

Substituting auditory for visual feedback to adapt to altered dynamic and kinematic environments during reaching

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Abstract The arm movement control system often relies on visual feedback to drive motor adaptation and to help specify desired trajectories. Here we studied whether kinematic errors that were indicated with auditory feedback could be used to control reaching in a way comparable with when vision was available. We randomized twenty healthy adult subjects to receive either visual or auditory feedback of their movement trajectory error with respect to a line as they performed timed reaching movements while holding a robotic joystick. We delivered auditory feedback using spatialized pink noise, the loudness and location of which reflected kinematic error. After a baseline period, we unexpectedly perturbed the reaching trajectories using a perpendicular viscous force field applied by the joystick. Subjects adapted to the force field as well with auditory feedback as they did with visual feedback and exhibited comparable after effects when the force field was removed. When we changed the reference trajectory to be a trapezoid instead of a line, subjects shifted their trajectories by about the same amount with either auditory or visual feedback of error. These results indicate that arm motor networks can readily incorporate auditory feedback to alter internal models and desired trajectories, a finding with implications

for the organization of the arm motor control adaptation system as well as sensory substitution and motor training technologies.

Keywords Auditory feedback · Visual feedback · Sensory substitution · Motor adaptation · Motor training

Introduction

Sensory substitution refers to the ability of the nervous system to interpret information derived from an artificial sensor using a sensory system not normally used to transduce this information (Auvray et al. 2007; Bach-y-Rita et al. 1969; Bach-y-Rita and Kercel 2003). For example, visual-to-tactile substitution devices convert pictures into tactile representations (Bach-y-Rita et al. 1969). Individuals with temporary or permanent sensory impairments can use sensory substitution to perform a variety of tasks including reading, object recognition, localization, and motion detection (for recent reviews, see Collignon et al. 2011; Reich et al. 2012). Imaging studies indicate that sensory substitution activates brain areas associated with the sensory modality usually used to perform the task (reviewed in Reich et al. 2012). This has led to the “flexible task machine” hypothesis of a “highly flexible task-oriented sensory-independent brain” (Reich et al. 2012). In this model of perception, the brain readily uses data from whichever sensory modality presents task-relevant information, relying on networks related to the task rather than on the sensory modality per se.

Consistent with other findings in sensory substitution, auditory substitution allows basic performance of pointing, reaching, and object localization tasks (Auvray et al. 2007; Brown et al. 2011; Proulx et al. 2008). However, it is still

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unclear whether auditory feedback is sufficient to drive motor adaptation of reaching in altered dynamic and kinematic environments. Normally, the arm motor control system relies on a blending of visual and proprioceptive signals to estimate the kinematic error used to drive motor adaptation (Scheidt et al. 2005). The question of whether it could readily use auditory information in a similar way is of practical importance for the design of substitution devices for manipulation, but it is also of interest because of what it would imply about the organization of the arm motor control adaptation system. If individuals can readily incorporate auditory feedback to adapt their arm movements, this would suggest a modular view of error estimation, consistent with the flexible task machine hypothesis of Reich et al. (2012). That is, it would suggest that a variety of sensory inputs feed into a unifying motor error estimation system and that the output of this module is then used to control motor adaptation rather generically. An alternate hypothesis, that the brain sets up dedicated auditory-motor, or visuomotor, or proprioceptive-motor control systems based on experience, would be contradicted. Further, if auditory signals can be used to drive motor adaptation, this suggests that they may be a viable means to enhance sensory feedback for motor training applications such as rehabilitation therapy and sports training.

The goal of this study was therefore to determine whether the arm motor control system can use auditory feedback to adapt to changed dynamic and kinematic environments, with an efficacy comparable with when visual feedback is available.

Methods

Subjects

Twenty healthy subjects (mean age, 27.48 ± 4.01 , 14 males, 6 females) participated in the experiment. All participants reported they had normal vision, no color blindness, no hearing problems and were right-handed. The experimental procedure was approved by the Institutional Review Board of the University of California at Irvine, and the participants provided their informed consent.

