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Peripheral neuropathy and object length perception by effortful (dynamic) touch: A case study

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Abstract

The spatial extents of hand-held objects can be perceived nonvisually by wielding them. This ability of effortful or dynamic touch to exploit the mass moments of an object to perceive its length was evaluated with a 40-years old right-handed woman with surgically treated Arnold-Chiari Type 1 Malformation and cervical syrinx. At the time of the experiment she presented with loss of discriminative touch in the left arm but no comparable sensory deficits in the right arm or the lower extremities. She could neither identify objects in her left hand nor tell that they were in the hand while manipulating them. She could, however, grasp an object tightly and wield it on request. In the experiment she wielded weighted rods of 45, 60, and 80 cm length about the wrist. There were two main results. First, her nonvisual perception of rod length by the insensate left arm scaled systematically with rod moment of inertia. The scaling matched that of the intact right arm and the nondominant arm of haptically unimpaired controls tested with rods of similar dimensions. Second, her right arm was superior in accuracy and reliability than her insensate left arm and was equal to or better than the dominant arm of the control group on key measures of nonvisual length perception. The first result was evaluated in respect to the notions of numb touch and differences in the neural bases of discriminative and effortful touch. The second result was discussed in terms of contralateral cortical enhancement by deafferentation.

Keywords: Dynamic touch; Handedness; Haptic perception; Peripheral neuropathy

The haptic system is the basis of perceiving the environment adjacent to the body by means of the body [5]. Often this perception is tied to circumstances that affect predominantly the receptor states of muscle and its attachments (tendons and ligaments) to the skeleton. Such perception implicates a haptic subsystem referred to variously as *effortful touch*, *dynamic touch*, *kinesthetic touch* and, most classically, *muscle sense* [3,5,10]. Effortful touch is perhaps the most common form of touch, albeit the least apparent. It is functioning whenever one grasps something and moves it in some fashion (e.g., lifts a cup, carries a book, stacks a plate, etc.) or uses a tool or implement to act upon or explore the environment.

In Gibson's [5] scheme effortful touch is distinguished from cutaneous touch (perception arising from stimulation of skin and deeper tissue without joint movements) and haptic touch (perception arising from stimulation of skin and deeper tissues together with movements of the joints). Conventionally, the latter two kinds of touch are referred to as discriminative touch. In the present research we examined the aforementioned distinction. If discriminative touch is impaired, is effortful touch similarly impaired? The question was posed experimentally to a person lacking discriminative touch in her left, nondominant arm.

Among the many functional achievements of effortful touch is the nonvisual perception of the length of a hand-held object (e.g., a rod) achieved by wielding it [18]. Perception is scaled to the moments of the object's mass distribution. Many experiments have pointed to the significance of the second moment (moment of inertia [3]) but others point to contributions of the zeroth moment (mass) and the first moment (static moment; e.g., [7]). For present purposes, the key issue is whether the ability to perceive length by effortful touch is preserved in a limb that lacks discriminative touch. The specific version of the experimental question was whether length perception of wielded rods

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would be comparable for the two hands despite the left limb's sensory neuropathy.

The participant AA was a 40-year-old right-handed female. She had given her consent in accordance with the University of Connecticut's internal review board's regulations for studies with human participants. Prior to the experiment AA presented with Arnold-Chiari Type 1 Malformation and cervical syrinx. An occipital-cervical fusion was followed 6 months later by additional surgery to drain a thoracic syrinx and a year later by surgery to drain the cervical syrinx. Although many of the original symptoms were reduced or eliminated, several persisted including numbness in the upper limbs. At the time of the experiment AA experienced insensitivity in the left arm, extending from the hand through the elbow with some involvement of the shoulder but no comparable sensory deficits in the lower extremities.[1] This unilateral manifestation of "suspended alteration of sensation" localized her lesion to the lower cervical (C5-7) and upper thoracic (T1and possibly T2) segments on the left of the dorsal column system.

The absence of discriminative touch in the left hand was confirmed by a form identification task conducted prior to the experiment proper. Number-shaped 3D plastic objects (approximately 2 cm × 2 cm × 1 cm) were placed in one hand singly, in random order. While blindfolded, AA correctly identified by manipulation every number immediately with the unaffected hand but none using the numb hand. She declined to continue after dropping the first three objects, noting that she could not feel anything. She was willing, however, to keep her hand tightly closed if requested, a capability that was essential to the evaluation of effortful touch (see below).

