Research Article

Extended Multisensory Space in Blind Cane Users

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ABSTRACT—***In the present work, we investigated whether an auditory peripersonal space exists around the hand and whether such a space might be extended by a brief tool-use experience or by long-term experience using a tool in everyday life. To this end, we studied audio-tactile integration in the space around the hand and in far space, in blind subjects who regularly used a cane to navigate and in sighted subjects, before and after brief training with the cane. In sighted subjects, auditory peripersonal space was limited to around the hand before tool use, then expanded after tool use, and contracted backward after a resting period. In contrast, in blind subjects, peri-hand space was immediately expanded when they held the cane but was limited to around the hand when they held a short handle. These results suggest that long-term experience with the cane induces a durable extension of the peripersonal space.***

In a variety of species, stimuli from different sensory modalities are integrated in a limited space surrounding the body. This space has been termed *peripersonal space* (Rizzolatti, Fadiga, Fogassi, & Gallese, 1997). In monkeys, neurons located in different brain areas, especially in the precentral gyrus (Rizzolatti, Scandolara, Matelli, & Gentilucci, 1981a, 1981b; Fogassi et al., 1996; Graziano, Yap, & Gross, 1994) and in the ventral intraparietal area (Colby, Duhamel, & Goldberg, 1993; Duhamel, Colby, & Goldberg, 1998), have been shown to respond to both tactile and visual stimuli presented on or around the hand or the face, and to both tactile and acoustic stimuli presented on or around the head (Graziano, Reiss, & Gross, 1999). These neurons do not respond when multimodal stimuli are presented far from the animal's body part, that is, about 30 cm away.

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The existence of a multisensory peripersonal space in humans has been shown by neuropsychological studies of cross-modal extinction with double simultaneous stimulation in brain-damaged patients (Bender, 1952; Mattingley, Driver, Beschin, & Robertson, 1997). In these studies, contralesional tactile perception was affected by concurrent ipsilesional visual stimuli presented close to the patient's hand or face, and by auditory stimuli presented close to the patient's head, but not by multimodal stimuli presented far apart, in the extrapersonal space (di Pellegrino, Làdavas, & Farnè, 1997; Farnè & Làdavas, 2000). The near-far modulation of cross-modal extinction has been considered the behavioral hallmark of multisensory integrative systems that code peripersonal space in humans (see Làdavas & Farnè, 2004, for a review). Thus, converging evidence supports the existence of multiple peripersonal-space representations functionally organized in modules, each centered around a specific body part (Farnè, Dematte, & Làdavas, 2005; Graziano, Gross, Taylor, & Moore, 2004): Visual peripersonal space has been described around the head and the hand (see Graziano et al., 2004, and Làdavas, 2002, for reviews), whereas up to now, auditory peripersonal space has been described only around the head (Farnè & Làdavas, 2002; Graziano et al., 1999). The first aim of the present work was to study whether there is also an auditory peripersonal space around the hand.

Peripersonal-space representations are highly plastic, changing with experience. Indeed, in the case of visuo-tactile interaction, it has been shown that the extent of visual peri-hand space increases after training consisting of using a tool to reach far space, both in monkeys (Iriki, Tanaka, & Iwamura, 1996; Ishibashi, Hihara, & Iriki, 2000) and in humans (Farnè & Làdavas, 2000; Maravita, Husain, Clarke, & Driver, 2001; for reviews, see also Maravita & Iriki, 2004; Ishibashi, Obayashi, & Iriki, 2004; and Holmes & Spence, 2006). In particular, Iriki and his colleagues (Iriki et al., 1996; Ishibashi et al., 2000) showed that visual receptive fields of bimodal neurons in the intraparietal sulcus, which normally are limited to around the monkey's arm, expand to include the tip of a rake used to reach food pellets dispensed beyond the animal's reaching space. Analogously, Farnè and Làdavas (2000) showed that visuotactile extinction in brain-damaged patients, normally limited to near the hand, extends to the space around the tip of a rake after the patients have used this tool to retrieve tokens presented in far space.

The expansion of peripersonal space after tool use has been described as lasting only for short time intervals. Visual peri-hand space contracts back to its pre-tool-use level several minutes after the training, even if subjects hold the tool passively in their hand (Ishibashi et al., 2004; Làdavas & Farnè, 2006). A long-term expansion of peripersonal-space representations has never been described, at least to our knowledge.

