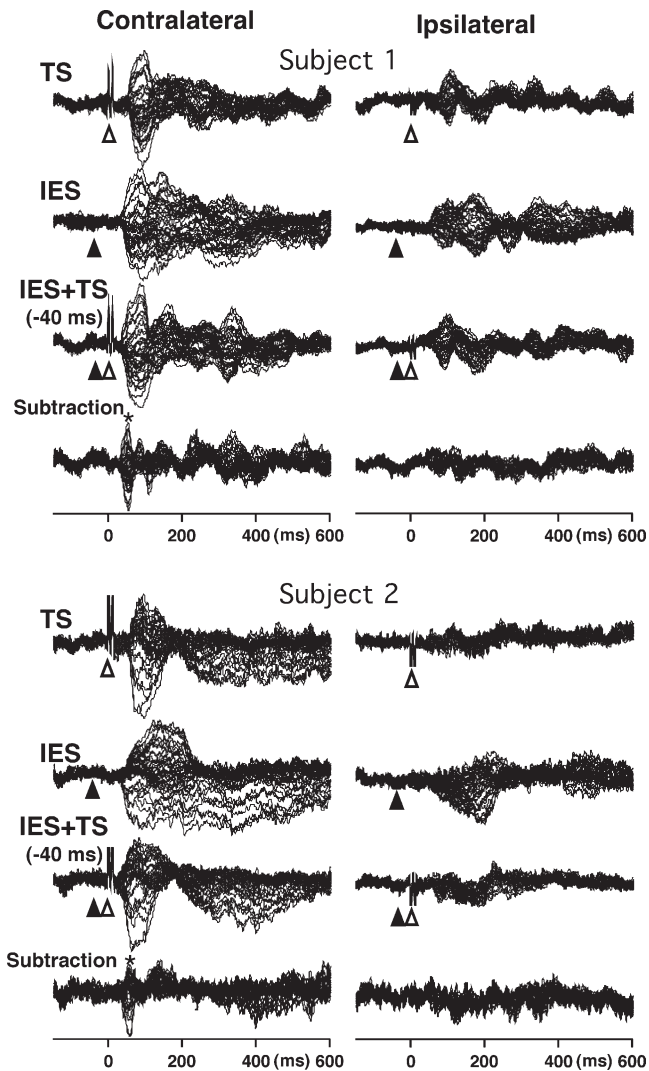


Figure 5. Inhibition of the IES-evoked response by TS delivered 40 ms later than IES. Waveforms recorded by two probes (contralateral and ipsilateral hemispheres) are separately shown in this figure. Open and filled triangles indicate timing of TS and IES, respectively. Note that waveforms recorded from both hemispheres are very similar between the TS and IES + TS conditions in both subjects except that waveforms in the IES + TS condition have activity due to IES at the very beginning of the evoked component as shown by an asterisk.

It is probable that the failure to find an inhibitory effect of a stroke of the fingers on laser-evoked potentials was due to the non-time-locked conditioning stimuli. An important technical issue of the present study was the use of an intra-epidermal electrical stimulation (IES) method that could selectively activate A-delta fibers with constant activation timing in each trial, and therefore enabled us to study interactions between two different modalities with precise timing. In previous studies, we confirmed that signals evoked by IES are conveyed through peripheral A-delta fibers at a conduction velocity of ~ 15 m/s (Inui *et al.*, 2002a,b). In this study, the latency difference of evoked cortical activity between TS and IES was ~ 38 ms, which was almost consistent with the estimated latency difference based on the reported conduction velocities of peripheral A-beta and A-delta signals in the human spinal cord. The sharp pricking sensations without any tactile sensations evoked by IES also support that IES activates A-delta

fibers selectively. Furthermore, the present result itself showed that IES selectively stimulates A-delta fibers. If IES activates A-beta and A-delta fibers simultaneously (i.e. CTI = 0 ms), the responses evoked should be similar in latency to those evoked by TS.

