Somatosensory & Motor Research 2000; 17(2): 195–204

The effects of stimulus location on the gating of touch by heat- and cold-induced pain

STANLEY J. BOLANOWSKI[1,2], LISA M. MAXFIELD[1,3], GEORGE A. GESCHEIDER[1,4] and A. VANIA APKARIAN[1,5]

[1]*Institute for Sensory Research, Syracuse University, Syracuse, NY 13244–5290, USA*; [2]*Department of Bioengineering and Neuroscience, Syracuse University, Syracuse, NY 13244, USA*; [3]*Department of Psychology, California State University, Long Beach, CA 90840, USA*; [4]*Department of Psychology, Hamilton College, Clinton, NY 13324, USA; and* [5]*Department of Neurosurgery, SUNY Health Sciences Center, Syracuse, NY 13210, USA*

Abstract

The influence of heat- and cold-induced pain on tactile sensitivity, a "touch gate", was measured under conditions in which the location of the noxious stimuli was varied with respect to the tactile stimulus applied to the thenar eminence of humans. Vibrotactile thresholds were measured in the absence of pain and during administration of a painful stimulus, with the stimulus frequencies selected to activate independently the four psychophysical channels hypothesized to exist in human glabrous skin. Heat-induced pain produced by spatially co-localizing the noxious stimuli with the tactile stimuli was found, on average, to elevate threshold amplitude by 2.2 times (6.7 dB). Co-localized, cold-induced pain raised the average thresholds by about 1.5 times (3.6 dB). Heat-induced pain presented contralaterally produced no change in vibrotactile sensitivity indicating that the effect is probably not due to attentional mechanisms. Ipsilateral heat-induced pain caused an elevation in tactile thresholds even when the noxious and non-noxious stimuli were not co-localized, and the effect may seem to require that the painful stimulus be within the somatosensory region defined possibly in terms of dermatomal organization. Thus the effect is probably related to somatotopic organization and is not peripherally mediated. A brief discussion as to the possible locus of the touch gate within the nervous system is also given.

Key words: *pain, somatosensation, taction, vibrotaction, touch gate, psychophysics*

Introduction

Somatosensory sensations and perceptions often are the result of the combinations and interactions of information conveyed by the somatosensory submodalities of taction, thermal sensation and pain. For example, Weber (1846) first noted that objects of equal weight are perceived to be heavier when they are cold than when they are warm, the observations later verified quantitatively by Stevens (1979). Indeed, that the information transmitted by the different submodalities interact to various degrees has been demonstrated in the influence of touch on pain (e.g., Wall and Cronly-Dillon, 1960; Melzack *et al.*, 1963; Melzack and Wall, 1965; Sullivan, 1968; Pertovaara, 1979; Ottoson *et al.*, 1981; Ekblom and Hansson, 1982; Lundberg, 1983; Bini *et al.*, 1984; Sherer *et al.*, 1986; Calford and Tweedale, 1991; Marchand *et al.*, 1991; Zoppi *et al.*, 1991) and thermal–pain interactions as well (Bini *et al.*, 1984; Wahren *et al.*, 1989; Yarnitsky and Ochoa, 1990; Casey *et al.*, 1993; Craig and Bushnell, 1994). Apkarian *et al.* (1994) have also reported another submodality interaction, called the "touch gate", whereby the presence of heat-induced pain can significantly diminish tactile sensation. Such interactions among the various somatosensory submodalities indicate that unified somatosensory impressions are largely a result of high-level neuronal mechanisms (Bolanowski, 1996, 1998). However, these mechanisms and their precise locations within the central nervous system are, for the most part, presently ill-defined.

The research reported herein was performed to further delineate the requirements for the effective activation (closing) of the hypothesized touch gate and in so doing gather psychophysical evidence to help determine the basis of the effect. For example, the touch gate was originally discovered using heat-induced pain and by spatially co-localizing the noxious stimuli with the tactile (vibratory) test stimuli on the thenar eminence of the right hand of human subjects. In the present study, the heat-pain was induced at several ipsilateral and contralateral

Correspondence: Stanley J. Bolanowski, Institute for Sensory Research, Syracuse University, Syracuse, NY 13244–5290, USA. Tel.: (315) 443–4164; Fax: (315) 443–1184; E-mail: sandy_bolanowski@isr.syr.edu

ISSN 0899–0220 (print)/ISSN 1369–1651 (on line)/00/020195–10

locations relative to the vibratory stimuli that were always delivered to the right thenar eminence. A contralateral effect would demonstrate that the touch gate operates bilaterally. Such a result would indicate that the effect is not peripherally mediated. If contralaterally applied heat-pain activates the touch gate, the locus of the effect could be anywhere within the central nervous system where bilateral convergence is found. In addition, the existence of a contralateral effect could be used to argue that the mechanism might be in nature cognitive (i.e., attentional; see, for example, Bushnell *et al.*, 1985), and not due solely to sensory processes. Alternatively, the lack of a contralateral effect would suggest that mechanisms residing at levels of the nervous system below bilateral innervation could mediate the effect and it would be more difficult to interpret the results in terms of cognitive factors. Furthermore, ipsilateral, non-coincident testing should provide a measure of the somatotopic distance of the effect, perhaps indicating the territory of neuronal pain–touch influences in the peripheral or central nervous system. Along similar lines, the original study used only heat-induced pain. Since there are differences in the peripheral and central representation of cold-pain compared with heat-pain (e.g., Willis, 1985), the effectiveness of cold-induced pain in closing the gate was also tested. Lastly, the touch gate was originally determined using tactile stimuli that preferentially activated only three of the four psychophysically defined tactile channels [i.e., Pacinian, (P), non-Pacinian I (NP I) and non-Pacinian III (NP III)] hypothesized to exist in the glabrous skin of humans (Bolanowski *et al.*, 1988). In the original study (Apkarian *et al.*, 1994) it was found that the induced decrease in tactile sensitivity was approximately the same irrespective of the tactile channel tested. If a similar decrease in sensitivity is found for the fourth channel (NP II), then it might be that the touch gate resides at a central-nervous-system locus where input from the four channels converge, rather than at lower levels where the channels are believed to be somewhat independent (see, for review, Dykes, 1983; Bolanowski, 1996, 1998). Preliminary reports related to the research presented herein have been given (Maxfield and Bolanowski, 1994, 1995).