However, tool use can be a quite common experience in everyday life, and in fact there are some subjects who habitually and functionally use a tool to interact with far space. This is the case, for example, with blind people who use a cane to navigate in their environment every day. Therefore, in the present work, we studied whether such prolonged experience of tool use might result in a durable expansion of peripersonal-space representation. To this end, we investigated audio-tactile integration in the space around the hand and in far space in blind cane users and in sighted, blindfolded subjects who had never used a cane to navigate. We hypothesized that sighted subjects do have a limited auditory peripersonal space around the hand. In addition, we hypothesized that this space shows the same dynamic properties as visual peri-hand space—that it expands after brief training in using a tool to reach far space and contracts after a period of not using the tool. Finally, we hypothesized that a long-term tool-use experience can induce a durable extension of peripersonal space; that is, we predicted that integrative properties of auditory space would be manifest in blind cane users both around the hand and at the tip of the cane.

To test our hypotheses, we asked subjects to verbally identify a weak electrical stimulus (target) that was interspersed with stronger electrical stimuli on their right index finger. A concurrent auditory stimulus, which was to be ignored, was presented either near the stimulated hand (i.e., near peripersonal space) or on the floor at a distance of about 125 cm (i.e., the average length of a cane) from the hand (i.e., far space). Mean reaction times (RT) to the weak electrical stimuli were compared between the two conditions. We reasoned that if audio-tactile information is integrated in a limited space around the hand, sighted subjects would respond faster to tactile targets associated with near sounds than to those associated with far sounds.

In addition, if auditory peri-hand space can be dynamically expanded by tool use, the difference in RTs between the two conditions should be reduced after subjects use a tool to explore far space. To test this prediction, we examined RTs of sighted participants before and after 10 min of training in using a cane to find objects placed on the floor in the dark. Moreover, to test whether expanded auditory peripersonal space contracts backward when a tool is no longer used, we examined whether the advantage for RTs to electrical stimuli associated with near sounds returned in a testing session 1 day after the end of tool use.

Finally, if constant, everyday life experience with a cane results in a durable extension of peripersonal space, integrative properties of auditory peripersonal space in blind cane users should be found for the space around the tool: Blind subjects should be equally fast in responding to tactile stimuli when concurrent sounds are presented in near and far space if the far space coincides with the tip of the cane. Indeed, we hypothesized that in blind cane users, the extended peripersonal-space representation is selectively and functionally activated depending on contextual demands: An expanded representation of peripersonal space might be automatically and specifically evoked when blind subjects hold the cane. To test this prediction, we compared blind subjects' performance in two conditions: while they held a typical Canadian cane for the blind (125 cm long), which terminated at the source of the far sounds, and while they held a 14-cm-long, weight-matched handle. In this latter condition, we expected auditory peripersonal space to be limited to around the hand, as in sighted subjects.

METHOD

Subjects

Eight blind subjects (4 female) participated in the study. They were recruited at Istituto David Chiossone Onlus, Genova, Italy, and selected by an expert trainer in use of the cane. To be included in the study, subjects had to be completely or legally blind and to have long-term experience (more than 1 year) using the cane. A questionnaire was administered to confirm that subjects used the cane regularly in everyday life at the time of testing. Blind subjects' mean age was 51 years ($SD = 11$, range: 34–59 years). Sixteen subjects (10 females) reporting normal or corrected-to-normal vision, matched for age to the blind subjects, were also studied. All participants were right-handed and had normal hearing and touch. All subjects gave their informed consent to participate in the study, which was performed with approval of the local ethics committee and in accordance with the Declaration of Helsinki.

Procedure and Materials

The experimental setup is illustrated in Figure 1. On each trial, participants received either a weak (target) or a strong (nontarget) electrical stimulus on their right index finger; these stimuli were delivered through two pairs of electrodes. A concurrent sound was presented either in close proximity to the stimulated hand (near) or on the floor at a distance of about 125 cm (far). A total of 150 trials was administered: 30 target trials with the near sound, 30 target trials with the far sound, 30 nontarget trials with the near sound, 30 nontarget trials with the far sound, and 30 catch trials (i.e., trials on which only a sound was presented).