That AA could not identify an object in her hand, nor tell whether an object was in the hand even when manipulating it, suggests ahylognosia (disturbance in the ability to discriminate materials), tactile agnosia (inability to recognize familiar objects), and amorphognosia (disturbance in the ability to discriminate forms). The foregoing are strong indicators of a compromised basis for discriminative touch within the dorsal column system.

Length perception was evaluated using a typical methodology (Fig. 1). Ash dowels were cut into three sets of three lengths ($L = 45$, 60, and 80 cm). In order to manipulate the moments of the mass distribution, one member of each length set was presented with a metal disk at $1/3L$, one with the disk at $2/3L$, and one without a disk. The size of the attached disk was chosen so that the weighted rods would total 100 g regardless of the mass of the individual rods of different lengths. The values of the maximal principal moment of inertia I_1 (in g cm^2) for the 0, 1/3, and 2/3 disk attachments, respectively, were 32623, 42507, and 89757 for $L = 45$; 49444, 75648, and 147648 for $L = 60$; and 160538, 168896, and 236095 for $L = 80$. Each of the nine rod-configurations was presented three times in random order.

Fig. 1. Methodology for numb and intact hands (top). While the numb hand wielded a rod hidden from view by an opaque curtain, AA adjusted the report apparatus with her right hand (bottom). While the intact hand wielded the occluded rod, AA directed one of the Experimenters to adjust the report apparatus.

Perceived length was evaluated for the numb hand in the first block of 27 trials. Prior to the trials AA was shown a 75 cm rod (without an added mass) and informed that her task would be wielding such a rod out of sight and attempting to assess its length. There were two experimenters (Fig. 1), one to record AA's judgment and one to position her forearm on a support, place each rod in her hand, and monitor her wielding. On a trial, AA closed her affected left hand tightly on request, with the experimenter ensuring that the rod was suitably positioned within the grasp. "Suitably positioned" meant that the proximal end was flush with the lower surface of the hand. AA then performed (without objection) wielding motions of her tightly closed hand. (She would even try to wield when her grasp included, unknowingly and inadvertently, the experimenter's fingers as well as the rod. Also, on occasions, her wielding arm would rise off the support without her knowledge; the experimenter simply placed it back in the appropriate position, in alignment with the report apparatus.) Her specific objective was to adjust the visible report apparatus with her right hand so as to identify the location she felt could be reached if the rod were held forward and horizontally [17].

In the second block of 27 trials AA wielded the rod with her unimpaired right hand. She found it difficult to use the impaired left hand to manipulate the string of the report apparatus, in part

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[1] AA still used the affected arm in her daily activities, albeit not effectively if her visual attention was distracted (e.g., she reported crushing a piece of cake when she looked away from her hand). But speech-related gestures involving both (visible) hands appeared to be synchronized in space and time.

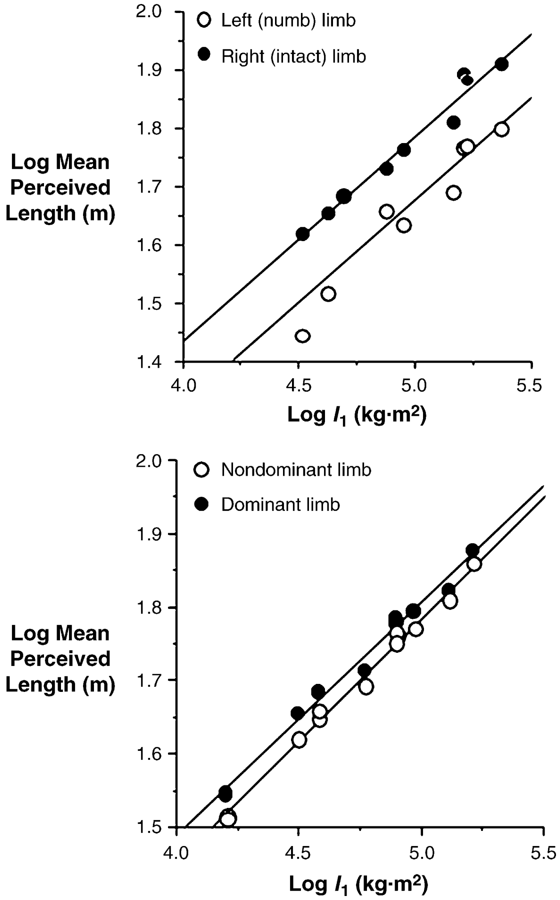

Fig. 2. Perceived length as a function of rotational inertia (top). Perception by AA's intact dominant) and numb (nondominant) hands differed by a scale factor (bottom). Perception by dominant and nondominant hands of nonimpaired participants did not differ.

due to having to direct her vision to the marker rather than to her impaired hand. Consequently, the experimenter who recorded her responses made the back-and-forth adjustments according to AA's instructions (Fig. 1bottom). The latter experimenter, like AA, was unable to see the wielded rod. AA was given no information about the number of rods she was wielding, their lengths, or that any of them were weighted.