Experimental setup

As shown in Fig. 1, the subjects sat on a chair with a force-feedback joystick (Immersion Impulse Stick, maximum force 14.5 N) placed in front of them on a table. A white cardboard panel blocked vision of the hand and joystick. The reaching task required subjects to perform forward and back (defined as the $\pm y$ direction, respectively) 10 cm long

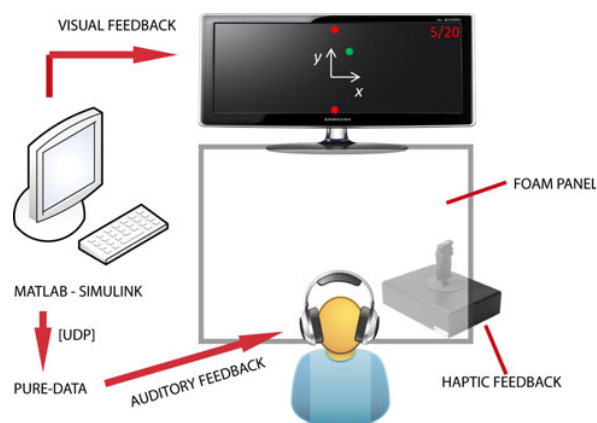


Fig. 1 Simplified layout of the experimental setup with a feedback-system scheme. A 2-DoF force-feedback joystick was placed on a table while a white cardboard panel blocked vision of the hand and joystick

reaching movements, synchronized for the entire experiment to the sound of a metronome playing at 33 bpm (1 beat every 1.8 s). The targets were set up so that the mechanical end of the range of motion of the joystick was at the outside edge of the targets, so that subjects could not overshoot the targets. The joystick was controlled with real-time software (Matlab Simulink R2010b, Windows DirectX) running at 200 Hz.

The subjects were randomized into two groups based on the kind of feedback provided during the experiments: 10 subjects received auditory feedback of trajectory errors and 10 subjects received visual feedback of trajectory errors.

For the visual feedback group, two circular red targets were displayed at the opposite ends of an LCD display. The diameter of targets was 0.4 cm in the joystick space, corresponding to about 1 cm on the screen. A green circular cursor of the same size denoted the current position along y and the current position error along the x axis, computed as the difference between the current joystick position and the desired reference path (either a straight line at $y = 0$ or a trapezoid, see below).

For the auditory-feedback group, an audio signal was developed with a real-time audio synthesis platform (Open-source PureData) and was provided to the subject by headphones (Bose QuietComfort 15). The subject's performance data were sent in real-time from the Simulink model to a PureData patch through the OSC (Open Sound Control) protocol, as depicted in Fig. 1. The audio error feedback was generated by multiplying the absolute value of the movement error in the left-right direction (x -axis position error) with the output of a pink noise generator filtered through a bandpass filter with 500-Hz center frequency and Q factor equal to 9. The signal was then binaurally spatialized through the headphone, so that the

sound was perceived at a left-right location related to the x -position error. Subjectively, the audio feedback sounded like a whooshing wind, with the loudness and location proportional to the kinematic error in the x direction. The reason for making loudness proportional to error is that auditory spatial localization alone tends to be more variable than visual (Ghahramani et al. 1997), and more variable feedback can lead to a slower rate of adaptation (Burge et al. 2008). For the same reason, since the x -error was expected to be very small, the spatial relationship of x -position error to auditory feedback was exaggerated to achieve sufficient movement precision.

Experimental protocol

Participants were instructed to grasp the joystick on the top for the whole experiment. They were then instructed to move the joystick back and forth to the sound of the metronome in the y direction as straight as possible. They were allowed a 30-s warm-up to practice the rhythm of the task dictated by the metronome and with continuous visual feedback of the cursor. The experiment was then divided into three stages (A—baseline, B—adaptation, and C—washout). During stages A, B and C, subjects received either visual or auditory feedback of the left-right reaching error depending on the group into which they had been randomized. A counter of repetitions was shown on the display.

Stage A (Baseline) consisted of 20 repetitions of the reaching task (repetition = single reach, that is, back or forward). During this stage only, the auditory feedback group (AF) received visual feedback intermittently to help

with learning the task and with interpreting the auditory feedback. Specifically, the two targets were shown on the screen during repetitions 1 to 5, 10, 15 and 20, whereas the hand cursor was shown when its current position along y was within half diameter of one of the two targets displayed. This basic visual feedback was sufficient to help the subjects memorize the position of targets and practice the reaching task. A 10-s rest separated this stage from the next one.