Materials and methods

Six healthy subjects (three males, three females) familiar with somatosensory experiments participated in the study. Seven conditions were designed to explore the extent to which thermally induced pain can diminish tactile sensation. The conditions varied the site of the thermally induced pain relative to the vibratory stimulus that was always applied to the right thenar eminence. The conditions included the following: (a) coincident (to vibration) heat-pain; (b) coincident cold-pain; (c) ipsilateral heat- pain presented to the volar forearm approximately 21 cm from the site of vibration; (d) ipsilateral heat-pain applied to the dorso-medial forearm approximately 21 cm from the site of vibration; (e) ipsilateral heat-pain applied to the dorso-medial wrist approximately 7 cm from the site of vibration; (f) contralateral heat-pain presented to the thenar eminence; and (g) contralateral heat-pain presented to the volar forearm. The subjects were tested during 21 separate sessions, three sessions per condition. During each daily session only a single condition (a–g) was tested and the conditions were randomized both within and across subjects.

The apparatus used to deliver the vibratory and thermal stimuli was the same as that used by Apkarian *et al.* (1994) in which the touch gate was first described. The apparatus is described in considerable detail in Bolanowski and Verrillo (1982; see also Verrillo and Bolanowski, 1986; Bolanowski *et al.*, 1988, 1994). Vibratory displacements of the skin were produced with an electromagnetic shaker under computer control. The vibrator and attached equipment rested on the base of a modified drill-press platen the height of which could be adjusted. The subject was seated to one side of the stimulator and placed the right hand, palm down, onto the stimulator. The vibration assembly, subject and other accessory equipment were located in a sound-and-vibration attenuating chamber.

Vibrotactile stimuli delivered to the right hand were applied with either a large (2.9 cm^2) or small (0.008 cm^2) aluminum contactor surrounded by a rigid aluminum annular-shaped surround that confined the skin-surface deformations to the area of stimulation. The contactor and surround were separated by a 1 mm gap so that, for the large contactor, the surround's surface area was 33 cm^2, and it was 35.8 cm^2 when the small contactor was used. The stimuli were presented around a static indentation of 0.5 mm to ensure continuous contact between the stimulator and the skin. Vibratory displacements were monitored with a linear-variable differential transformer (LVDT). The vibratory stimuli were bursts having durations calculated at the half-power points of 1,000 ms and rise–fall times of 50 ms shaped with a cosine function. When using the large contactor, the frequencies of stimulation were either 1, 10, or 100 Hz, so chosen to selectively activate three of the four psychophysically defined tactile channels of glabrous skin, the Pacinian (P), non-Pacinian I (NP I), and non-Pacinian III (NP III), respectively (see Bolanowski *et al.*, 1988). To activate NP II, the small contactor was used in conjunction with a 250 Hz vibration. It has been shown that innocuous variations in skin-surface temperatures alone can produce significant changes in tactile thresholds (Green, 1977; Bolanowski and Verrillo, 1982; Verrillo and Bolanowski, 1986). Because of this, the stimuli were chosen specifically to activate the individual channels at frequencies where skin-surface temperature changes do not affect thresholds

(Bolanowski and Verrillo, 1982; Verrillo and Bolanowski, 1986; Bolanowski *et al.*, 1988).

For coincident vibratory and thermal stimulation, the temperature of the skin surface was controlled by circulating water at the appropriate temperature through hollow chambers in the large contactor and the surround. A heating and refrigeration unit and pump regulated the water temperature and circulation-flow rate. The skin-surface temperature at both the contactor/skin interface and the surround/skin interface, monitored by a telethermometer attached to small thermistors, was always within 1.9°C. With this arrangement, the vibratory stimuli were applied to the central 2.9 cm^2 area and the thermal stimuli were applied over an area of 35.9 cm^2. The size of the small contactor precluded circulating water through it. Consequently, water only flowed through the surround for the experiments using the small contactor. With this arrangement, the vibratory stimuli were applied to the central 0.008 cm^2 area and the thermal stimuli were applied over an area of 35.8 cm^2. For the non-coincident vibratory and thermal stimulation, a second thermal stimulator fashioned in a manner similar to that just described was used. Generally then, the surface of the skin receiving the noxious stimuli had an area of about 35.9 cm^2, the exception to this was the right dorsomedial wrist condition. Because the wrist is narrower than the diameter of the circular stimulator, a smaller area received the painful stimuli relative to the other conditions. During the non-coincident vibration and thermal-pain conditions the skin-surface temperature at the site of vibration was maintained at 31.0 ± 0.5°C (SD) while various pain-inducing temperatures were used at the thermal-pain site. The skin-surface temperatures used in the heat-pain experiments ranged from 31.0 to 45.0 ± 0.6°C with the higher temperatures (> 43.0°C) capable of inducing the sensation of pain. The temperature range used in the cold-pain studies was from 31.0 to 12.0 ± 0.6°C with the very low temperatures (< 14.0°C) inducing pain.

The experiments were designed to test how the different locations of pain relative to the location of vibratory stimuli affect tactile thresholds, rather than the effects of pain magnitude on tactile sensations. We chose to assess the effects of a "moderate" pain state on tactile thresholds, irrespective of the skin-surface temperature inducing the perceived pain. In order to do this, the subjects were first informed about the qualitative (i.e., unpleasantness) and quantitative (i.e., intensity) aspects of pain (see Price *et al.*, 1983, 1989; Price, 1988; Apkarian *et al.*, 1994). They were then asked to rate only their perception of pain intensity on a graded analog scale that was visible to the subject at all times. The scale was divided into six categories numbered from 0 to 9 such that 0 signified "no pain", 1–2 corresponded to "mild pain", 3–4 signified "moderate pain", 5–6 meant "strong pain", 7–8 corresponded to "intense pain", and 9 signified "intolerable pain" (see Price *et al.*, 1983; Ellenmeier *et al.*, 1991; Apkarian *et al.*, 1994). The reported ratings were not recorded, but were used by the experimenter to adjust the skin-surface temperature so that a moderate level (3–4) of pain was maintained. In all cases, subjects were instructed to continuously monitor their pain state and to report verbally if the level of pain was other than moderate in intensity. If it was, then the experimenter adjusted the skin-surface temperature to reinstate a moderate pain level. The entire duration of the thermal stimulus used during the vibratory testing while the subjects were experiencing pain was 22.2 ± 4.3 min (SD).

