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Sensorimotor attenuation by central motor command signals in the absence of movement

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Voluntary actions typically produce suppression of afferent sensation from the moving body part. We used transcranial magnetic stimulation to delay the output of motor commands from the motor cortex during voluntary movement. We show attenuation of sensation during this delay, in the absence of movement. We conclude that sensory suppression mainly relies on central signals related to the preparation for movement and that these signals are upstream of primary motor cortex.

Self-generated actions often lead to an attenuation of sensation from the moving body part[1] and from other parts of the body that are actively contacted[2,3]. The underlying neural mechanism may involve efference copy attenuating movement-related sensations[4,5]. Recent results have suggested an important peripheral component to this attenuation: during active wrist movements in the primate, cutaneous inputs are presynaptically inhibited at the spinal cord afferents before movement[6]. Other studies have demonstrated attenuation centrally within the brain. For example, the amplitude of cortical somatosensory-evoked potentials (SEPs) or somatosensory-evoked magnetic fields (SEFs) is reduced before the onset of movement, before any peripheral feedback[7–9]. However, SEP attenuation is often dissociated from perception: changes in sensory perception may occur without the modulation of SEPs, and vice versa[10]. Therefore, it remains unclear how and to what extent central signals influence subjective perception during movement. We therefore investigated whether earlier stages of the motor hierarchy, which prepare motor commands before their dispatch to the spinal cord, contribute to the attenuation of sensory inputs. An ideal, if somewhat artificial, situation to address this question would involve a motor command being generated centrally, but its dispatch from the brain to the spinal cord being blocked or delayed. Transcranial magnetic stimulation (TMS) over primary motor cortex during voluntary movement induces such a delay in corticospinal output without otherwise affecting the motor pattern[11]. This delay seems to be largely central in origin: spinal excitability increases[12], or remains unchanged[13], rather than decreases during the TMS-induced delay period. We used this paradigm to investigate whether attenuation would occur after the preparation of motor commands and before their dispatch to the periphery[12].

To measure sensory suppression, we applied brief electrical cutaneous stimuli simultaneously to left and right index fingers of 21 subjects (**Fig. 1**; informed written consent was obtained; for details, see **Supplementary Methods** online). The left finger served as a reference, remaining at rest and receiving a fixed stimulus intensity throughout. The stimulus to the right finger was varied from trial to trial. We used a two-alternative forced-choice paradigm to search for the level at which subjects perceived the stimuli to the two fingers as being equal in magnitude (point of subjective equality: PSE). Subjects either lifted their right index finger in time with the last of three auditory tones played at 1-s intervals (**Fig. 1b**,**c**,**e**) or, in control conditions, remained still (**Fig. 1a**,**d**). Cutaneous stimuli were triggered by the movement of the subject's right finger. The movement caused the PSE to increase by

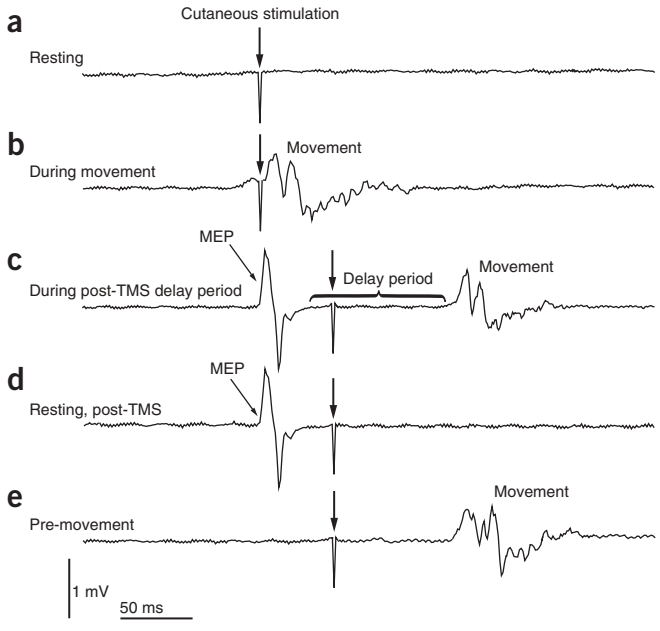

Figure 1 EMG recordings from the first dorsal interosseous muscle (FDI) of the right hand. (**a**–**e**) Traces show the time of cutaneous stimuli (vertical arrows), finger movement and the TMS-induced twitch (motor-evoked potential (MEP): diagonal arrows) for illustrative trials in each condition. (**a**) Resting condition. The cutaneous stimulus was applied at random times within a time window of 150 ms after the 'go' signal. (**b**) Movement condition in which cutaneous stimuli were triggered by the movement onset. (**c**) Post-TMS delay condition in which movement onset was delayed by a TMS pulse and the cutaneous stimuli were delivered 70 ms after the TMS pulse during the silent period after the MEP. (**d**) Resting, post-TMS condition in which a cutaneous stimulus occurred 70 ms after a single TMS pulse was applied. (**e**) Pre-movement condition in which the cutaneous stimuli were given 50–120 ms before movement onset. Note that FDI is not the prime mover muscle in the task but is always activated close to the onset time of physical displacement of the finger.