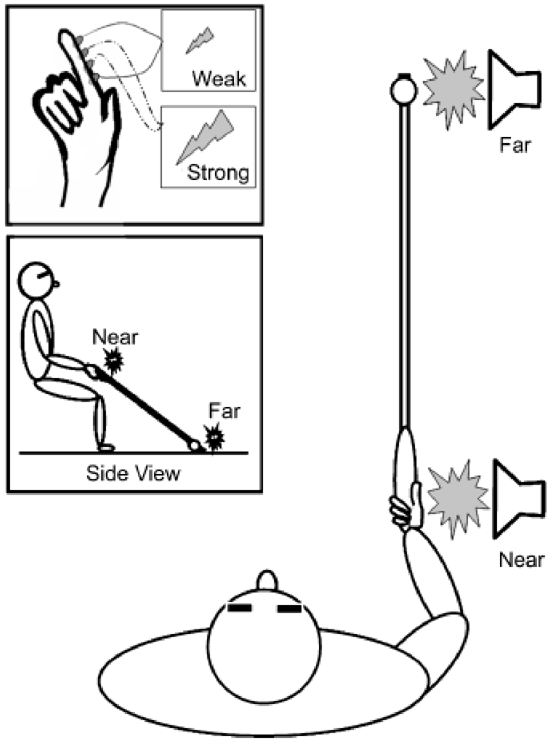

Fig. 1. The experimental setup. The small boxes show the placement of electrodes on a subject's finger and a side view of the setup shown in the larger illustration.

Subjects were explicitly instructed to respond vocally (saying "tah") only to the tactile target, and to respond as rapidly as possible while trying to ignore the sounds. Before the experiment, 30 trials were administered to familiarize subjects with the task.

Participants performed the task in two blocked conditions whose order was counterbalanced: In the *cane* condition, they passively held a 125-cm-long Canadian cane for the blind in their right hand (with the right arm lying on an armchair); the tip of the cane rested in a fixed position on the floor. In the *handle* condition, they passively held a 14-cm-long handle; the handle was made of the same material as the cane, and its weight was equated to that exerted by the cane in the former condition. Sighted participants performed the task in two additional cane conditions: one immediately after 10 min of training with the cane and the other 1 day after the training. The training consisted of using the tip of the cane to find objects placed on the floor at varying locations (within a space from 50 to 150 cm in front of the subject and up to 80 cm to the right and to the left of the subject's feet). Sighted subjects were blindfolded during both the experiment and the training.

Tactile stimuli were delivered by two constant-current electrical stimulators (DS7A, Digitimer, Hertfordshire, United Kingdom), via two pairs of neurological electrodes (Neuroline, Ambu, Ballerup, Denmark) placed on the upper side of the index finger. One pair of electrodes delivered the weak stimulus, and the other delivered the strong stimulus. Intensity of the stimuli was titrated for each subject in a pretest session so that the weak (target) stimulus could be perceived approximately 90% of the time and the strong (nontarget) stimulus could be perceived 100% of the time. To avoid any bias due to the positioning of the tactile stimuli on the finger, and to minimize the possibility that subjects could spatially discriminate the weak and strong stimuli, we used two different placements of the electrodes: For half the subjects, the two electrodes generating the weak electrical stimulus were placed in between the two electrodes generating the strong stimulus, and for the other half of the subjects, the reverse positioning was used.

Auditory stimuli were 150-ms bursts of white noise; the intensity of the near and far sounds was set to be equal (70 dB) as measured by a sound meter at the subject's ear. Sounds were generated by two identical loudspeakers placed near and far from the stimulated hand. Inspection of phono-spectral waves (recorded by a computer) from the two loudspeakers ensured that the sounds were equal at their origin.

The tactile and near acoustic stimuli were delivered simultaneously. The far sound had an onset 5 ms before the onset of the tactile stimuli in order to compensate for the delayed arrival of the far sound relative to the near sound, because of the difference in distance. RT was measured by means of a voice-activated relay. A computer running XGen (Rorden, n.d.) software was used to control the presentation of the stimuli and record responses.

Statistical Analyses

Statistical analyses were performed on RTs and errors. We present only significant results for the crucial interactions (i.e., those related to the experimental predictions), reporting p_{rep} (probability of replication) in place of p values: High p_{rep} values correspond to low p values (e.g., $p = .05$ corresponds to $p_{rep} = .875$). In analyses with degrees of freedom greater than 1 in the numerator, p, rather than p_{rep}, values are reported (see Killeen, 2005).