Vibratory thresholds were measured using a two alternative, forced- choice tracking procedure (Zwislocki *et al.*, 1958). Subjects judged which of two sequential intervals of time, demarcated by reference lights and separated by 1,000 ms, contained the test stimulus. The probability of the test stimulus occurring in one interval vs the other was 0.5. The subject's judgments were made by depressing one of two switches. Feedback as to whether the response was correct or incorrect was provided via a visual (light) cue. The stimulus intensity was increased by 1 dB for every response error and decreased by 1 dB for every three correct (not necessarily consecutive) responses. In this manner, the criterion used to determine threshold was 75% correct detection over a period of 3 min. The actual period of stimulation was considerably longer than this since the stimulus intensity was always set at a suprathreshold level at the beginning of each test. Nominally a period of 3–6 min was required before the subject reached the approximate threshold level at which time the 3 min period of 75% correct responding was started. Threshold data are expressed in decibels (dB = 20 log D_1/D_0) where the reference, D_0, is 1.0 μm peak displacement. During each session, vibratory thresholds in the absence of pain and during pain for each vibratory stimulus were obtained and used to calculate mean threshold values for the individuals for each condition. The individual mean values were used to calculate group means. The results are presented as group means, however, the results are similar for individual subjects. The effects of the presence of thermally induced pain are calculated by subtracting the average pre-pain threshold values from the averaged thresholds measured during pain. Because the effect of thermally induced pain on tactile thresholds is given in dB it should be noted that a 6 dB increase in the vibratory threshold corresponds to a doubling of stimulus amplitude required to achieve a threshold response. Variability of the threshold measures, when stated, is given as the standard error of the mean values and was about ± 1.5 dB.

A typical session lasted approximately 1.5 h. At the beginning of a session vibrotactile thresholds at 1, 10, and 100 Hz were measured on the right thenar

eminence at a skin-surface temperature of 31.0°C. The order of threshold measurements was randomized across subjects. For the 0.008 cm^2 contactor condition, however, threshold was only measured at a single frequency, 250 Hz. Subsequent to the measurement of vibratory thresholds in the non-pain condition and with the right hand remaining on the stimulator, the site at which the noxious stimulus was to be presented was then heated or cooled to a temperature at which the subject rated the pain as "moderate". Typically, the subjects reported the presence of pain at a moderate level (category values of 3–4) within 10–15 min from the beginning of the heating or cooling process. Thresholds were again measured at each of the frequencies tested, with the order of threshold measurements varied randomly across subjects. The threshold determination in the painful condition took about 20 min. After the during-pain vibratory thresholds were obtained, the painful stimulus was removed. Vibration thresholds in the non-pain condition were always measured prior to measuring vibratory threshold in the pain condition. This was done since Apkarian *et al.* (1994) had already found that vibratory thresholds, post-pain, were significantly elevated above the pre-pain conditions.

The statistical analysis was performed as follows. For each pain site (relative to vibration) or pain type (heat vs cold) condition, a 2 (pre-pain and pain) × 3 (frequency—1, 10, and 100 Hz) repeated measures ANOVA was carried out except for the small-contactor condition where only pre-pain and pain conditions were compared. An additional repeated measures ANOVA was conducted to compare hot- vs cold-coincident pain effects.

Results

The effect of coincident (i.e., both the thermal and vibratory stimuli were applied to the right thenar eminence) heat-induced pain on the average vibratory thresholds are shown in Figure 1. The figure shows the pre-pain and during-pain thresholds as obtained at 1, 10, and 100 Hz using the large contactor, and at 250 Hz obtained with the small contactor. Coincident heat-induced pain was found to produce a significant elevation in threshold [$F(1, 4) = 61.78, MS_e = 5.659, p < 0.01$]. This effect did not differ across frequency ($p > 0.9$). For the large contactor, heat-induced pain raised vibrotactile thresholds by 7.0, 6.6, and 7.0 dB at 1, 10, and 100 Hz, respectively. This increase in threshold during heat-induced pain corresponds, on average, to a 2.2 times increase in threshold as expressed in stimulus amplitude. The result is in good agreement with the results of Apkarian *et al.* (1994) who, for the same conditions, found an across-frequency average increase in tactile threshold of 2.3. For the small contactor, 250 Hz condition, a significant heat-pain induced elevation in vibrotactile threshold of 4.8 dB

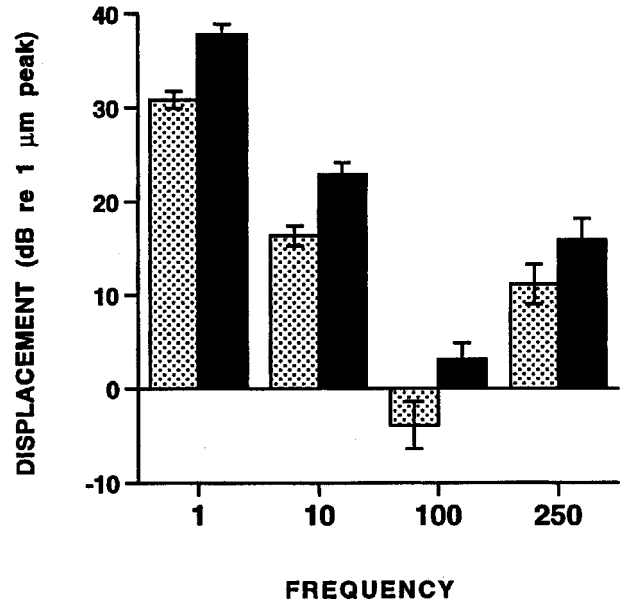

FIGURE 1. Vibratory thresholds obtained during the pre-pain (stippled bars) and during heat-induced pain (solid bars) conditions as obtained using a 2.9 cm^2 contactor (1, 10, and 100 Hz) or a 0.008 cm^2 contactor (250 Hz).

was found [$F(1, 4) = 52.33, MS_e = 1.085, p < 0.01$].

Coincident, cold-induced pain also was found to significantly decrease sensitivity to the vibratory stimuli [$F(1, 4) = 18.09, MS_e = 5.23, p < 0.02$], as shown in Figure 2, although not to the same degree as that obtained with the heat-induced pain (see below). The results obtained with the large contactor show that the cold-induced pain elevated tactile thresholds by 2.8, 4.8, and 3.1 dB at 1, 10, and 100 Hz, respectively. Across stimulus frequency, this

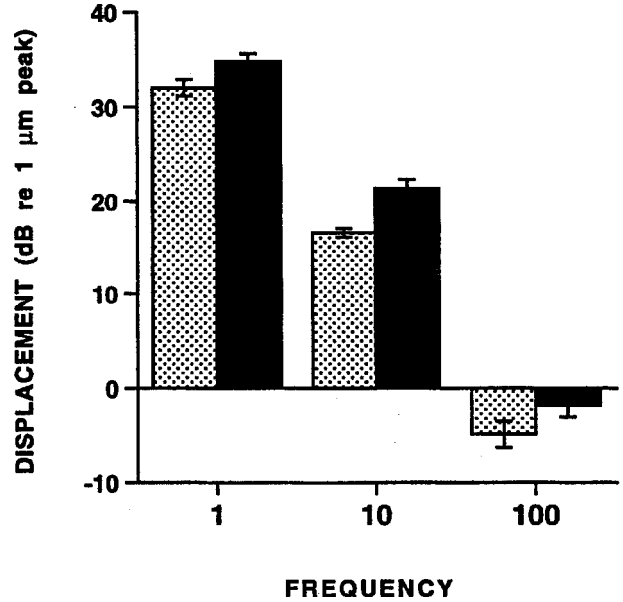

FIGURE 2. Pre-pain (stippled bars) and during pain (solid bars) coincident cold thresholds for all frequencies tested.