Stage B (Adaptation) consisted of 140 reaches with either visual or auditory feedback. A viscous force field F_x was applied after the 10th reach until the end of the stage. The force was computed as a function of the velocity of the hand along the y axis:

$$\mathbf{F} = \begin{Bmatrix} F_x \\ F_y \end{Bmatrix} = \begin{Bmatrix} 0 & 35 \\ 0 & 0 \end{Bmatrix} \cdot \begin{Bmatrix} v_x \\ v_y \end{Bmatrix} \tag{1}$$

Here, the end point force, \mathbf{F} is given in Newtons, the viscosity is in Newtons per meter per second, and the velocity, \mathbf{v} is in meters per second.

During this stage, after adaptation to the force field, starting on the 71st trial and for 40 trials, the reference path was gradually changed from a straight line to a trapezoid with front and rear ramps of 2-cm distance in the y direction. The final amplitude of the trapezoid was an x offset of 2.5 cm to the right (see Fig. 2). The straight reference path was restored in the last 30 trials of Stage B. The change in the reference path produced a motor perturbation since the x error was fed back to the user instead of x position. A correct trapezoidal movement in hand space would result in either a straight motion of the green dot for the visual feedback group or no auditory feedback in the headphones

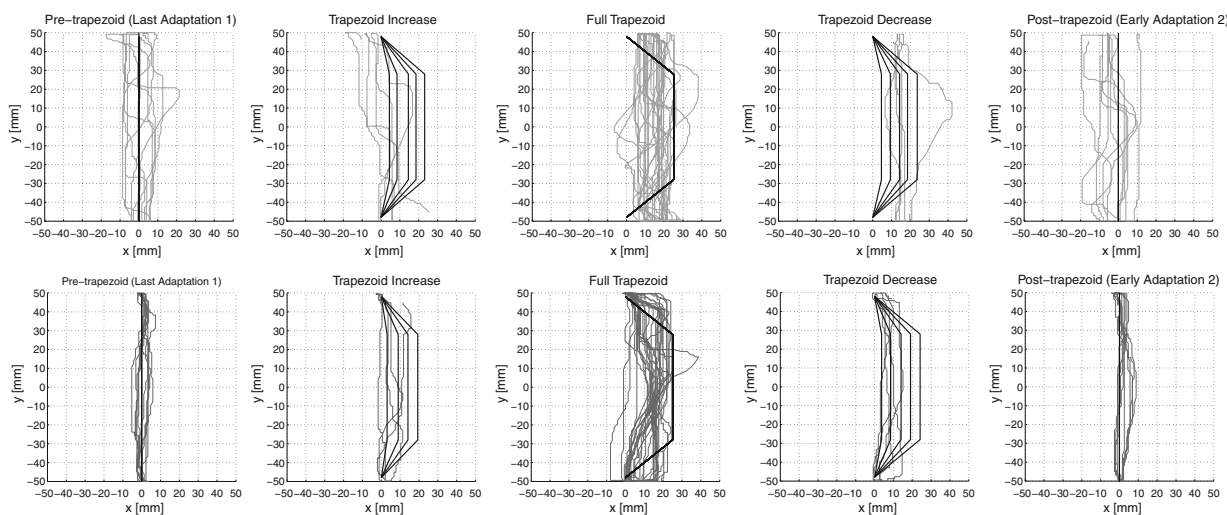


Fig. 2 Example trajectories taken from the experimental stage in which subjects adapted to the kinematic perturbation of movement (desired trajectory was gradually distorted to be a trapezoid). Representative subject from the auditory feedback group (*top row*)

and representative subject from the visual feedback group (*bottom row*). The reference trajectory (either straight or trapezoidal) is shown in *black*

for the auditory feedback group. After completing the 140 trials in this stage, subjects paused for 5 min keeping their hand motionless on the base of the joystick.

Stage C (Washout) consisted of 30 reaches in the same force field, followed by 30 reaches without the force field to measure aftereffects.