An ANOVA conducted with individual trials as "subjects" revealed the standard findings (see [19]). Mean length perceived, LP, increased with L (41 ± 11, 52 ± 9, 69 ± 11 cm for L's of 45, 60, and 80 cm, respectively), $F(2, 8) = 123.62$, $p < .0001$, and mean LP increased with the attached disk and its distance from the hand (50 ± 17, 52 ± 15, 60 ± 14 cm for no disk, 1/3L, and 2/3L, respectively), $F(2, 8) = 8.66$, $p < .01$. LP with the numb hand was smaller than LP with the intact hand, $F(1, 8) = 18.50$, $p < .02$, and this interacted weakly with L, $F(2, 8) = 4.24$, $p < .06$. For the three L's, the right hand yielded mean LP's of 48 ± 8, 56 ± 11, and 79 ± 8 cm; the left hand yielded mean LP's of 35 ± 9, 48 ± 5, and 60 ± 5 cm.

These findings can be expressed compactly and more usefully in terms of the maximal principal moment of inertia, I_1. For both AA's numb and intact hands, a power function is revealed (in double logarithmic coordinates; Fig. 2top): $\mathrm{LP} = a(I_1)^b$. The power b was the same (.35) for the two hands and in close agreement with the value (.33) expected from dimensional analysis and standard experimental observations [19]. In contrast, the coefficient a was not the same between the hands. In overview, LP increased with I_1 at the same rate for both hands, but was systematically smaller at each I_1 for the numb hand.

A measure of the consistency or reliability of AA's perception of a given rod of length L wielded by a given hand is the average deviation (AD) expressed as a percentage of ⟨LP⟩, the mean of the three trials for that rod/hand combination:

$$\mathrm{AD\%} = \frac{(\sum |\mathrm{LP}_i - \langle \mathrm{LP} \rangle|)/3}{\langle \mathrm{LP} \rangle} \times 100,$$

where i signifies trial ($i = 1$–3). A higher value indicates less consistency (more variability). Averaged across the nine rods, mean AD% yields the reliability measure for the hand. For the numb and intact hands, mean reliability was 10% and 7%, respectively.

The corresponding accuracy is provided by a measure that is best referred to as mean-root-square (MRS) errors.[2] These reveal how much AA's LP varied from L (calculated as a percentage of L). A higher value indicates less accuracy. The percentage MRS error for LP was calculated according to the following equation:

$$\mathrm{MRS\%} = \frac{\sum^{\mathrm{o}}\sum^{\mathrm{r}}(\sqrt{(\mathrm{LP} - L)^2}/L)}{\text{objects} \times \text{repetitions}} \times 100,$$

where summation is over the number of rods and the number of repetitions. For the numb and intact hands, MRS% was 23% and 12%, respectively.

It is instructive to compare reliability and accuracy [2]. Suppose that one had to measure a well-defined length with a ruler. One source of uncertainty or error would arise from interpolating between scale markings. This error would probably be random given that the interpolation is just as likely to result in an underestimation as it is to result in an overestimation. The reliability measure captures this random error. A contrasting systematic uncertainty or error would arise if the ruler was distorted in some way—for example, it had been stretched or shrunk. A stretched ruler would always underestimate, a shrunk ruler would always overestimate. The accuracy measure captures this systematic error. Returning to AA's length measures by effortful touch, and in agreement with the standard findings (e.g., [2]), MRS% was greater than AD%. AA's length judgments were systematically distorted—as they should be if the basis for her length judgments was a rod's mass distribution rather than its metric length.