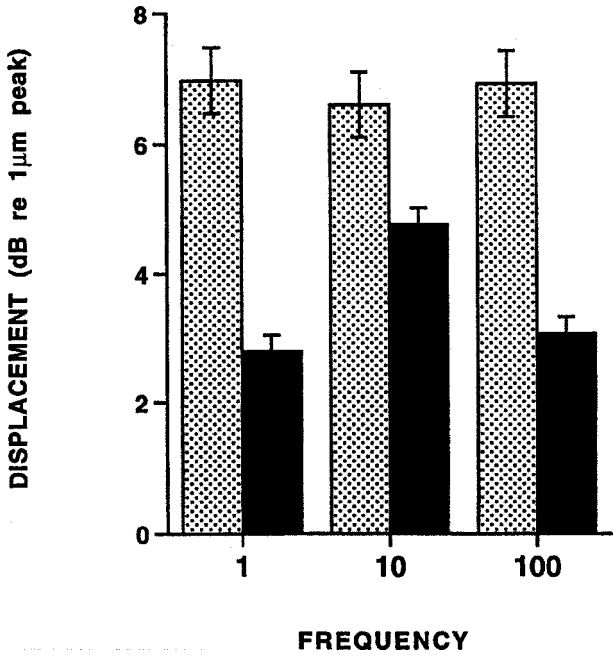

FIGURE 3. Mean increases (in dB) in thresholds for coincident heat-induced (solid bars) and cold-induced (stippled bars) pain.

corresponds to a 1.5 times decrease in tactile sensitivity. The decrease in tactile sensitivity did not differ across the vibratory frequencies tested [$F(2, 8) = 0.676, MS_e = 4.15, p > 0.5$]. The effects of cold-induced pain on tactile thresholds measured with the small contactor were not determined.

An additional analysis showed that the effect of cold-induced pain (mean elevation = 3.6 dB) is significantly smaller than that for heat-induced pain (mean elevation = 6.9 dB) [pain × thermal type interaction—$F(1, 4) = 15.33, MS_e = 2.287, p < 0.03$]. For purposes of comparison, the heat-induced and cold-induced pain effects on vibrotactile sensitivity as measured with the large contactor are shown in Figure 3. In all instances, the heat-induced pain produced a greater change in tactile sensitivity than the cold-induced pain, in spite of the fact that the observers rated the perceived amount of pain as moderate during both pain-producing conditions (see Materials and methods).

Heat-induced pain also was found to produce elevations in threshold when the vibration and pain were non-coincident. However, the effect did not occur for all non-coincident conditions. The results are given in Figure 4, where the five panels show the effects of heat-induced pain on the average vibrotactile thresholds measured at the three frequencies using the large contactor. As described in Materials and methods, the vibratory stimuli were applied to the right thenar eminence while the noxious heat stimuli were presented to either the right dorso-medial forearm, the right dorso-medial wrist, the right volar forearm, the left thenar eminence, or the left volar forearm. It was found that heat-induced pain increased tactile thresholds when to the right dorso-medial forearm [Fig. 4A; $F(1, 4) = 7.92, MS_e = 5.35, p < 0.05$] as well as to the right dorso-medial wrist [Fig. 4B; $F(1, 4) = 24.96, MS_e = 0.936, p < 0.01$], although the size of the effect is significantly smaller (on average, 1.77 and 2.38 dB for dorso- medial wrist and forearm, respectively) [$F(1, 4) = 20.44, p < 0.01$] than that obtained with coincident heat-induced pain. The effects did not differ across vibration frequencies [$F(2, 8) = 1.91, MS_e = 0.76, p > 0.2$] of 1, 10, and 100 Hz for the right dorso-medial forearm site with the change in sensitivity equaling 2.98, 2.64, and 1.52 dB, respectively. Averaged across stimulus frequency, this change in threshold corresponds to a 1.3 times increase in tactile thresholds. However, there was a marginal pain × frequency interaction detected in the right dorso-medial wrist site condition [$F(2, 8) = 4.33, MS_e = 1.054, p < 0.06$]. Simple main effects tests revealed a significant tactile threshold elevation for the 1 and 10 Hz vibration of 2.82 and 2.25 dB, respectively (about 1.33 times), but not for the 100 Hz frequency ($p > 0.7$) which only produced a 0.24 dB (1.02 times) elevation in tactile threshold. Referring again to Figure 4, heat-induced pain had no measurable effect on thresholds when presented to the other regions tested: right volar forearm (Fig. 4C; mean increase = 0.3 dB); left thenar eminence (Fig. 4D; mean increase = 0.3 dB); or left volar forearm (Fig. 4E; mean increase = 0.7 dB).

Discussion

The results show that both heat- and cold-induced pain can decrease tactile sensitivity (see Figs 1–3) and that the decrease in tactile sensitivity, at least for co- localized heat-induced pain (Fig. 1), is approximately the same across all four glabrous-skin information-processing channels. In addition, it was found that in order for heat-induced pain to elevate vibrotactile thresholds, the tactile and painful stimuli must be within an ipsilateral, prescribed region on the body (Fig. 4). The lack of a contralateral effect is similar to that in studies investigating the effects of tactile stimuli on pain perception (Bini *et al.*, 1984).