RESULTS

RTs more than 2 standard deviations from the mean were considered outliers and thus trimmed from the analyses (less than 4% of trials). First, we tested whether visuo-tactile stimuli are integrated in the peri-hand space and whether the extent of such an integrative space can be modulated by short-term tool-use experience. Sighted subjects' RTs were compared before, immediately after, and 1 day after training with the cane by performing an analysis of variance (ANOVA) with sound (near or far) and condition (cane before tool use, cane immediately after tool use, or cane 1 day after tool use) as within-subjects factors. The critical Sound × Condition interaction was significant, $F(2, 30) = 5.33$, $p < .02$, $\eta^2 = .342$. Scheffé post hoc tests

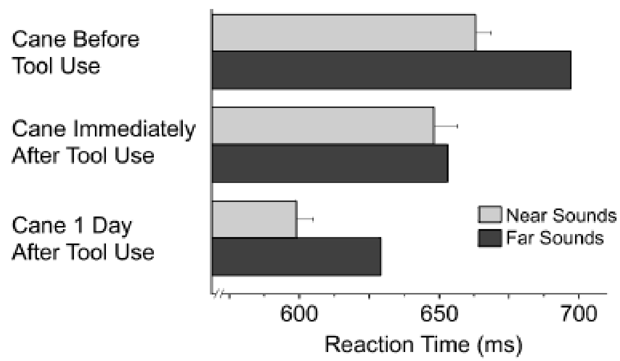

Fig. 2. Dynamic changes in auditory peripersonal space in sighted subjects as a function of tool use. The graph shows mean reaction times to the target in the cane condition before, immediately after, and 1 day after tool-use training, separately for targets presented concurrently with sounds originating near the stimulated hand and targets presented concurrently with sounds originating far from the stimulated hand. Error bars represent standard errors for the difference between the near and far conditions.

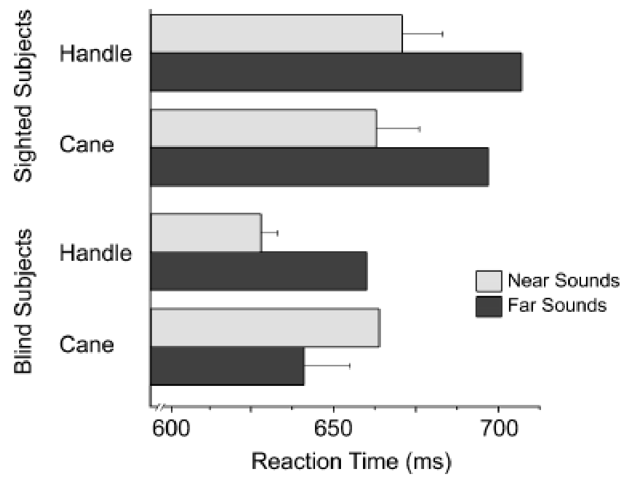

Fig. 3. Different representations of space in sighted and blind subjects. The graph shows mean reaction times to the target in sighted and blind participants in the handle and cane conditions, separately for targets presented concurrently with sounds originating near the stimulated hand and targets presented concurrently with sounds originating far from the stimulated hand. Error bars represent standard errors of the means for the difference in reaction time between near and far sounds in each condition.

showed that before any use of the tool, blindfolded sighted subjects were faster in responding to the target when it was associated with near (mean RT = 663) rather than far (697 ms) sounds, $p_{\text{rep}} = .979$. Immediately after tool use, this difference in RT was eliminated, resulting in equal RTs for targets associated with near (648 ms) and far (653 ms) sounds. Tool use specifically changed audio-tactile interaction in far, but not near, space: RTs for targets associated with near sounds were not different before and after tool use ($p_{\text{rep}} = .564$), whereas RTs for targets associated with far sounds were speeded up after the training ($p_{\text{rep}} = .990$).

After 1 day without tool use, the difference between the near-sound and far-sound conditions reappeared (near = 599 ms vs. far = 629 ms, $p_{\text{rep}} = .973$), approximating the results in the pre-tool-use condition (see Fig. 2). These results provide evidence for a spatially limited auditory peri-hand space, within which acoustic and tactile information are integrated. This space dynamically expands and contracts depending on experience with using a cane.