Data analysis

For each participant, the average weighted x -axis (left-right) position error between the subject's current position and the reference path was calculated as follows:

$$e_x(k) = \frac{1}{M_k} \sum_{h=1}^{M_k} \left(\sum_{i=1}^{N_h} \frac{(x_s(i) - x_r(i)) \cdot [-\text{sign}(v_y(i))]}{N_h} \right)_h \quad (2)$$

where k denotes the portion (phase) of the stage, M_k is the number of reaches in phase k , N_h is the number of samples in reach h , x_s is the current position of the hand, and x_r is the reference position (a line or a trapezoid). This weighted formula assigns a positive value to error when it is in the opposite direction of the force field; this allowed errors for forward and backward reaches to be averaged, as the force field was in the opposite direction for each movement.

For each participant, the intra-subject standard deviation in phase k was calculated as the mean of the M_k standard deviations of the reaches performed by the subject in the phase. In this way, we aimed at catching the variations of subject's motion within reaches (which can be attributed to feedback) and at eliminating the variations between reaches (which derive from learning effects).

One participant in the auditory feedback group exhibited large variable errors and when questioned after the experiment it was apparent that he had misunderstood the task; thus his data were excluded.

Normality tests (Shapiro–Wilk normality test and D'Agostino–Pearson omnibus normality test) indicated a Gaussian distribution of errors for both feedback groups. To compare performance in different phases between and within groups, we performed a two-way repeated-measures ANOVA of the average weighted x -position error, with the various phases of the experiment being the repeated measures of error, and VF and AF as the two groups. In the presence of a significant effect of time, pairwise post hoc comparisons (Bonferroni's test) were used to determine which blocks were different from other blocks. To compare group (inter-subject) variances, the variance ratio test (or F test) was used. High inter-subject variance in one feedback group would suggest that different subjects interpret such feedback differently. To compare intra-subject variance, we calculated the variance for each subject in each phase, took the mean of the variances for the AF group and

the VF group in each phase, and compared those with a two-way repeated measures ANOVA. Higher intra-subject variance in one feedback group would suggest that such feedback is harder to use than the feedback provided to the other group. Finally, the adaptation curves were fitted with a one-phase decay exponential function, and the fitted values for the first trials (Bonferroni's test) and the decay constants (unpaired t-test between VF and AF groups) were compared.

In the following presentation of results and figures, we grouped the experimental trials into eight main phases, according to motor adaptation literature (Scheidt et al. 2000; Shadmehr and Mussa-Ivaldi 1994):

1. *Null force field*: the movements performed without force feedback (repetitions 1–10 in Stage B).
2. *Direct effect*: the first reach with exposure to the perpendicular force field (repetition 11 in Stage B).
3. *Adaptation 1 (pre-trapezoid)*: the phase, after the direct effect, during which the subjects adapted to the force field (repetitions 12–70 in Stage B). It was divided into three sub-phases: *early* (repetitions 12–30), *medium* (repetitions 31–50) and *late* (repetitions 51–70).
4. *Visuomotor perturbation*: the phase, after the first adaptation, during which a new reference path was provided, from a straight line to a trapezoid (trapezoidal reference phase, repetitions 71–110 in Stage B). The visuomotor perturbation phase was split into three sub-phases: *trapezoid increase* (repetitions 71–75), *full trapezoid* (repetitions 76–105) and *trapezoid decrease* (repetitions 106–110).
5. *Adaptation 2 (post-trapezoid)*: the phase after restoring the straight reference (repetitions 111–140 in Stage B). It was divided into three sub-phases: *early* (repetitions 111–120), *medium* (repetitions 121–130) and *late* (repetitions 131–140).
6. *Retention*: the phase during which the subjects (after a pause of 5 min) were again exposed to the force field (repetitions 1–30 in Stage C).
7. *After effect*: the first reach after the sudden removal of the force field (repetition 31 in Stage C).
8. *Re-adaptation*: the phase during which the subjects re-adapted to the null force field (repetitions 32–60 in Stage C).