That heat-induced pain can decrease tactile sensitivity agrees with previous findings (Apkarian *et al.*, 1994) showing a decrease in this sensitivity of 8.4, 7.5, and 5.9 dB at 1, 10, and 100 Hz, respectively, for co-localized heat-induced pain. In the present study, the decreases in sensitivity amounted to 7.0, 6.6, and 7.0 for the 1, 10, and 100 Hz conditions, respectively. Across frequency, then, both studies find about a 7.0 dB (2.2 times) change in sensitivity in the presence of heat-induced pain. The results of the two studies are within one standard error of the mean (± 1.5 dB, see Materials and methods) of the threshold measurements, indicating that the different subject populations and the techniques by which thresholds were determined (i.e., modified method

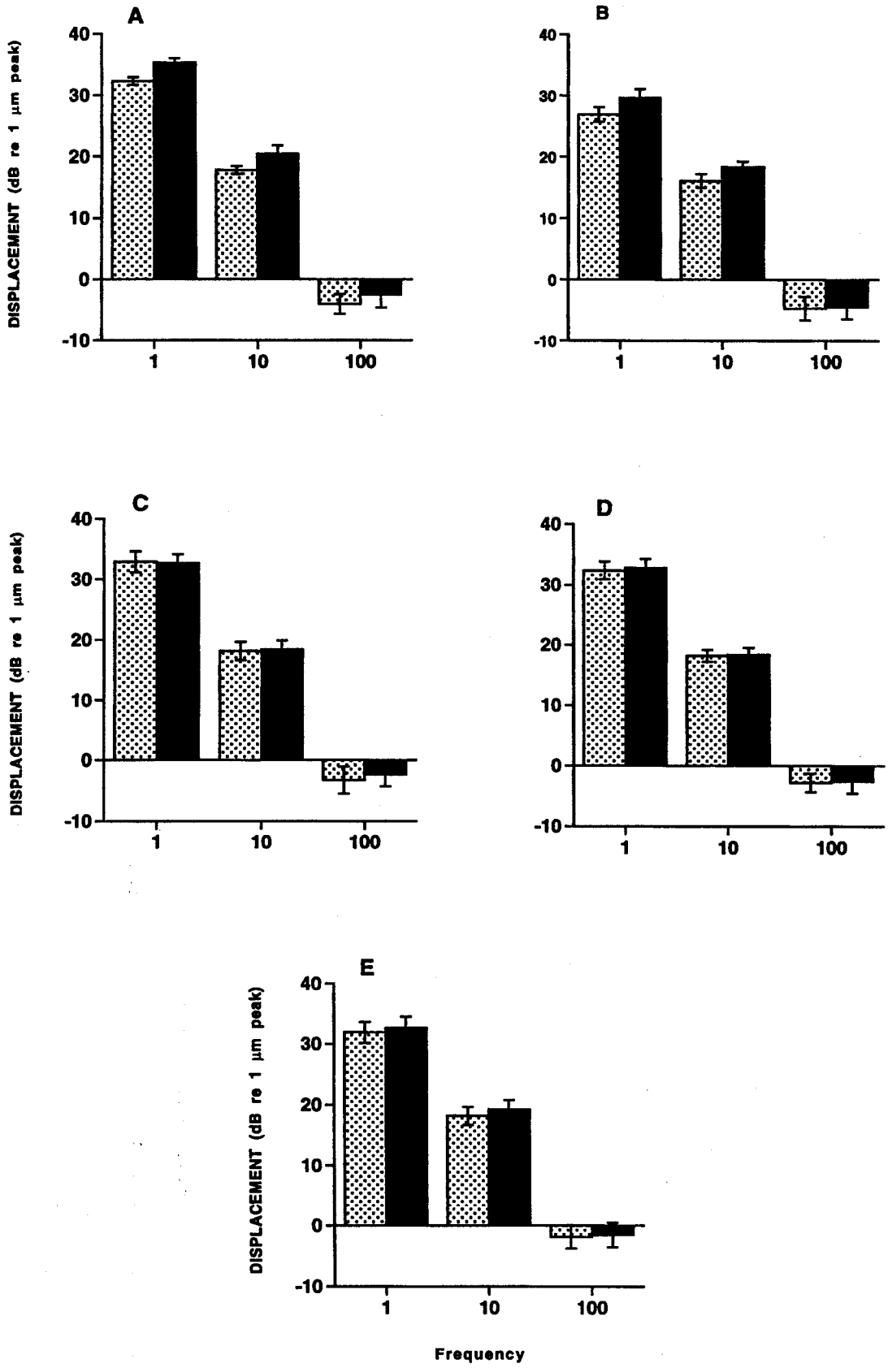

FIGURE 4. Pre-pain (stippled bars) and during pain (solid bars) thresholds for all conditions where heat-induced pain and vibration were not coincident. The thermal stimulus locations are: (A) ipsilateral dorso-medial forearm; (B) ipsilateral dorso-medial wrist; (C) ipsilateral volar forearm; (D) contralateral thenar eminence; (E) contralateral volar forearm.

of limits vs two-alternative, forced choice) did not contribute significantly to the size of the measured effects.

One important issue regarding the results presented here and in Apkarian *et al.* (1994) is whether cognitive factors such as "attention" (sensory- specific and otherwise) are interfering with the detection of tactile stimuli in the presence of pain. That is, it is possible that the noxious stimulus (heat or cold) or the mere presence of pain distracts subjects from the critical task, and in itself causes the reduction in tactile sensitivity. This issue is germane since separate research has concluded that responses to noxious stimulation (Bushnell *et al.*, 1985; Post and Chapman, 1991) and reports of intensity of painful stimuli (Miron *et al.*, 1989) are particularly susceptible to attentional manipulation. In Apkarian *et al.* (1994) it was argued that because auditory thresholds remained unchanged before and during the painful episodes, the effect was not due to general attentional mechanisms. This finding, however, did not rule out somatosensory-specific attentional processes. That these latter processes are probably not involved is supported by the current findings that contralateral and certain conditions of ipsilateral heat-induced pain are not effective in inducing modifications in tactile thresholds. A similar finding was obtained by Dowman and Zimmer (1996) who measured the effects of noxious heat on electrically evoked non-noxious stimuli. Thus while attentional mechanisms may play a role on sensory perception (e.g., Drevets *et al.*, 1995), it is unlikely that the increased vibrotactile thresholds found in this and the Apkarian *et al.* (1994) study could have been the result of attention. However, it could be argued that attentional mechanisms that are site specific may be the basis of the observed phenomenon, but the experiments reported here were not designed to test this. More recently, Gescheider *et al.* (1996) and Bolanowski *et al.* (submitted) in studies that measured how the touch gate affects intensity discrimination, found that blood pressure did not change during the painful episodes. This observation further indicates that the effect of heat- and cold-pain on tactile thresholds probably is not a result of (uncontrolled) autonomic functions, but is due to sensory-specific, touch–pain interactions.