To assess whether this scale difference was due to the fact that AA's numb hand was her nonpreferred hand, an experiment was conducted to determine whether participants without haptic impairment likewise exhibit a magnitude difference in LP between the two hands. Participants (18–22 years old) were

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[2] In contrast with the standard root mean square (RMS), in which the deviations of perceived from actual are summed prior to taking the root, the benefit of MRS is that it scales the error as a dimensionless Weber fraction (and functions, therefore, like the reliability measure). The standard RMS is not invariant over different units of measurement and, in consequence, is more difficult to interpret. RMS and MRS are linearly correlated.

recruited from University of Connecticut undergraduates on the basis of the Edinburgh Handedness Inventory, EHI [12]. All gave their consent in accordance with the University's internal review board regulations for studies with human participants. Only those who scored greater than |.64| on the EHI were chosen (eight right-handers averaged .79; eight left-handers averaged −.86). Pine dowels cut to the same lengths and with the same attached masses that were used with AA were used for presentation to the left-handers (LH) and the right-handers (RH). The values of I_1 (in g cm^2) for the 0, 1/3, and 2/3 disk attachments, respectively, were 12586, 30632, and 78593 for $L = 45$; 35105, 58590, and 141591 for $L = 60$; and 76147, 92098, and 163419 for $L = 80$. (These values are smaller than those for AA's rods because pine is a less dense wood than ash.) The methodology followed that used with AA with the exception that the participant adjusted the report apparatus on all trials. As before, trials were blocked by hand (the order of the blocks was counterbalanced over participants) and each rod was presented three times.

Importantly, neither handedness (LH mean = 54 ± 16 cm, RH mean = 55 ± 16 cm) nor dominance (dominant mean = 56 ± 16 cm, nondominant mean = 53 ± 15 cm) was significant ($p > .05$). In agreement with standard observations, mean LP increased with L (45 ± 15, 54 ± 13, 64 ± 13 cm for L's of 45, 60, and 80 cm), $F(2, 28) = 129.66$, $p < .0001$, and mean LP increased with the attached disk and its distance from the hand (46 ± 14, 51 ± 13, 66 ± 13 cm for no disk, 1/3 L, and 2/3 L), $F(2, 28) = 89.72$, $p < .0001$. Additionally, there was a length by weighting interaction, $F(4, 56) = 4.49$, $p < .01$.

Power functions relating LP (averaged over participants) to I_1 for the dominant and nondominant hands both showed 1/3 scaling (.31 and .33 for the dominant and nondominant hands, respectively) and similar intercepts (Fig. 2bottom). Regressions were conducted for each hand of each participant. Handedness × Dominance ANOVAs were then conducted on the beta weights for the obtained intercepts and slopes and on Fisher's z-transform of the r values. A Bonferroni adjustment for multiple comparisons requires $p = .015$ to get an overall alpha level of .05. These analyses revealed no significant differences in regression parameters. In particular, the intercepts for dominant and nondominant hands (which differed significantly for AA) did not differ for unimpaired controls, $F(1, 14) = 1.56$, $p > .20$. Nor did the dominant and nondominant limbs differ in reliability or accuracy. A Handedness × Dominance × Measure ANOVA found only an effect of measure, $F(1, 14) = 109.61$, $p < .0001$, with MRS% (25%) greater than AD% (8%). For all other factors and interactions, F's < 1.

A qualitative comparison of AA's perceptual performance to that of the haptically unimpaired participants reveals many similarities and a few differences. The slopes of all of the power laws (dominant and nondominant for AA and for the haptically unimpaired participants) were approximately 1/3. The tightness of the fit for her dominant limb appears better. Of the 16 haptically unimpaired participants, none exhibited a higher dominant r^2 and only one had a dominant r^2 of equal magnitude. The fit for her nondominant (numb) limb appears somewhat worse. Fourteen of the 16 unimpaired participants had a higher nondominant r^2 than AA. Although the coefficient a for AA's nondominant (numb) limb is negative – in contrast to the positive a-coefficients for her dominant limb and both limbs of the healthy controls – 7 of the 16 healthy participants also had a negative coefficient for their nondominant limb.

AA's dominant accuracy (as indexed by 12% MRS) exceeded the dominant limb accuracy of all 16 haptically unimpaired participants (for whom the most accurate was 14% and the average was 24%). In contrast, AA's nondominant accuracy (as indexed by 23% MRS) was comparable to the mean of the nondominant limbs of the unimpaired participants (8 of whom were better, 8 of whom were worse, with an average of 25%). AA's dominant reliability (as indexed by 7% AD) was better than 10 of the 16 unimpaired participants (who averaged 8% AD). Her nondominant AD (10%), however, was poorer than 14 of the unimpaired participants (who averaged 8%).