As possible mechanisms underlying pain relief by vibrotactile stimulations, those operating at the periphery (Campbell and Taub, 1973), dorsal horn of the spinal cord (Melzack and Wall, 1965) and other regions of the central nervous system (Melzack, 1971) have been postulated. In the major hypothetical mechanisms at the spinal level, it has been suggested that a 'gate control' mechanism exists in the dorsal horn of the spinal cord, where signals through large diameter fibers are said to inhibit the central transmission of signals through small diameter fibers (Melzack and Wall, 1965). In the present study, noxious stimuli-induced cortical responses were equally inhibited by simultaneous (CTI 0 ms) and delayed (CTI -40 and -20 ms) innocuous stimulations, excluding the possibility of peripheral mechanisms. The findings of a substantial inhibition of the IES-induced response in the IES + TS conditions with a negative CTI of > -20 ms suggest that the inhibition occurs without any contribution at the spinal level, including descending inhibitory actions on spinal neurons, at least in these conditions because signals evoked by IES reach the spinal cord earlier than those evoked by TS. The findings in the IES + TS -100 to -40 ms conditions indicate that the inhibition occurs at the cortical level. Although our results could not clarify the extent to which the spinal mechanisms contributed to the inhibition in the IES + TS 0 to 500 ms conditions, the powerful inhibition in the IES + TS -40 ms and IES + TS -20 ms conditions and the low pain rating for the IES + TS -20 ms condition imply that any inhibitory action at the spinal cord is weak. This notion is consistent with the fact that, in general, repetitive and high intensity stimulations of a peripheral nerve, which activate both A-beta and A-delta fibers, are required to suppress noxious stimuli-evoked responses in the dorsal horn neurons in animal studies (Cervero *et al.*, 1976; Chung *et al.*, 1984; Lee *et al.*, 1985). Whitehorn and Burgess (1973) showed that primary afferent terminals of a particular sensory fiber type are depolarized by activity arising in fibers of the same type. Similar findings were reported by Brown and Hayden (1972). Therefore, inhibition of the nociceptive neurons in the dorsal horn by repetitive stimulation of a peripheral nerve at noxious intensities or by applying intense mechanical stimuli to the skin seems to be largely due to presynaptic inhibition by A-delta or C fiber inputs rather than A-beta fibers. The notion that nociceptive neurons in the dorsal horn cannot be easily suppressed by signals from low-threshold mechanoreceptors is supported by the findings of Manfredi (1970) and Pomeranz (1973), who examined post-synaptic activity of the dorsal horn neurons in the lateral tract in cats and found no inhibitory effects of A-beta fiber inputs. The fact that stimulation of C-fibers generates a primary afferent depolarization but not a primary afferent hyperpolarization in the spinal cord (Zimmermann, 1968) also does not support the gate control theory.

Since the main component of the evoked magnetic fields in the present study originated mainly from SII and SI, and since SI and SII were sequentially activated by IES in our previous study (Inui *et al.*, 2003a,b), the inhibitory action should take place in SI neurons or in both SI and SII neurons. Several lines of evidence show that SI nociceptive neurons play a role in the discriminative aspect of pain (Kenshalo and Willis, 1991;