With respect to the ipsilateral conditions, noxious heat applied to the dorso-medial wrist and forearm produced a modest reduction in tactile sensitivity (1.8 and 2.38 dB, respectively) compared with the co-localized condition, while that applied to the volar forearm did not reduce tactile sensitivity (see Fig. 4). These results are similar to those found in studies assessing vibration-induced analgesia. That is, the greatest effect of tactile stimuli on pain perception occurs when the stimuli are co-localized (Wall and Cronly-Dillon, 1960; Melzack *et al.*, 1963; Sullivan, 1968; Pertovaara, 1979; Bini *et al.*, 1984). For example, Bini *et al.* (1984) showed that moderate vibration within the area of perceived pain induced by intrafasicular electrical stimulation was better at diminishing pain than when the vibratory stimuli were applied outside of the painful area. In the volar and dorso-medial forearm conditions, the distance between the noxious heat and vibrotactile stimuli was approximately 21 cm. Since the gate was activated in the latter, but not the former condition, spatial separation between the tactile and noxious stimuli cannot in itself explain the inhibitory effect. Indeed, when the noxious heat stimuli were applied to the dorso-medial wrist approximately 7 cm from the location of the vibratory stimuli, at least for the 1 and 10 Hz conditions (Fig. 4), the elevation in threshold was the same as that in the dorso-medial forearm condition. Furthermore, since ipsilateral dorso-medial forearm and wrist stimulation induced the effect, it is unlikely that the effect is skin-type specific in that the wrist and forearm skin is hairy and the skin of the thenar eminence is glabrous (see Bolanowski *et al.*, 1994, for a discussion regarding the differences in hairy and glabrous skin vibrotactile organization). The absence of an effect in the 100 Hz, dorso-medial wrist condition is curious since it suggests that nociceptive activity from hairy skin may act differently on the P channel than nociceptive activity from glabrous skin. Additional support for this idea is the finding that in the hairy skin of the dorso-medial forearm, the magnitude of the gating effect as measured at 100 Hz was less than that for the 1 and 10 Hz conditions. This channel-specific effect is consistent with the possibility that the touch gate operates separately on the tactile channels, that is, prior to channel convergence.

The fact that heat-pain applied to the dorso-medial forearm, but not the volar forearm activates the touch gate supports the possibility that the effect is somehow related to somatotopic organization. It is interesting that heat-pain located at the volar forearm did not activate the touch gate given that this region and the thenar eminence are both innervated by the median nerve. Since the radial nerve largely innervates the dorso-medial forearm (and wrist) it seems that the effect is not related to peripheral-nerve organization. Alternatively, the effect may have a dermatomal basis, although it must be noted that dermatomes overlap extensively. Specifically, the ipsilateral dorso-medial forearm and wrist are in the same clinically described dermatome (see Netter, 1983) as the thenar eminence, while the volar surface of the forearm is in a different dermatome than the thenar eminence.

As described in the Introduction, the vibratory stimuli were selected to activate independently the different information-processing channels hypothesized to exist for the glabrous skin of thenar eminence. Specifically for the large contactor, the 100 Hz stimulus at threshold levels activates only the P channel that is mediated by Pacinian afferents. Similarly, at threshold, the 10 Hz stimulus activates

the NP I channel which is thought to be formed by the rapidly adapting (RA) afferents, while the 1 Hz stimulus activates NP III and probably the slowly adapting type I (SAI) afferents. Furthermore, NP II which is thought to be mediated by SAII afferents, can be independently activated at threshold by using a 250 Hz vibration applied with a small contactor (i.e., 0.008 cm^2, see Bolanowski *et al.*, 1988). The results presented here indicate that all four channels are affected similarly by the co-localized heat-induced pain. This result is different from that found for the effects of tactile stimulation on pain perception. For example, Pertovaara (1979, see also Sullivan, 1968) has shown that the effect of vibration on pain relief occurs for stimuli that activate the P, but not the NP channels. The finding in the present study that all four channels are similarly affected by the heat-induced pain is consistent with the idea that the mechanisms involved in the gating of touch by pain is similar across the four psychophysical channels. That the mechanisms are similar across the channels is also supported by the finding that cold-induced pain also decreased vibrotactile sensitivity in the same manner for the three tactile channels tested (Fig. 2). These results in themselves, however, cannot definitively determine the locus of the gate since the mechanisms could operate either before (e.g., spinal cord) or after channel convergence (e.g., somatosensory cortex).

The frequencies of vibration used to measure the tactile thresholds were selected not only to selectively activate the different vibrotactile channels, but also because thresholds measured at these frequencies are unaffected by skin-surface temperatures which are non-noxious (20–40°C, see Bolanowski and Verrillo, 1982; Verrillo and Bolanowski, 1986; Bolanowski *et al.*, 1988). Because of this, the effect of noxious heat and cold elevating vibrotactile thresholds indicates that the gate is likely controlled by activity originating in nociceptive afferents. Current thinking (see Yarnitsky and Ochoa, 1990; Strassman *et al.*, 1993, for review) on the topic of temperature-induced pain is that both heat-induced and cold-induced pain is mediated by the unmyelinated C polymodal nociceptors (van Hees and Gybels, 1972; Torebjörk, 1974), although in both instances there is some participation of small myelinated A∂ nociceptors (LaMotte and Campbell, 1978; LaMotte and Thalhammer, 1982). Since attentional mechanisms probably are not involved in the reduction of tactile sensitivity by the presence of either heat- or cold-pain (see above) it is possible that the effect is due primarily to activity in polymodal C-nociceptors, even though the activity may be subthreshold to pain perception. Support for this is given in Apkarian *et al.* (1994) who reported elevated tactile thresholds in response to thermal (heat) stimuli just below the pain threshold. More recently, Hollins *et al.* (1996) found that patients with temproromandibular disorders in which chronic pain of myalgic origin is present show elevated vibrotactile thresholds as measured on the facial skin overlying the affected musculature. This indicates that the pain gate may not be solely controlled by cutaneous nociceptors, but can also be activated by input from deep nociceptors present in and around muscle underlying the skin proper. Following along similar lines, Checkosky *et al.* (1996) measured vibrotactile sensitivity in patients with carpal tunnel syndrome (CTS). It was found that vibrotactile thresholds measured on the thenar eminence and the first phalange of the forefinger were not affected in patients with CTS as compared with normative controls. This was true regardless of whether the patients were experiencing pain in the palmer aspects of the hand or not. This latter observation supports the idea that it may not be the mere presence of pain mediated by any nociceptor fiber group at the site of tactile stimulation that is required to activate the touch gate, but that the gate requires activation of certain cutaneous (i.e., polymodal C-nociceptors) and/or deep nociceptors. In this regard it would be interesting to test whether pain induced chemically by, for example capsiacin, can activate the touch gate.

