Human locognosic acuity on the arm varies with explicit and implicit manipulations of attention: implications for interpreting elevated tactile acuity on an amputation stump

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Abstract

In Experiment 1, normal subjects’ ability to localize tactile stimuli (locognosia) delivered to the upper arm was significantly higher when they were instructed explicitly to direct their attention selectively to that segment than when they were instructed explicitly to distribute their attention across the whole arm. This elevation of acuity was eliminated when subjects’ attentional resources were divided by superimposition of an effortful, secondary task during stimulation. In Experiment 2, in the absence of explicit attentional instruction, subjects’ locognosic acuity on one of three arm segments was significantly higher when stimulation of that segment was 2.5 times more probable than that of stimulation of the other two segments. We surmise that the attentional mechanisms responsible for such modulations of locognosic acuity in normal subjects may contribute to the elevated sensory acuity observed on the stumps of amputees. © 2001 Elsevier Science Ireland Ltd. All rights reserved.

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Somatotopic maps within the somatosensory cortex (SSC) of adult, non-human animals become reorganized following limb amputation or peripheral nerve injury (see Ref. [7]). Within 2 months of amputation of the middle finger of adult owl monkeys, for example, the cortical representation of digits 2 and 4 in area 3b expands to occupy the cortical region in which the amputated digit was previously represented [10]. There is also evidence for analogous changes in human SSC. Such evidence is, however, more indirect and derives primarily from non-invasive imaging and electrophysiological studies (see Ref. [12]), and from studies of the perceptual consequences of deafferentation [1,3–6,9,11–13,18,20,21].

Stimulation of the face ipsilateral to an upper limb amputation, for example, has been reported to evoke phantom limb sensations [1,4,6,18]. It has been argued that this phenomenon reflects the invasion of the deafferented area of SSC limb representation by expansion of the neighbouring area of face representation [18], as has been shown in macaque monkeys [16]. Furthermore, the tactile acuity of the skin on an amputation stump in humans is higher than that of the skin on the equivalent region of the intact limb, as indicated by a lower tactile detection threshold [5] and higher acuity of two point discrimination [5,9,21] and point localisation [5]. These observations have been interpreted to imply central reorganization of somatotopic maps and that such reorganization is of adaptive functional significance [5,21].

On the other hand, referral of stimulation of the face to the phantom limb occurs in less than 7% of arm amputees [4,12], so that its general significance is unclear and, on the basis of electrical source imaging, it has been argued that reorganization of SSC in amputees is observed only in case of phantom limb pain [3]. Human subjects, moreover, are capable of interpreting accurately information from nerve fascicles in transected median or ulnar nerves [12,20], and there is no change in the sensory acuity of normal skin lying adjacent to an area rendered anaesthetic by nerve injury [13]. Such results, it has been argued [12,20], do not seem
to be consistent with the idea that deafferentation-induced SSC reorganization in humans is of adaptive functional significance.

In an attempt to reconcile such apparently inconsistent observations, Moore et al. [11] have suggested that elevated tactile acuity on an amputation stump [5,9,21] might arise, at least in part, from a mandatory redistribution of available attentional resources from, potentially, the whole intact limb before amputation, to the stump alone afterwards. Here, we report the results of two experiments in which we replicated and extended the findings of Moore et al. [11]: we show that the acuity with which human subjects can localize tactile stimuli (locognosia) delivered to the intact arm varies systematically with both explicit and implicit attentional manipulations.

With the approval of the local Research Ethics Committee, and with subjects’ informed consent, we estimated subjects’ locognosic acuity on the skin of the non-dominant arm, using the method introduced by Noordenbos [14]. Subject sat in a quiet room with the ventral surfaces of the hands and forwardly extended arms resting comfortably on pillows on a table. Throughout an experimental session, the subject wore goggles with red lenses. At the start of a session, the subject’s arm on the dominant side was exposed to the shoulder and 30 stimulation points, in a 5 × 5 session, the subject’s locognosic acuity on the skin of the non-dominant arm was measured to 0.5 mm, was taken as the locognosic error (LE) for that trial. The experimenter then stimulated a given point on the arm using a 65 mN von Frey hair, and subjects were subsequently required, with eyes open and using a yellow pen held in the dominant hand, to mark the point at which they thought that they had been stimulated. Subjects then closed their eyes while the experimenter measured the distance between the red and yellow points, neither of which subjects could see through the red goggle lenses, was drawn across the skin of the dorsal surfaces of each of three segments of that arm: upper arm, lower arm and hand. The grids were located centrally on each segment and were aligned consistently in different subjects by reference to conventional anatomical landmarks. At the start of each trial in each experiment, subjects closed their eyes. The experimenter then stimulated a given point on the arm using a 65 mN von Frey hair, and subjects were subsequently required, with eyes open and using a yellow pen held in the dominant hand, to mark the point at which they thought that they had been stimulated. Subjects then closed their eyes while the experimenter measured the distance between the red and yellow points, neither of which subjects could see through the red goggle lenses: this distance, measured to 0.5 mm, was taken as the locognosic error (LE) for that trial.