Results

Twenty participants were instructed to reach as straight as possible while holding a joystick that perturbed their movements. Half of the participants received visual feedback of their lateral reaching error, while the other half

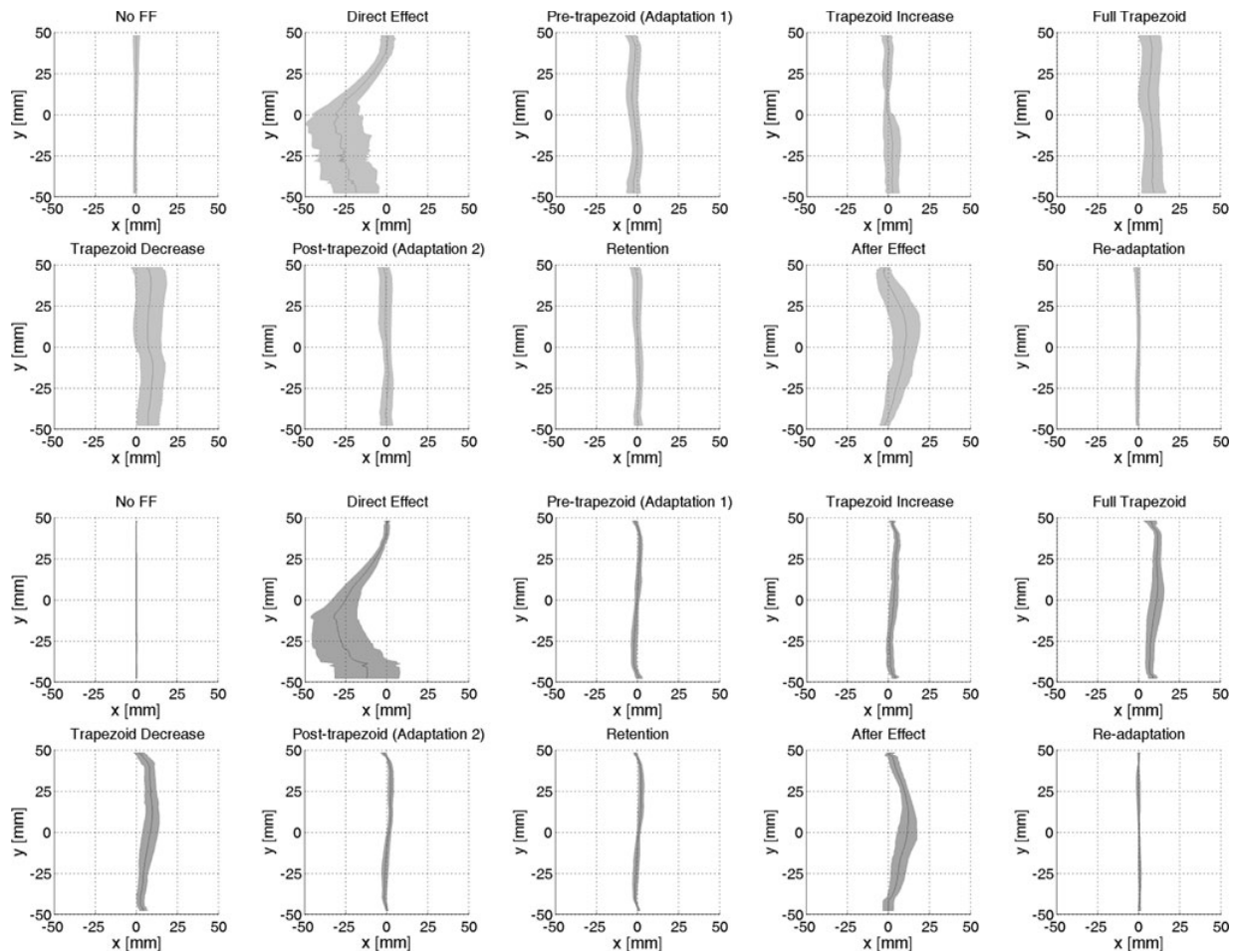


Fig. 3 Trajectories of auditory feedback group (first two rows) and visual feedback group (third and fourth rows) in different phases of stages B (adaptation) and C (washout). Average trajectory (solid lines) and standard deviation (patches) of the groups are shown

received auditory feedback of this error in the form of a whooshing sound, the loudness and location of which reflected the error. Figure 2 shows an example of movements during adaptation to the changed desired trajectory, for one subject from the AF group and one subject from the VF group. The black line paths represent the reference that moves toward the right side. In order to have no audio on the headphones (AF group) or no visual error on the screen (VF group), the subjects had to move the hand along the trapezoidal path. The mean trajectories and the standard deviations, averaged over concerned trials of all subjects, are shown in Fig. 3 for the key phases of the experiment. Figure 4 shows the mean error and its standard deviation (inter-subject) for both groups during the main phases, except from the visuomotor perturbation phase, which is shown in Fig. 5.