The observation that equal moderate levels of heat- and cold-induced pain activate the touch gate, but to differing degrees, is particularly interesting especially because of a report by Craig and Bushnell (1994) who performed psychophysical and physiological studies dealing with Thunberg's thermal grill illusion. The thermal grill illusion that elicits "synthetic heat pain" is produced with an apparatus that has two independent sets of thermally controllable elements arranged either orthogonally or alternately to each other and onto which the body part (e.g., hand) is placed. When the two sets of elements are equally warmed the perception is that of warmth. When the two sets of elements are equally cooled, a cold perception is experienced. When one set of elements is warmed and the other cooled, the perception is that of heat-induced pain. Based on recordings from lamina I spinothalamic tract cells in response to the various grill-stimulation conditions, they concluded that the thermal grill illusion comes about from an unmasking of polymodal C-nociceptors by a relative reduction in activity of cold fibers when one-half of the grill elements are warmed (i.e., the illusory condition). They concluded that the interaction (inhibition) of centrally located polymodal C-nociceptors by cold fibers takes place either in the thalamus or the cortex. Since no such inhibition by warm fibers is found in centrally located polymodal C-nociceptors mediating heat-pain (i.e., warm fibers generally are not activated at temperatures exceeding 47°C, see, for example, Hensel, 1973), noxious-cold stimuli should produce less activity in cold-activated pain pathways than that produced by painfully hot stimuli. Thus it would be expected that if the touch gate is located higher in the nervous system than the pain–thermal interactions

reported by Craig and Bushnell (1994), the effects of cold-induced pain on the touch gate should be less than that for heat-induced pain, as shown in Figure 3. Furthermore, if the processing of neural information responsible for the thermal grill illusion and the inhibition of cold-pain pathways is located in the thalamus or cortex, as Craig and Bushnell (1994) propose, then the touch gate may be located either in the primary somatosensory cortex or at higher levels within the somatosensory/association cortices. In fact, the original basis for exploring these pain–touch interactions was the finding of Apkarian *et al.* (1994) who demonstrated that painful thermal stimulation of the hand resulted in decreased contralateral somatosensory cortical activity. It was reasoned that since the somatosensory cortex, in particular areas 3b and 1, is critical for vibrotactile perception, inhibition within 3a and 1 should translate into decreased ability of vibrotactile perception. Few additional brain-imaging or physiological studies have directly assessed the locus to the pain–touch interactions. Support for a cortical basis for the touch gate can be found, additionally, in Tommerdahl *et al.* (1996). Using optical intrinsic signal imaging, they showed a reduced intrinsic signal in areas 3b and 1 in the presence of noxious thermal stimuli. This inhibition could be the basis for the touch gate whereby the presence of pain diminishes tactile sensations.

Acknowledgments

We would like to thank Drs Ronald T. Verrillo and James C. Makous for helpful comments regarding the manuscript. The work was supported in part by the National Institutes of Health, DC00380 and DC38661.

References

Apkarian, A.V., R.A. Stea, and S.J. Bolanowski (1994) Heat-induced pain diminishes vibrotactile perception: A touch gate. *Somatosens Mot Res* **11**: 259–267.

Bini, G., G. Cruccu, K.-E. Hagbarth, W. Schady, and E. Torebjörk (1984) Analgesic effect of vibration and cooling on pain induced by intraneural electrical stimulation. *Pain* **18**: 239–248.

Bolanowski, S.J. (1996) Information processing channels in the sense of touch. In *Somesthesis and the Neurobiology of the Somatosensory Cortex*, O. Franzén, R. Johansson, and L. Terenius, eds., pp. 49–58, Birkhäuser, Basel.

Bolanowski, S.J. (1998) Tactile channels and their interactions. In *Fourteenth Meeting of the International Society for Psychophysics*, Quebec City, Canada, Y. Lacouture, and S. Grodin, eds., pp. 103–108, International Society for Psychophysics.

Bolanowski, S.J., G.A. Gescheider, A.M. Fontana, J.L. Niemiec, G. Shea, and J.L. Tromblay (submitted) The effects of heat-induced pain on the detectability, discriminability, and sensation magnitude of vibrotactile stimuli. *Somatosens Mot Res*.

Bolanowski, S.J., G.A. Gescheider, and R.T. Verrillo (1994) Expansions of the four-channel model for touch: Hairy skin. *Somatosens Mot Res* **11**: 279–290.

Bolanowski, S.J., G.A. Gescheider, R.T. Verrillo, and C.M. Checkosky (1988) Four channels mediate the mechanical aspects of touch. *J Acoust Soc Am* **84**: 1680–1694.

Bolanowski, S.J., and R.T. Verrillo (1982) Temperature and criterion effects in a somatosensory subsystem: A neurophysiological and psychophysical study. *J Neurophysiol* **48**: 837–856.

Bushnell, M.C., G.H. Duncan, R. Dubner, J.L. Jones, and W. Maixner (1985) Attentional influences on noxious and innocuous cutaneous heat detection in humans and monkeys. *J Neurosci* **5**: 1103–1110.

Calford, M.B., and R. Tweedale (1991) C-fibres provide a source of masking inhibition to primary somatosensory cortex. *Proc R Soc Lond B* **243**: 269–275.

Casey, K.L., M. Zumberg, H. Heslep, and T.J. Morrow (1993) Afferent modulation of warmth sensation and heat pain in the human hand. *Somatosens Mot Res* **10**: 327–337.

Checkosky, C.M., S.J. Bolanowski, and J. Cohen (1996) Assessment of vibrotactile sensitivity in patients with carpal tunnel syndrome (CTS). *J Occupat Environ Med* **38**: 1–9.

Craig, A.D., and M.C. Bushnell (1994) The thermal grill illusion: Unmasking the burn of cold pain. *Science* **265**: 252–255.

Dowman, R., and D. Zimmer (1996) Heat pain increases the perceived magnitude of an innocuous electrical stimulus: Evidence for a peripheral mechanism. *Somatosens Mot Res* **13**: 255–262.

Drevets, W.C., H. Burton, T.O. Videen, A.Z. Snyder, J.R. Simpson, Jr., and M.E. Raichle (1995) Blood flow changes in human somatosensory cortex during anticipated stimulation. *Nature* **373**: 249–252.

Dykes, R.W. (1983) Parallel processing of somatosensory information: A theory. *Brain Res Rev* **6**: 47–115.

Ekblom, A., and P. Hansson (1982) Effects of conditioning vibratory stimulation on pain threshold of the human tooth. *Acta Physiol Scand* **114**: 601–604.

Ellenmeier, W., W. Westphal, and M. Heidenfelder (1991) On the "absoluteness" of category and magnitude scales of pain. *Percept Psychophys* **49**: 159–166.