In Experiment 1, we employed an explicit attentional manipulation in testing 40 right-handed Subjects (30 females, ten males) with a mean (SD) age of 19.7 (4.2). Subjects were tested under two attention conditions (Attended (A) and Unattended (U)) under each of two task conditions (Single (S) and Dual (D)), giving rise to four conditions in total (SA, SU, DA, DU), the presentation order of which was counterbalanced across subjects using a 4 × 4 Latin square. In the U conditions, subjects were told to attend to all three segments of the arm and that stimuli would be delivered with equal probability to each segment, to each of which ten stimuli were delivered in pseudorandom order across segments (no one segment was stimulated more than twice on successive trials), across pre-determined, pseudorandomly distributed loci within the matrices on each segment. For each segment, the mean LE across the ten trials was calculated. In the A conditions, a black line, visible through the red goggle lenses, was drawn across the elbow crease and subjects were told to attend, and that stimuli would be delivered, only to the upper arm segment, to which 30 stimuli were delivered successively, one to each matrix locus in a pre-determined, pseudorandom order. The mean LE was calculated for ten of the 30 trials, these ten being matched exactly to those delivered to the upper arm in the U conditions, with respect to their grid loci and ordinal positions within the sequence of 30 stimuli. In the dual-task (D) conditions, subjects were required, when their eyes were closed during the period of stimulation, to count aloud backwards in threes or sevens from a given number, thereby loading their attentional/processing resources by comparison with the single-task (S) conditions in which they were free to concentrate on the task of identifying the locus of stimulation (e.g. Ref. [8]). Aside from the imposition of a secondary task, the procedures employed in, and the structures of, S and D conditions were identical. The inter-trial interval was approximately 12 s, the duration of each of the four blocks of trials was approximately 6 min, and an interval of 2 min intervened between each block of trials.

The LE (Fig. 1) for stimulation of the upper arm segment in the single-task condition was significantly smaller (by 12%; two-tailed $P = 0.043$, Wilcoxon) when subjects attended selectively to that segment (SA condition: group mean (SD) LE = 17.5 (6.4) mm) than when they distributed their attention across the whole arm (SU condition: group

![Fig. 1. Mean (+ SEM) locognosic error on Attended (A) and Unattended (U) arm segments in Experiment 1 (explicit attentional manipulation; S = Single Task; D = Dual Task) and Experiment 2 (implicit attentional manipulation; plotted data values are the antilogs of the corresponding log-transformed values employed in statistical analysis). Note that the plotted mean errors for Experiment 1 (means for upper arm only) are larger than those for Experiment 2 (means of upper arm, lower arm and hand) simply because locognosic acuity is considerably higher on the hand than on the lower and upper arms.](image-url)
mean (SD) LE = 19.9 (8.0) mm). This finding replicates that reported by Moore et al. [11]. There was, moreover, no significant difference (\( P = 0.69, \) Wilcoxon) in LE between A and U conditions when subjects’ attentional resources were divided during stimulation by their having to perform simultaneously a secondary task (DA condition: group mean (SD) LE = 21.2 (7.7) mm; DU condition: group mean (SD) LE = 21.4 (6.6) mm).