Performance comparison (average weighted x -position error) showed a lack of difference between the VF and AF groups ($F_{1,803} = 1.381, p = 0.1775$). Group effect on

performance can be considered non-significant ($F_{3,890} = 0.0074, p = 0.9325$), whereas there was a significant effect of time ($F_{1,803} = 63.26, p < 0.0001$). Pairwise post hoc analyses indicate that both groups exhibited significant direct effects when the force field was first applied ($p < 0.001$) and then reduced their trajectory error to near zero. Both groups showed also significant after effects ($p < 0.001$) when the force field was unexpectedly removed. Such effects were comparable in magnitude between groups ($p > 0.05$).

Thus, the first result is that the participants exhibited comparable evidence of adaptation to the force field and consequent formation of an internal model, regardless of whether error feedback was delivered through vision or hearing. Regarding the size of the direct effect and after-effect, we must underline that their measures contain only one trial per subject and they are therefore very noisy if compared to other measures that average over several trials. This might be the primary reason for the lack of

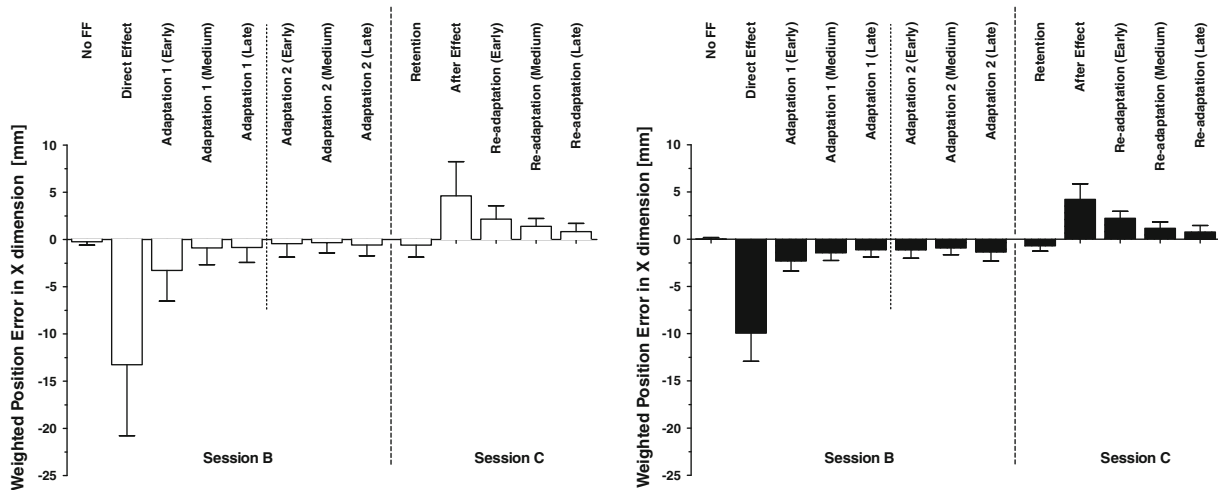


Fig. 4 Average weighted position error in the x direction for the auditory feedback group (to the left) and for the visual feedback group (to the right), for different phases of stages B (adaptation) and C (washout). The error bars represent the inter-subject standard

deviation, that is, the standard deviation computed in each phase by using the weighted position error of each subject as data set. The visuomotor perturbation phase of session B is not shown here (see Fig. 5 for details)

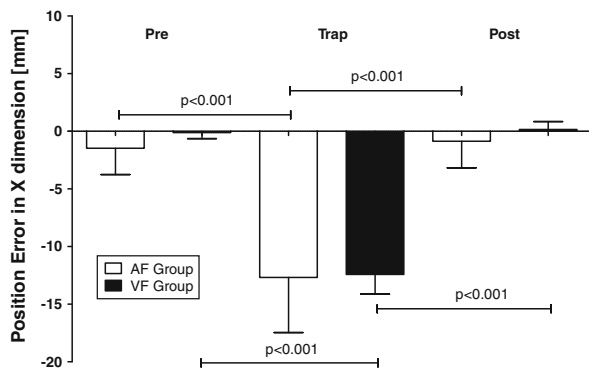


Fig. 5 Average position error in the x direction in different phases of session B (adaptation) for the auditory feedback (AF, white) and the visual feedback (VF, black) groups. The error bars represent the inter-subject standard deviation, that is, the standard deviation computed in each phase by using the position error of each subject as data set. The pre-trapezoid, trapezoid and post-trapezoid phases are shown