Gescheider, G.A., S.J. Bolanowski, A.F. Fontana, J.L. Niemiec, G. Shea, and J.L. Tromblay (1996) The effects of heat-induced pain on tactile difference limens, *International Society for Psychophysics Meeting*, pp. 263–268.

Green, B.G. (1977) The effect of skin temperature of vibrotactile sensitivity. *Percept Psychophys* **21**: 243–248.

Hensel, H. (1973) Cutaneous thermoreceptors. In *Handbook of Sensory Physiology*, Vol. II, A. IGGO, ed., pp. 79–110, Springer-Verlag, Berlin.

Hollins, M., A. Sigurdsson, L. Fillingim, and A.K. Goble (1996) Vibrotactile threshold is elevated in temporomandibular disorders. *Pain* **67**: 89–96.

LaMotte, R.H., and J.N. Campbell (1978) Comparison of responses of warm and nociceptive C-fiber afferents in monkey with human judgments of thermal pain. *J Neurophysiol* **41**: 509–528.

LaMotte, R.H., and J.G. Thalhammer (1982) Response properties of high- threshold cutaneous cold receptors in the primate. *Brain Res* **244**: 279–287.

Lundberg, T. (1983) Vibratory stimulation for the alleviation of chronic pain. *Acta Physiol Scand* **523**: 1–51.

Marchand, S., M.C. Bushnell, P. Molina-Negro, S.N. Martinez, and G.H. Duncan (1991) The effects of dorsal column stimulation on measures of clinical and experimental pain in man. *Pain* **45**: 249–257.

Maxfield, L.M., and S.J. Bolanowski (1994) Vibrotactile thresholds under thermal pain: Spatial factors and temperature effects. *Psychonomic Soc* **35**: 33.

Maxfield, L.M., and S.J. Bolanowski (1995) Coincident or dermatomal thermally induced pain affects vibrotactile sensitivity. *Soc Neurosci Abstr* **21**: 1636.

Melzack, R., and P.D. Wall (1965) Pain mechanism: a new theory. *Science* **150**: 971–979.

Melzack, R., P.D. Wall, and A.Z. Weisz (1963) Masking and metacontrast phenomenon in skin sensory systems. *Exp Neurol* **8**: 35–46.

Miron, D., G.H. Duncan, and M.C. Bushnell (1989) Effects of attention on the intensity and unpleasantness of thermal pain. *Pain* **39**: 345–352.

Netter, F.H. (1983) *The CIBA Collection of Medical Illustrations: Vol. 1, Nervous System*, 239 pp., CIBA-GEIGY Corp.

Ottoson, D., A. Ekblom, and P. Hansson (1981) Vibratory stimulation for the relief of pain of dental origin. *Pain* **10**: 37–45.

Pertovaara, A. (1979) Modification of human pain threshold by specific tactile receptors. *Acta Physiol Scand* **107**: 339–341.

Post, L.J., and C.E. Chapman (1991) The effects of cross-modal manipulations of attention on the detection of vibrotactile stimuli in humans. *Somatosens Mot Res* **8**: 149–157.

Price, D.D. (1988) *Psychophysical and Neural Mechanisms of Pain*, Raven Press, New York.

Price, D.D., P.A. McGrath, A. Rafii, and B. Buckingham (1983) The validation of visual analogue scales as ratio scale measures for chronic and experimental pain. *Pain* **17**: 45–56.

Price, D.D., J.G. McHaffie, and M.A. Larson (1989) Spatial sumation of heat-induced pain: Influence of stimulus area and spatial separation of stimuli on perceived pain sensation intensity and unpleasantness. *J Neurophysiol* **62**: 1270–1279.

Sherer, C.L., J.A. Clelland, P. O'Sullivan, D.M. Doleys, and B. Canan (1986) The effect of two sites of high frequency vibration on cutaneous pain threshold. *Pain* **25**: 133–138.

Stevens, J.C. (1979) Thermo-tactile interactions: Some influences of temperature on touch. In *Sensory Functions of the Skin of Humans*, D.R. Kenshalo, ed., pp. 207–218, Plenum, New York.

Strassman, A.M., B.P. Vos, Y. Mineta, S. Nadari, D. Borsook, and R. Burstein (1993) *FOS*-like immunoreactivity in the superficial medullary dorsal horn induced by noxious and innocuous thermal stimulation of facial skin in the rat. *J Neurophysiol* **70**: 1811–1821.

Sullivan, R. (1968) Effect of different frequencies of vibration on pain- threshold detection. *Exp Neurol* **20**: 135–142.

Tommerdahl, M., K.A. Delemos, C.J. Vierck, O.V. Favorov, and B.L. Whitsel (1996) Anterior parietal cortical response to tactile and skin-heating stimuli applied to the same skin site. *J Neurophysiol* **75**: 2662–2669.

Torebjörk, H.E. (1974) Afferent C units responding to mechanical, thermal and chemical stimuli in human non-glabrous skin. *Acta Physiol Scand* **92**: 374–390.

van Hees, J., and J.M. Gybels (1972) Pain related to single afferent C fibers from human skin. *Brain Res* **48**: 397–400.

Verrillo, R.T., and S.J. Bolanowski (1986) The effects of skin temperature on the psychophysical responses to vibration on glabrous and hairy skin. *J Acoust Soc Am* **80**: 528–532.

Wahren, L.K., E. Torebjörk, and E. Jörum (1989) Central suppression of cold-induced C fibre pain by myelinated fibre input. *Pain* **38**: 313–319.

Wall, D.P., and B.A. Cronly-Dillon (1960) Pain, itch and vibration. *AMA Arch Neurol* **2**: 19–29.

Weber, E.H. (1846) Der Tastsinn und das Gemeingefühl. In *Handwörterbuch der Physiologie*, Vol. 3, R. Wagner, ed., pp. 481–588.

Willis, W. (1985) *The Pain System: The Neural Basis of Nociceptive Transmission in the Mammalian Nervous System*, Karger, Basel.

Yarnitsky, D., and J.L. Ochoa (1990) Release of cold-induced burning pain by block of cold-specific afferent input. *Brain* **113**: 893–902.

Zoppi, M., M.R. Voegelin, M. Signorini, and A. Zamponi (1991) Pain threshold changes by skin vibratory stimulation in healthy subjects. *Acta Physiol Scand* **143**: 439–443.

Zwislocki, J.J., A.S. Marie, A.S. Feldman, and H.J. Rubin (1958) The effect of practice and motivation on the threshold of audibility. *J Acoust Soc Am* **30**: 254–262.