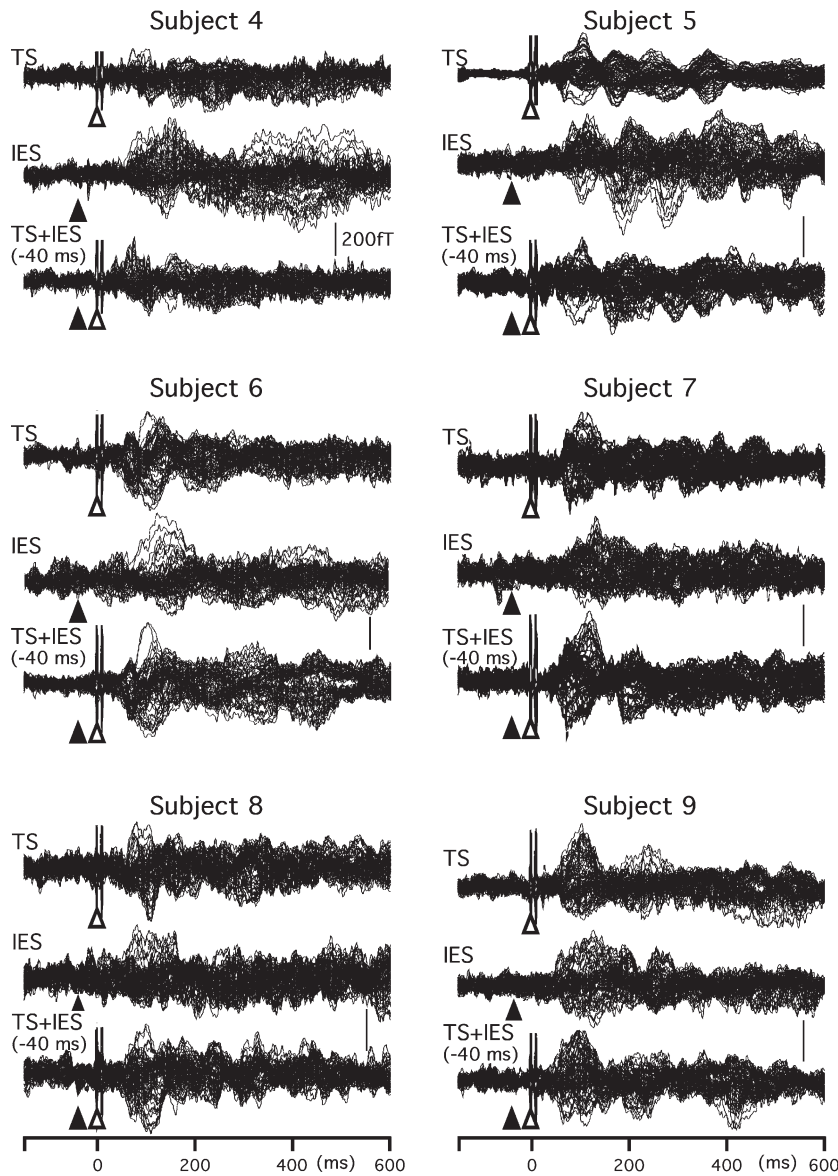


Figure 6. Waveforms in the IES + TS –40 ms condition of six subjects. Note that the waveform in the IES + TS condition is similar to the waveform in the control TS condition. Waveforms of three other subjects in this condition are shown in Figures 1, 5 and 7.

Bushnell *et al.*, 1999). Since the IES-evoked later components, which originated from the insular cortex, medial temporal area around the amygdala or hippocampus and cingulate cortex (Inui *et al.*, 2003a), were attenuated as well as the main early component in this study, there might be direct inhibitory actions on these areas independent of those on SI and SII. The origin of the inhibitory action is unclear from the present results, but TS-driven thalamic and cortical activities are candidates. The present study suggests that activation of the tactile pathway at a certain level higher than that in the spinal cord can inhibit cortical responses to noxious stimuli. In the major tactile pathway, the dorsal column is known to alleviate chronic pain when electrically stimulated (Shealy *et al.*, 1970). In addition, behavioral responses to noxious stimuli in rats (Saadé *et al.*, 1986) as well as experimentally evoked pain in humans (Marchand *et al.*, 1991) are reduced by stimulation of the dorsal column. Although the mechanisms responsible for

pain inhibition on stimulation of the dorsal column are still unclear, the nociceptive thalamus-SI pathway might be modulated. Larson *et al.* (1974) showed that evoked potentials recorded in human somatosensory cortex, and those recorded in monkey ventroposterior lateral nucleus (VPL) of the thalamus and sensorimotor cortex are attenuated by stimulation of the dorsal column. Bantli *et al.* (1975) examined the effects stimulating the dorsal column on the cortical responses to stimulation of the ventral quadrant of the spinal cord in monkeys and found that evoked activities in both SI and SII were inhibited, similar to the present results.

In the main tactile pathway, the VPL and the ventroposterior medial nucleus (VPM) of the thalamus are shown to reduce experimentally induced pain in humans when electrically stimulated (Marchand *et al.*, 2003). In addition, electrical stimulation of VPL/VPM is effective in relieving chronic pain (Hosobuchi *et al.*, 1973; Mazars *et al.*, 1973) and allodynia