Next, we tested whether sighted and blind subjects integrate tactile and auditory stimuli differently in different sectors of space as a function of whether or not they are holding a cane. We analyzed mean RTs on correct trials using an ANOVA with group (sighted subjects before tool use or blind subjects) as a between-subjects factor and sound (near or far space) and condition (handle or cane) as within-subjects factors (see Fig. 3). The crucial three way Group × Sound × Condition interaction was significant, $F(1, 22) = 6.35$, $p_{\text{rep}} = .93$, $\eta^2 = .224$. Scheffé post hoc comparisons showed that blindfolded sighted subjects were faster in responding to the target when it was associated with near sounds, both when they held the handle (mean RT = 671 ms for near sounds vs. 707 ms for far sounds, $p_{\text{rep}} = .979$) and when they held the cane (mean RT = 663 ms for near sounds vs. 697 ms for far sounds, $p_{\text{rep}} = .965$). Blind subjects showed opposite patterns of results for the cane and handle conditions: When they held the handle, their RTs were faster for targets associated with near sounds than for targets associated with far sounds (mean RT = 628 ms for near sounds vs. 660 ms for far sounds, $p_{\text{rep}} = .958$), as in sighted subjects. However, when blind subjects held the cane, the effect of near and far sounds reversed: RTs were faster when sounds were presented in far rather than in near space (mean RT = 664 ms for near space vs. 641 ms for far space, $p_{\text{rep}} = .892$). For blind subjects, holding the cane rather than the handle speeded up the processing of tactile stimuli associated with far sounds ($p_{\text{rep}} = .892$) and, at the same time, eliminated the RT benefit for tactile stimuli associated with near sounds ($p_{\text{rep}} = .974$). These results suggest that holding the cane evokes an extended representation of peripersonal space in blind subjects.

Finally, to demonstrate that none of the described effects on RT were due to a speed-accuracy trade-off, we conducted the same analyses taking accuracy scores as the dependent variable. Accuracy was equally high in all conditions (between 85 and 90% correct responses). In the ANOVA conducted on sighted subjects' results, the Sound × Condition interaction was not significant, $F(2, 30) < 1$. The ANOVA with group, sound, and condition as factors likewise yielded no significant results, $F(1, 22) = 1.10$, n.s., for the Group × Sound × Condition interaction. Subjects responded to less than 1% of catch trials.

DISCUSSION

In the present study, we investigated whether there is an auditory peripersonal space around the hand and whether its characteristics vary as a function of short-term or long-term use of a cane. The results suggest three main novel conclusions.

First, there exists a limited space surrounding the hand within which audition and touch are integrated; that is, there is an auditory peri-hand space. Indeed, in sighted subjects, RT to tactile stimuli was speeded up when concurrent sounds were presented close to the hand compared with when the sounds were presented far from the hand.

Second, this space can be dynamically extended by brief use of a tool to explore far space. Indeed, after sighted subjects had 10 min of training with a cane, their RT to tactile stimuli associated with far sounds was speeded up, resulting in equal RTs for targets associated with sounds presented in near and far space. However, when sighted subjects were tested after 1 day without using the cane, the advantage for targets associated with near sounds was again evident, as before any tool use. These findings suggest that auditory peripersonal space expands and contracts depending on tool use.

Finally, long-term experience with a tool, such as in blind people who use a cane every day to navigate, results in a quite different representation of peripersonal space. Indeed, when holding a short handle, blind subjects showed faster RTs to tactile stimuli associated with near sounds than to those associated with far sounds, as sighted subjects did. However, when blind subjects held the cane, this pattern reversed: RT was faster to tactile stimuli associated with far sounds than to tactile stimuli associated with near sounds.

It is worth noting that an auditory peri-hand space has not been previously described, at least to our knowledge. Indeed, previous studies on both monkeys (Graziano et al., 1999) and humans (Farnè & Làdavas, 2002) focused on audio-tactile interaction around the head. Researchers have proposed that in everyday life, auditory peripersonal space may have a strong adaptive value in aiding the detection of stimuli approaching the body. This function of auditory peripersonal space might be of special importance in blind people, who need to use auditory information in order to localize external obstacles and avoid collisions during locomotion. The space around the hands might have a special role in detecting external stimuli before any contact with the body (as we discuss later).