A final comparison complementary to the preceding comparisons is provided by plotting LP of one hand against LP of the other. Degree of linearity and proximity to a slope of 1 may be taken as indicative of degree of sameness in the processes underlying the perceptual performances of the two hands. The linear fit for AA ($r^2 = .85$) was similar to the mean fit (.87) of the unimpaired participants (7 of the 16 had a lower r^2 than AA). Additionally, although her slope (.73) was lower than the mean slope of the unimpaired participants (.87), it was closer to 1 than the slopes of four of the individual participants. In summary, the similarity between AA's two upper limbs was not especially different from the between-limbs similarity of the unimpaired participants.

Two primary conclusions can be drawn about the haptic perception capabilities of AA. (1) Although her left (nondominant) arm was insensate by measures of discriminative touch, effortful touch was preserved. The scaling of LP to I_1 for rods wielded in her left hand was equal to that for her right hand and to that of the nondominant hands of haptically unimpaired participants. The same was not true, however, of the reliability of her length perceptions. It was significantly lower. (2) Effortful touch by her right (dominant and haptically intact) arm was superior to her left arm and equal or better on key measures to the dominant arm of the haptically unimpaired participants.

With respect to (1), the issue is how to comprehend AA's definite and systematically varying impressions of object length given her left arm's numbness. To the extent that effortful and discriminative touch share a common basis, conclusion (1) might be considered an instance of *numb sense* [15], a somesthetic equivalent to *blind sight*. Numb sense or numb touch has been demonstrated in a paradigm in which tactile stimuli applied to a patient's numb arm cannot be detected or localized verbally but can be localized by pointing with the unimpaired arm [13,15]. In the present research, AA could not feel the rod in her hand but she could adjust a report board to produce systematic estimates of the wielded rod's length. Despite the obvious parallels, the numb touch hypothesis seems less accommodating than the hypothesis that AA's effortful touch with the affected arm was not as compromised as her discriminative touch.

Although AA expressed frustration with the discriminative touch task of identifying a hand-manipulated shape with her numb hand, she never complained about the request to wield a rod in her numb hand and judge its length. Her acceptable perceptual performance with the numb limb could have been due to the effects that the wielding forces had on less sensory-impaired tissues such as the muscles of her upper arm and shoulder (see [14]). Three-dimensional wielding about the wrist (cf. Fig. 1) engages all the muscles of the arm to some degree. Alternatively, her acceptable perceptual performance with the numb limb may reflect a distinction in the neural basis of discriminative and effortful touch. Afference from the upper extremities is carried by fasciculus cuneatus within the dorsal column. The afferents for joint receptors terminate in lamina 6 of the dorsal horn while those for the receptors of the skin – underlying soft tissues and hair follicles – all terminate in more superficial laminae (3–5). Additionally, from the second thoracic segment upwards, the pathway carrying afference from muscle spindles is in a separate, more superficial region of the dorsal column, relative to the afferents associated with discriminative touch. It is possible therefore that, given AA's intramedullary cystic formations, inputs from joints and muscles were spared to a greater degree than inputs from the skin. Consistent with the preceding conjecture is the preservation of effort-based sensory experience following peripheral deafferentation [8,9,16].

With respect to (2), the issue is whether the data suggestive of superior effortful touch by AA's unaffected arm is indicative of enhanced function associated with changes in ipsilateral cortical areas due to either increased use of the right limb or sensory loss in the left limb, or both. Somatosensory cortical regions have been shown to expand with increases in the tactile experience they subserve with corresponding improvement in tactile resolution (e.g., [4,6]). If magnitude of experience in effortful touch was the key factor, one ought to expect generally superior performance by the dominant limb. As present results indicate (e.g., Fig. 2bottom), however, length perception by effortful touch is equivalent for the two limbs. Enhancement of AA's right limb perceptual performance by deafferentation of her left limb seems to be the better hypothesis.

Experiments using ischemic techniques applied to one hemisphere or to one limb show that the induced unilateral short-term deafferentation promotes a bilateral reorganization of cortex [11,20], an improvement of motor skill in the rat [11], and an improvement in tactile spatial acuity of the nondeafferented limb in the human [1,21]. In sum, AA's superior right-limb performance may point to the inclusion of effortful touch in the capabilities open to improvement through cortical reorganization by deafferentation.

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