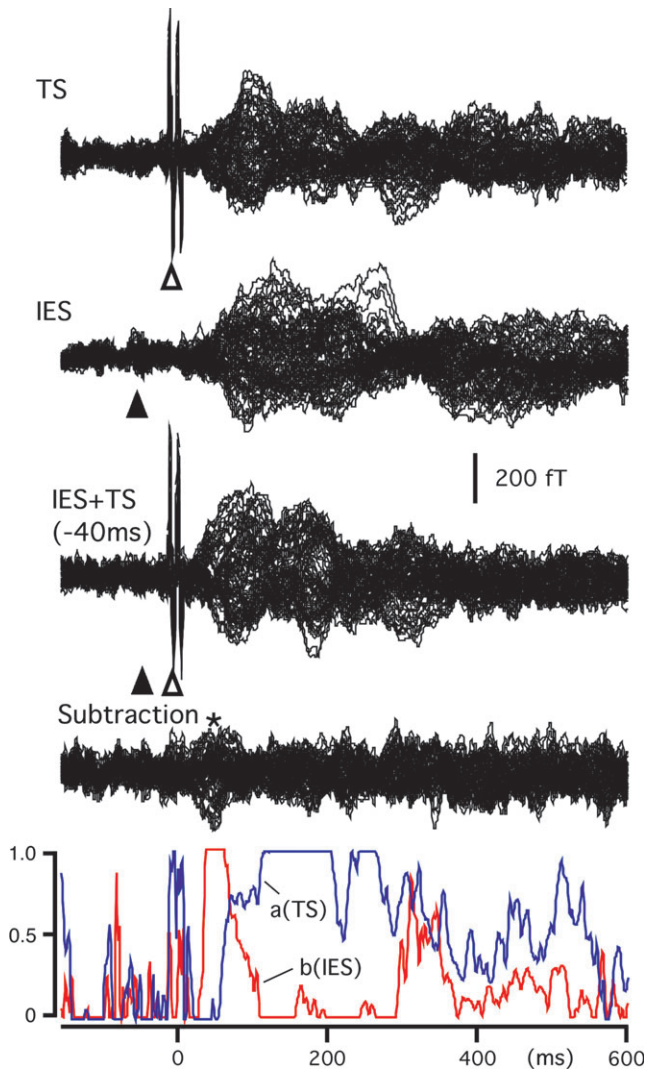


Figure 7. Contribution of the control TS- and IES-evoked responses to the responses evoked by paired stimuli. By use of a least squares fit, we calculated how the control TS and IES waveforms explained the waveforms in IES + TS conditions. The bottom traces show the time course of coefficients for TS (a) and IES (b). The result of this case (subject 3) shows that magnetic fields evoked by paired stimuli can be explained by only the control TS-evoked response except at a latency period of ~30–60 ms after TS, where the control IES-evoked response alone can explain the response shown by an asterisk.

in rats (Kupers and Gybels, 1993). Like stimulation of the peripheral nerve and dorsal column, the stimulation of VPL/VPM usually elicits paresthetic sensations without sensations of pain. In addition, the electrode must be placed in the somatotopic part of the VPL/VPM nuclei that represents the painful site to obtain pain relief (Gybels, 2001), which mimics rubbing a bruised area to reduce pain. These thalamic nuclei send dense projections to SI. Therefore, this thalamo-cortical pathway may mediate analgesia produced by thalamic stimulation. The fact that successful stimulation in patients with chronic pain produces localized paresthetic sensations in the painful area and increases cerebral blood flow in SI and the thalamic region stimulated (Katayama *et al.*, 1986; Duncan *et al.*, 1998) appears to support the involvement of the VPL/VPM-SI pathway in pain relief by thalamic stimulation. The inhibition of nociceptive SI neurons by sensory thalamus

stimulation may explain why electrical stimulation of this area rarely produces painful sensations though VPL/VPM contains considerable numbers of nociceptive neurons (Kenshalo *et al.*, 1980; Chung *et al.*, 1986; Bushnell *et al.*, 1993; Apkarian and Shi, 1994). Davis *et al.* (1996) examined effects of microstimulation in the ventrocaudal nucleus of the thalamus of patients with chronic pain and found that the stimulation frequently evoked sensations of pain in patients with post-stroke pain but only paresthetic sensations in non-stroke patients. The increased incidence of thalamic-evoked pain in such patients may be due to the relative dominance of the nociceptive thalamus-SI pathway following loss of low-threshold mechanoreceptor thalamic neurons or reduced tonic inhibition of thalamic or cortical nociceptive neurons. This notion is similar to Mazars's original hypothesis of pain relief by thalamic stimulation that when pain is due to a lack of proprioceptive information reaching the thalamus from the damaged region, it might be controlled by thalamic stimulation in place of physiological stimuli running through the dorsal column.