The present results also show that auditory peri-hand space has the same dynamic properties as visual peri-hand space, as described in humans (Farnè & Làdavas, 2000) and in monkeys (Iriki et al., 1996). Ten minutes of using a cane to find objects placed on the floor, out of reaching range, resulted in a fast change in audio-tactile integrative space: Auditory stimuli arising from locations in proximity to the tip of the cane were processed similarly to those presented around the hand. This suggests that auditory peri-hand space was extended to include the space surrounding the cane; in other words, after tool use, far space became near space. The modulation of auditory peri-hand space is apparently highly plastic, varying as a function of experience: If tool use is not reinforced by further practice, audio-tactile space contracts back to its previous size. Indeed, after subjects spent 1 day not using the cane, the integrative space was again limited to the space around the hand.

In contrast, long-term experience using a tool to interact with far space, as in the case of blind cane users, can result in a durably extended representation of peripersonal space. This result is new, adding to an emerging body of evidence for brain plasticity in cases of long-term experience of sensory deprivation. Indeed, several studies have shown that when inputs from one sensory modality are missing, the perceptual system reorganizes to rely more heavily on inputs from intact modalities (Bavelier & Neville, 2002). Relevant to the present study, several studies have shown that visual deprivation induces perceptual and neural changes in the tactile and auditory systems, both in animals and in humans (see Röder & Rösler, 2004, and Merabet, Rizzo, Amedi, Somers, & Pascual-Leone, 2005, for reviews). Results from the present study are new in showing a form of perceptual reorganization that is based on the integration of different sensory modalities and directly mediated by long-term tool-use experience. Blind people who continuously use a cane to integrate auditory and tactile information in far space, in order to compensate for the lack of visual information, seem to generate a new representation of multisensory peripersonal space in which the space around the tip of the cane assumes all the integrative properties that normally are reserved to the space surrounding the hand. Interestingly, the processing of near space is changed as well: In our blind subjects, the integration of audition and touch became more effective in far space, but, at the same time, less effective in near space. We might say that the long-term experience with the cane "transformed" far space into near space and near space into far space. These results might be surprising given previous studies showing an effect on far space but not on near space after short-term tool-use training (see Làdavas, 2002). However, long-term experience with the cane could induce a remapping of both near and far space: If collisions with external objects are to be prevented, the space at the tip of the cane is much more important than that around the hand.[1]

These plastic changes in processing of peripersonal space may have a strong adaptive value in enhancing blind subjects' proficiency in avoiding harmful collisions. This suggestion fits well with the notion that one function of multisensory brain areas codifying peripersonal space might be to protect the body from noxious stimuli (see Graziano & Cooke, 2005, for a recent review; see also Tassinari et al., 2005). Indeed, electrical stimulation of multisensory neurons representing the peri-hand space in monkeys evokes withdrawing movements of the arm, as if to defend the hand from harm, and these movements entirely mimic those spontaneously performed to avoid potentially

[1]The current results do not provide any information about change in multisensory integration in space surrounding other body parts or other locations of far space. These issues are of great interest and need to be investigated.

dangerous objects (Graziano, Taylor, & Moore, 2002). In normal subjects, vision is usually the most effective way to detect stimuli approaching the body, because of vision's spatial acuity in distal space. Audition may intervene for portions of space outside the visual field, such as the back of the head (Farnè & Làdavas, 2002; Graziano et al., 1999). However, in the case of blindness, audition is the only sense able to gather information about distal space. Use of a cane likely enhances this function, by mediating the integration of auditory and tactile information in far space.

Finally, it is worth noting that this extended representation of peripersonal space is selectively activated when blind people hold the cane; for example, when they hold a short handle, the auditory peripersonal space is limited to around the hand, as in sighted subjects. This suggests that the remapping of space strictly depends on tools and on subjects' potential to functionally use them (see also Witt, Proffitt, & Epstein, 2005). This selectivity for an expanded representation of space when holding the cane is particularly important in showing that the special ability to integrate audio-tactile information found in blind subjects in the present study cannot be generically explained in terms of either enhanced tactile performance or enhanced ability to localize sounds; these general perceptual skills should be independent of whether or not subjects hold the cane. On the contrary, the present results suggest that there are multiple representations of peripersonal space, and that they can be dynamically and functionally engaged depending on contextual demands.

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