In Experiment 2, we employed an implicit attentional manipulation in testing 30 different subjects (24 females, six males) with a mean (SD) age of 21.9 (2.1) years 28 subjects were right handed and two were left handed. Three blocks of 56 trials were run with each subject. During each block, 40 trials were delivered to one of the three segments, designated the attended (A) segment, and eight trials to each of the other segments, designated the unattended (U) segments. Thus, the probabilities, during a block, of stimuli being delivered either to the attended segment or to one or other of the unattended segments were, respectively, 0.714 and 0.286 (0.143 for each segment). Subjects were told that, on different trials during a block, stimuli would be delivered to each of three arm segments (upper arm, lower arm or hand), and they were given no indication that the stimuli would not be distributed equally between segments, nor any instructions about how to distribute their attention between segments. Stimuli on the first four trials in each block were delivered to the attended segment and stimuli delivered to unattended segments were separated by at least one stimulus to the attended segment, else stimuli were delivered in random order to one or other segment, while maintaining the relative probabilities of stimulation of attended and unattended segments. Each segment served once in the three blocks of trials as the attended segment, and the six possible orders of presentation of the three conditions were counterbalanced fully across subjects. For each block, the mean LE for the unattended segments was taken as the mean of the two means across the eight trials to each of those segments. The mean LE for the attended segment was calculated across eight of the 40 trials to that segment, the stimulation loci of these eight trials being matched exactly to those of the eight trials when the same segment was unattended. The ordinal positions of the eight analyzed trials delivered to the attended segment within each of the three blocks of 56 trials were identical. The inter-trial interval was approximately 10 s, the duration of each of the three blocks of trials was approximately 10 min, and an interval of 2 min intervened between each block of trials.

Data were log-transformed to normalize, and to stabilize the variances of, sample distributions. A 2 (attended/unattended) \( \times \) 3 (segment) repeated-measures ANOVA of the transformed data revealed that, over the three segments, the group mean LE was significantly smaller (by 10%; main effect of attention condition: \( F(1, 29) = 10.04, P = 0.004 \)) when segments were attended (A condition: antilog group mean (SD) log LE = 12.5 (2.4) mm) than when they were unattended (U condition: antilog group mean (SD) log LE = 13.9 (2.6) mm; Fig. 1). The mean improvement in locognosic acuity afforded by the attention condition differed somewhat between the arm segments (hand 12%; lower arm 13%; upper arm 6%), but the interaction between attention condition and segment was not statistically significant (\( F(2, 58) = 0.54, \) Huyhn-Feldt corrected \( P = 0.58 \)).

In confirmation of the findings of Moore et al. [11], we have shown in Experiment 1 that the voluntary, conscious directing of attention selectively to the upper arm in normal subjects can give rise to a higher locognosic acuity to stimulation of the skin of that arm segment, by comparison to that observed when attention is voluntarily distributed across the whole arm. Furthermore, this elevation of acuity can be eliminated by division of subjects’ attentional or processing resources. While the exact relations between activity and function in SSC are far from clear, and it seems very unlikely that that the cortical processes which underlie somatosensory perception are restricted to SI, these results are consistent with, and provide a partial behavioural analogue of, the modulation of the functional topographic organization of the human SSC by the voluntary directing of attention to and from a given body locus (e.g. Ref. [15,19]) and by the anticipation of stimulation [2]. Similarly, in Experiment 2, we have demonstrated that heightened locognosic acuity can also arise in situations when perhaps more automatic [17] attentional mechanisms are engaged by variation in the relative probabilities of stimulation of different arm segments, in the absence of any explicit instruction to attend to one or other segment.

One important question to be addressed in future research concerns the degree to which the heightened tactile acuity observed on the stumps of amputees [5,9,21] might be explicable in terms of attentional mechanisms. The magnitudes of the effects of attentional manipulations on locognosic acuity reported here and by Moore et al. [11] are not as large as the magnitude of the difference in locognosic error between the stumps and intact arms of amputees reported by Haber [5]. However, the usefulness of quantitative comparisons of effect sizes in these studies is unclear in view of the considerable differences in subject groups and methodology employed in the different studies. We might add that while Haber [5] provided no details of how he measured localisation error in his amputees, we do know that he could not have used the method employed here, as this would have required his amputees to respond overtly with their phantoms!

In conclusion, we suggest that it is plausible that the mechanisms responsible for such attention-dependent modulations of locognosic acuity in normal subjects may contribute to the elevated sensory acuity observed on the stumps of amputees [5,9,21], in addition to deafferentation-induced changes in neural connectivity in the SSC following amputation. The degree to which other sensory or perceptual consequences of deafferentation might be explicable in
terms of post-traumatic changes in cognitive processing remains to be seen.