Another possible explanation of tactile-induced pain inhibition is that tactile inputs inhibit nociceptive brain areas other than the VPL-SI pathway via thalamo-thalamic, thalamo-cortical or cortico-cortical inhibitory projections. For example, Craig *et al.* (1994) demonstrated a very high concentration of pain- and thermo-specific neurons in the posterior part of the ventral medial thalamic nucleus (VMpo) in monkeys, which has dense lamina I spinothalamic tract terminations. In lamina I of the dorsal horn, there is a population of neurons specifically responding to noxious stimuli in cats (Christensen and Perl, 1970) and monkeys (Kumazawa *et al.*, 1975) similar to VMpo neurons. In addition, stimulation around VMpo elicits localized sharp painful sensations and nociceptive-specific neurons are recorded in this region in humans (Craig, 2003). VMpo projects to the dorsal part of the insula and other cortical areas such as area 3a of SI (Craig, 2003). Therefore, VMpo and its projection sites may be the target in tactile-induced inhibition of pain. We considered that a thalamo-cortical pathway via VMpo is one candidate for sites receiving inhibitory effects, although some recent studies questioned the existence of this nucleus (Willis *et al.*, 2002).

Previous studies suggested one primary site of pain processing in the dorsal posterior insula (Craig, 2003; Vogel *et al.*, 2003) where VMpo projects. In fact, activity from the dorsal part of the insula contributes to creating the major magnetic component evoked by IES (Inui *et al.*, 2003a), which was almost completely suppressed by TS in the present study. As for activity in area 3a, Tommerdahl *et al.* (1996) demonstrated clusters of nociceptive neurons that show an augmenting response to repeated brief heat stimuli in monkeys. In addition, they showed that activation in area 3a by noxious heat stimuli was accompanied by a reduction of activity in areas 3b and 1 produced by innocuous mechanical stimulation, which was likely mediated by long-distance horizontal connections that link area 3a and areas 3b/1. Given the inhibitory cortico-cortical projections from area 3a to areas 3b/1 in the pain-touch interaction, it seems possible that IES-evoked area 3a activity was inhibited by similar cortico-cortical projections from areas 3b/1 in the present study. Our data that the onset latency of the inhibition of the IES-evoked response by TS was ~20 ms later than the arrival of TS signals to the cortex (IES +TS conditions from -100 to -40 ms) are consistent with such a cortico-cortical inhibition. However, activation of neurons in the bottom of the sulcus creates

