Sensation at the tips of invisible tools

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When we touch something with a tool, we feel the touch at the tip of the tool[1,2], rather than at the hand that holds the tool. Here we show that the judgment of the temporal order of two successive stimuli, delivered to the tips of sticks held in each hand, was dramatically altered by crossing the sticks without changing the positions of the hands, where the actual mechanoreceptors are located. This provides experimental evidence for the referral of tactile signals to the tip of a tool in the hand.

Experiments were designed based on a recently discovered phenomenon, the reversal of subjective temporal order due to arm crossing[3]. When the arms are uncrossed, subjects correctly judge the temporal order of two stimuli delivered in succession, one to each hand, at intervals as short as 70 ms. Crossing the arms, however, causes subjects to misreport the temporal order at moderately short intervals (<300 ms), although at longer intervals (>1 s) they generally respond correctly.

In this study, we delivered two successive stimuli to the tips of two drumsticks, one held in each hand (inset, **Fig. 1**), and asked right-handed subjects ($n = 8$) to judge, with their eyes closed, the temporal order of the two successive stimuli. To compare the effects of arm crossing with those of stick crossing[4], four experiments (**Fig. 1a–d**) were designed in a two by two factorial manner: arms uncrossed or crossed (first/second columns in **Fig. 1**) by sticks uncrossed or crossed (first/second rows).

With the sticks and arms uncrossed (**Fig. 1a**), the subjects responded correctly in most trials (~90%), even at intervals as short as 100 ms. When the arms were crossed without crossing the sticks (**Fig. 1b**), a clear increase in error rate was observed at moderately short intervals (~100–400 ms) in particular. These effects of arm crossing were comparable to those observed when the stimuli are delivered to the hands themselves[3]. When the sticks were crossed with the arms uncrossed (**Fig. 1c**), the subjects again misreported the order at the moderately short intervals. The results indicate that the subjective temporal order was often misjudged by crossing just the sticks without crossing the arms. In addition, correct judgment was recovered by crossing the sticks in addition to crossing the arms (compare **Fig. 1d** with **b**).

If stimuli were perceived exclusively at the hands and processed in the brain as such, the subjective temporal order would never depend on the configuration of the sticks. Therefore, the decrease (**Fig. 1c**) and recovery (**Fig. 1d**) of correct judgment caused by crossing the sticks clearly indicate that this is not the case. The results show that the judgment of temporal order depended critically on whether the tip of each stick occupied the hemispace ipsilateral to the anatomical laterality of the hand holding the stick (**Fig. 1a** and **d**), or occupied the hemispace contralateral to the anatomical laterality of the hand (**Fig. 1b** and **c**).

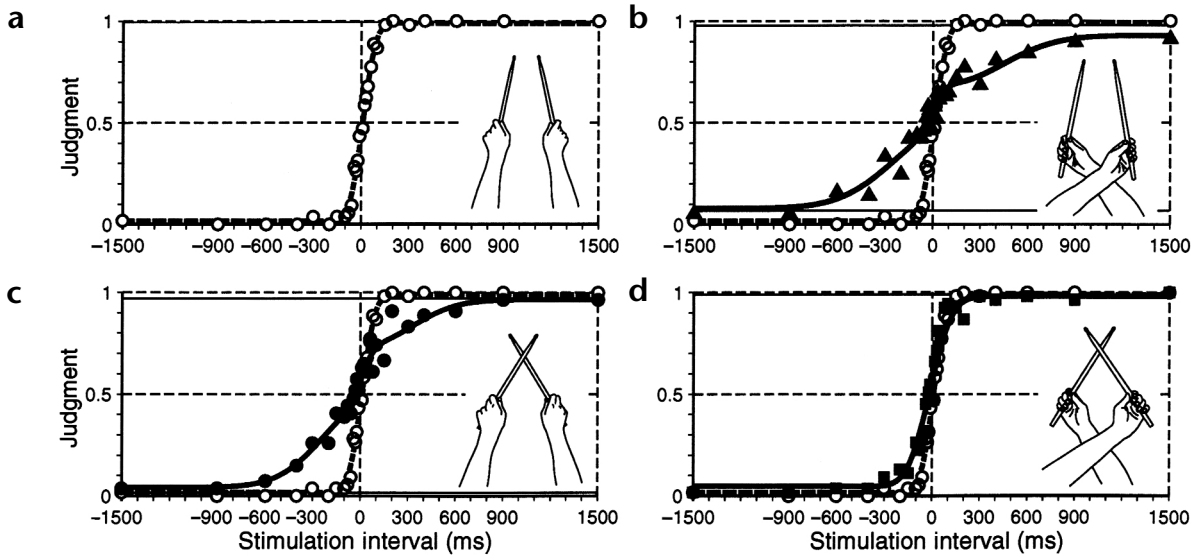

Fig. 1. The temporal order judgment of two stimuli delivered to the tips of two drumsticks with the sticks uncrossed (**a**, **b**)/crossed (**c**, **d**) and with the arms uncrossed (**a**, **c**)/crossed (**b**, **d**). The order-judgment probability (ordinate) that the stick in the right hand was stimulated earlier than the stick in the left hand is plotted against the stimulation interval (abscissa). Positive intervals show that the stick in the right hand was stimulated first. Each dot represents 56 judgments from 8 subjects. Curves show fitting by models described elsewhere[3]. Data in (**a**) (white circles and dashed curves) are superimposed on the other panels (**b–d**). The subjects, with their eyes open, placed the tips of the sticks on two levers, 10 cm apart, with the sticks and/or the arms crossed/uncrossed. A piezoelectric contactor[3] was placed on each tip to deliver mechanical stimuli by scratching the surface of the tip. The subjects were then asked to close their eyes through the rest of the experiment, and responded in a forced choice manner by pushing down one of the two levers with a stick that was judged to be stimulated earlier or later (in half of the experiments) than the other. Before each experiment, a single stimulus was delivered to only one of the two sticks for 60 trials. Horizontal lines in each panel show the correct response rates in the control trials with single stimuli. The subjects responded correctly in most trials (> 90%) with the single stimuli. The studies received approval from the institutional human review committee, and all subjects gave written informed consent according to institutional guidelines.

This strongly suggests that the somatosensory signals evoked at the hands were referred to the spatial locations of the tips of the sticks before these cutaneous signals were ordered in time.

The sensation of touch can be referred to alien limbs, such as rubber hands[5] or phantom limbs[6], but the referral reported to date only occurs when the touch is seen. In this study, we showed that referral of sensory signals off the body occurs even when there is no concurrent vision of the touch. In addition, we showed this without using any direct introspection about the referral of touch. Consequently, this behavioral protocol is useful for investigating how a unified image of a tool is formed through the dynamic combining of cutaneous, proprioceptive and visual inputs in a spatial coordinate framework not only in humans, but also in animals[7].

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