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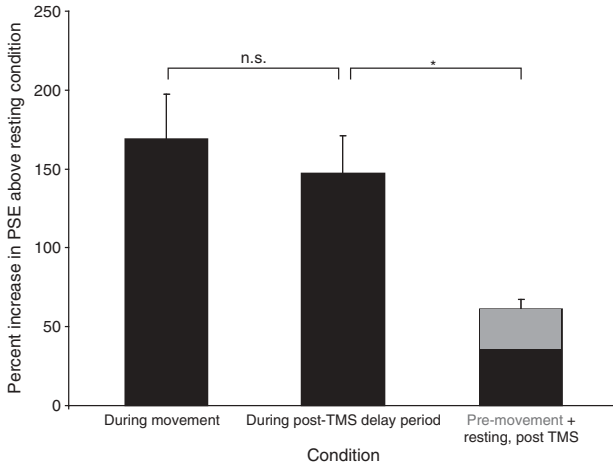

Figure 2 Sensory suppression expressed as a percentage change in the PSE from the resting condition (that is, PSE in resting condition = 0%) in the four experimental conditions. The last bar shows the summation of the attenuation in two control conditions: the pre-movement condition (gray) and the resting, direct-TMS condition (black). Error bars represent s.e.m. (*$P < 0.05$; n.s. = 0.502).

169 ± 28% (mean ± s.e.m., $P < 0.005$) from the PSE value when both fingers were at rest. That is, cutaneous stimulation to a moving finger had to be 169% larger (2.69 times the reference stimulus) to be perceived as being of the same intensity as the stimulation to a resting finger, indicating strong sensory suppression during movement.

On some trials, a single TMS pulse was applied over left primary motor cortex, synchronous with the last auditory tone when the movement would normally start (focal TMS with a figure-of-eight coil and a Magstim 200 stimulator). This caused an involuntary twitch in the right index finger, followed by a silent period without electromyographic (EMG) activity and then the delayed voluntary movement (**Fig. 1c**)[11]. TMS delayed the voluntary movement by 145 ± 46 ms (mean ± s.d.). The cutaneous stimuli were applied during the silent period, 70 ms after the TMS pulse, and thus on average 75 ± 46 ms before the onset of the TMS-delayed finger movement. The PSE increased in this condition by 147 ± 24% ($P < 0.05$) compared to the resting condition. Sensation was therefore attenuated during the silent period. Moreover, this sensory suppression was not significantly different from that found during movement ($P = 0.502$). A prior command to move was sufficient for sensory attenuation, and actual movement was not necessary.

To confirm the hypothesis that suppression arises from premotor command signals, we must rule out two other potential sources of suppression. First, suppression following TMS over motor cortex could be a consequence of current spread to primary somatosensory areas[14]. We controlled for this possible artefact in non-movement trials in which subjects received a single TMS pulse, followed 70 ms later by the cutaneous stimuli (**Fig. 1d**). The degree of attenuation is likely to depend on precise placement and orientation of the coil[15]. Indeed, a TMS pulse alone caused some sensory attenuation in non-movement trials, as predicted[14]. To isolate the effects of TMS-induced motor delay and minimize these confounding direct somatosensory effects, we excluded from all reported results those subjects in whom direct TMS suppression was as large as the suppression during movement ($n = 7$). For the remaining subjects, direct somatosensory TMS suppression increased the PSE by 36 ± 8% compared to the rest condition ($P < 0.05$). Second, TMS-induced delays change the interval between the cutaneous stimulus and movement onset. The degree of suppression varies with the temporal relation between stimulus and movement, beginning up to 100 ms before movement onset[6]. To ensure that suppression during the silent period was not due to this change in timing, in five subjects we applied the cutaneous stimuli before the onset of the finger movements, in the absence of TMS (**Fig. 1e**). Although subjects were again required to synchronize their movements to auditory tones, there was inevitably some variability, of around ± 70 ms, in their actual performance. To match the timings in this control condition as closely as possible to those in the TMS-delayed condition, we analyzed only trials in which the cutaneous stimulus occurred 50–120 ms before movement (that is, a temporal interval similar to that in the TMS-delayed condition). In the absence of TMS, we found only moderate and nonsignificant attenuation of the cutaneous stimulus resulting from temporal proximity alone (PSE increased by 25 ± 8% compared to baseline; $P = 0.14$). Critically, the sum of the increases in PSE resulting from direct somatosensory effects of TMS and from the temporal proximity to the upcoming movement was significantly lower than the increase in PSE in the condition where TMS delayed the voluntary movement (**Fig. 2**, $P < 0.05$). Therefore the sensory suppression seen during the delay period was not a result of direct TMS-induced attenuation, the characteristic time course of pre-movement suppression or the summation of these effects.

We conclude that a significant component of sensory suppression arises from the central signals related to the preparation of motor commands. As TMS over motor cortex induces delays at the final cortical output stage, our results show sensory attenuation during voluntary actions arising from an efferent signal. Previous electrophysiological studies have identified changes in SEPs associated with voluntary motor control[7–9]. Our findings link such changes to subjective perception and identify them with the earlier stages of the motor hierarchy that prepare motor commands rather than with the areas that finally dispatch those commands to the spinal cord and muscles. Sensory attenuation during voluntary movement therefore arises upstream of primary motor cortex.

Note: Supplementary information is available on the Nature Neuroscience website.

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COMPETING INTERESTS STATEMENT

The authors declare that they have no competing financial interests.

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