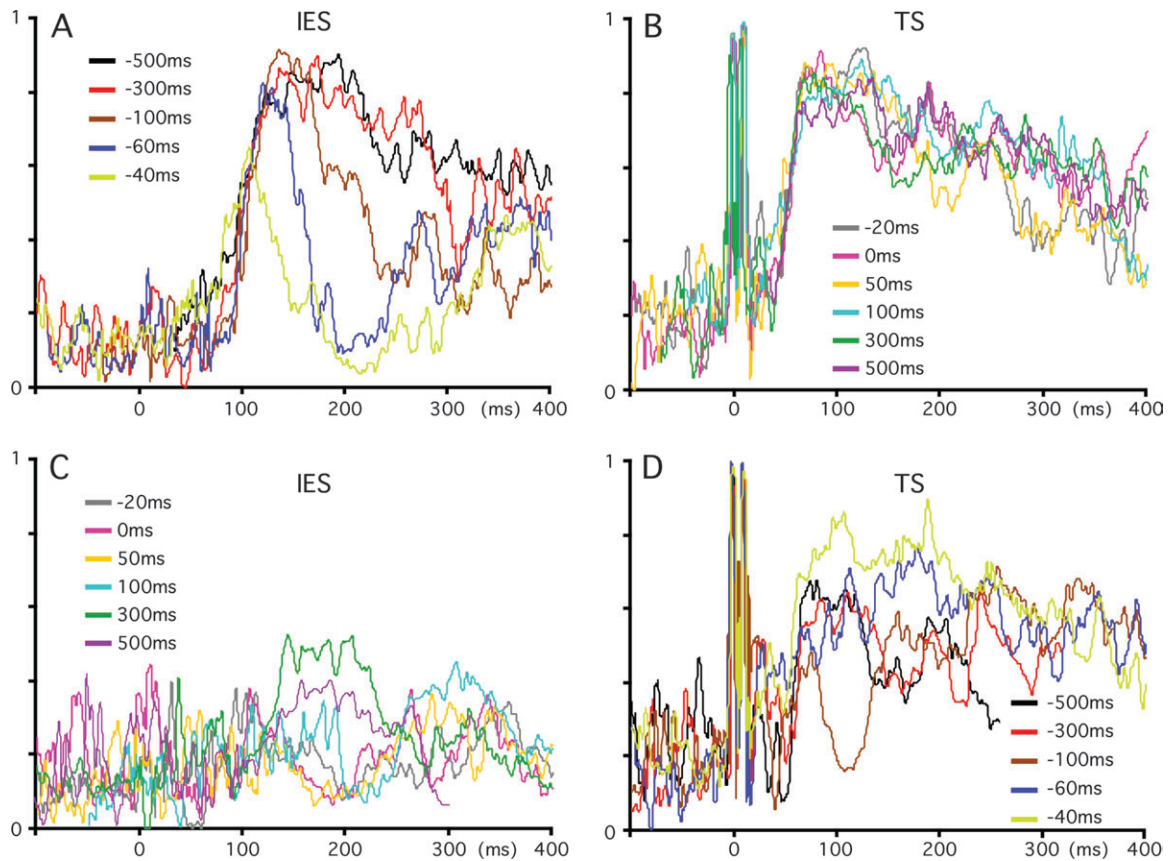


Figure 8. Group-averaged time course of the coefficients for TS and IES. (A) Effects of later arriving TS signals on the IES-evoked response. (B) Effects of later arriving IES signals on the TS-evoked response. (C) Effects of preceding TS signals on the IES-evoked response. (D) Effects of preceding IES signals on the TS-evoked response.

a dipole with a radial orientation that is difficult detect by MEG, therefore our recorded magnetic fields might not reflect activity from area 3a.

The role of SII in pain perception is unclear, largely due to the lack of unit study findings on nociceptive neurons in this area. In marked contrast with human neuroimaging studies in which activations in SII are constantly found after noxious stimulation, nociceptive neurons are rarely encountered in SII in animal studies (for review, see Schnitzler and Ploner, 2000). For example, the proportion of nociceptive neurons was 4% (5 of 123 neurons) in a study by Dong *et al.* (1989). The present finding of powerful inhibition by tactile inputs of responses to noxious stimuli in SII suggests that the paucity of nociceptive neurons in SII in animal studies might be a result of the use of a non-selective intense mechanical stimulation that activates low-threshold mechanoreceptors as well as nociceptors, since the present results showed that noxious stimuli-evoked SII activity was markedly inhibited when an innocuous stimulus was applied simultaneously (CTI 0 ms). If a selective noxious stimulation is used as a searching stimulus, a larger number of nociceptive neurons might be found in SII.

Although the pain rating was correlated with both the peak amplitude of the IES-evoked response (subtracted) and the integral strength of the coefficient for the IES-evoked response during the 50–300 ms latency, data in some conditions did not show a simple linear correlation between them. The rating for the IES + TS –40 ms condition (12.7) was not so different from that for the –20 ms (11.1) and 0 ms (13.7) conditions, while

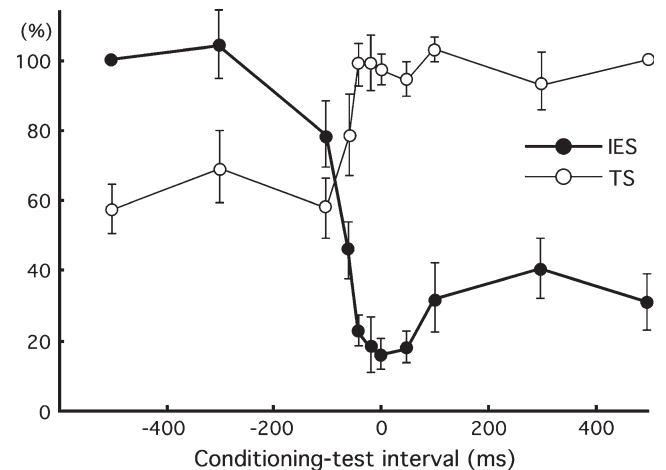


Figure 9. Amplitudes of the IES- and TS-evoked response represented as an integral of the respective coefficient value. Each value is the percentage of the area under the curve (AUC) during a latency period of 50–300 ms relative to that in the control condition (500 ms condition for TS and –500 ms condition for IES). Vertical bars indicate ± 1 SE.

the peak amplitude of the –40 ms condition (34.5% of the control) was apparently greater than that of the –20 ms (20.2%) and 0 ms (23.4%) conditions, due to the presence of an early sharp component that escaped the inhibition in the –40 ms condition. This result implies that the early sharp component in the –40 ms condition did not help to produce painful sensations.

We considered that the early activity in the -40 ms condition with a very short duration (shown by an asterisk) was not sufficient to evoke painful sensations, that is, below the level critical to drive the subsequent processing related with pain recognition or pain rating in amplitude or in duration. In contrast, the rating in the -60 ms condition (37.4) was much larger than that in the -40, -20 and 0 ms conditions, suggesting that the strength or duration of the early activity in this condition might exceed the critical level.

Although the present study found an inhibitory effect of noxious stimulus on the tactile-evoked cortical response, its manner was strikingly different from that observed in the IES-induced inhibition of the TS-evoked response in that the IES-evoked cortical response was strongly inhibited by later arriving TS signals whereas inhibitory effects of IES signals on the TS-evoked response were observed only when the IES signals preceded the TS signals. Therefore, there is a specific one-way touch-pain inhibitory action although the inhibitory effects of a preceding activation of one modality on the other may be reciprocal. The stronger inhibition of the IES-evoked response (Fig. 8C) than TS-evoked response (Fig. 8D) might be because the inhibition of the IES-evoked response was a summation of the specific touch-pain inhibitory action and a weaker reciprocal inhibitory mechanism. The inhibitory effect of pain on tactile processing is consistent with previous findings that tonic pain elevated vibrotactile perception thresholds (Apkarian *et al.*, 1994; Bolanowski *et al.*, 2000) and decreased proprioception (Rossi *et al.*, 1998), and that innocuous tactile stimulation-induced activations in SI (3b and I) were decreased during heat pain in monkeys (Tommerdahl *et al.*, 1996), although the mechanism of the inhibition might be different from that observed in this study, since the present study used a phasic pain stimulus instead of tonic pain. A few neurophysiological studies have assessed effects of pain on tactile processing using a phasic painful conditioning stimulus. In an MEG study, Tran *et al.* (2003) compared the effects of conditioning innocuous and noxious electrical stimulations to the finger on cortical responses to median nerve stimulation and found that noxious stimulation elicited greater effects in reducing the early SI activity evoked by median nerve stimulation at CTIs of 100–400 ms, indicating that activation of A-delta fibers significantly inhibited the cortical tactile response. On the other hand, Dowman (1999) and Ploner *et al.* (2004) used brief painful laser stimuli to examine touch-pain interaction and found an augmentation of tactile processing. However, both studies examined only one CTI (194 and 500 ms, respectively) and therefore could not assess the effects of conditioning noxious stimuli at various timings.

Although activities of nociceptive neurons in the dorsal horn have been shown to be modulated under various conditions, including segmental sensory stimulation (Handwerker and Zimmermann, 1975), noxious stimulation applied to various parts of the body (Le Bars *et al.*, 1979; Gerhart *et al.*, 1981), thalamic stimulation (Gerhart *et al.*, 1983) and dorsal column stimulation (Handwerker and Zimmermann, 1975; Foreman *et al.*, 1976), our results indicate that powerful modulation also occurs in the brain. There are surprisingly few studies dealing with such inhibitory mechanisms in the brain. This apparently shows that past studies have stressed the spinal mechanism of pain modulation. We consider that mechanisms in the brain as well as the spinal cord should be taken into consideration in both experimental and clinical studies.

There should be various types of modulation at various levels that interact with each other.

Notes

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Address correspondence to Koji Inui, Department of Integrative Physiology, National Institute for Physiological Sciences, Myodaiji, Okazaki 444-8585, Japan. Email: inui@nips.ac.jp.

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