Analysis of intra-subject variances revealed no significant interaction between group and time ($F_{1,803} = 0.4842, p = 0.9224$). There was a significant effect of time on standard deviations ($F_{1,803} = 77.44, p < 0.0001$), indicating that all subjects experienced comparatively similar levels of variability in different phases of the experiments. Significance was found also between groups ($F_{3,890} = 9.721, p = 0.0066$). However, pairwise post hoc analyses indicated that the difference between groups was significant in the direct-effect phase only ($p < 0.05$), and this result may be due to the fact that this phase included one trial only, as already stated. Being the variances comparatively similar between groups in all other phases, we can conclude that the auditory feedback employed was not harder to use than visual feedback. Moreover, the audio feedback proposed was interpreted homogeneously among subjects as much as video, as evidenced by a lack of significant difference of the inter-subject variances (variability of means between groups) in each phase of the experiment (F tests, $p > 0.05$).

significance between vision and sound in such phases. By fitting learning curves with one-phase decay exponential functions and by comparing the fitted values for the 1st trials, the size of the direct effect resulted to be significantly larger in the AF group with respect to the VF group ($p < 0.05$), whereas no statistical significance was found between the sizes of the aftereffects ($p > 0.05$). Unpaired t test on decay constants revealed no significant difference between groups ($p = 0.2414$ during adaptation, $p = 0.1681$ during re-adaptation), indicating comparable adaption rates under both feedback conditions.

Following adaptation to the force field, we slowly shifted the reference trajectory to be a spatial trapezoid that increased in amplitude up to a 2.5-cm displacement to the right. Figure 5 shows the average position error before the trapezoid (pre), during the trapezoidal reference phase (trap) and after restoring the straight reference (post). The two-way repeated measures ANOVA (group vs. time), performed on means and intra-subject standard deviations of x-position error, showed no significant difference between VF and AF groups in the adaptation to the new trapezoidal reference ($F_{1,708} = 0.9533, p = 0.5058$ for

means; $F_{1,708} = 0.2931$, $p = 0.9957$ for standard deviations). Bonferroni pairwise post hoc tests indicated that the mean error was comparatively greater in the *trap* phase if compared to *pre* ($p < 0.001$ for both groups) and *post* ($p < 0.001$ for both groups). Comparison between groups exhibited similar average errors ($p > 0.05$) and standard deviations ($p > 0.05$) in each of the three phases, indicating that both groups adapted to the visuomotor transformation in the presence of the viscous field.

Discussion and conclusion

We studied how individuals adapt their reaching movements to dynamic and kinematic perturbations with auditory feedback compared to visual feedback. The main findings for the dynamic perturbation condition were that auditory feedback allowed similar error reduction compared to visual feedback, and individuals in both groups exhibited similar after effects, indicating that they formed comparable internal models of the perturbation. Larger direct effects were measured in the auditory feedback group, suggesting that the auditory feedback employed in the experiments may be less efficacious than visual feedback in promptly feeding-back position error to the user after a sudden modification of the dynamic environment. Nonetheless, comparable adaptation rates were obtained under both feedback conditions. The main finding for the kinematic perturbation was that the subjects offset their trajectories to try to follow the changed desired trajectory in comparable ways. We first discuss implications of these findings for the structure of sensory motor adaptation, then implications for sensory substitution and motor training technologies.

Implications for sensory motor adaptation

The arm motor control system relies on sensory feedback of kinematic error to drive motor adaptation to novel dynamic environments and altered visual-motor transformations (Scheidt et al. 2005; Thoroughman and Shadmehr 2000). This information is usually delivered by both proprioceptive and visual systems. The motor system exhibits flexibility in blending these sensory modalities, depending on the availability and reliability of each modality (Reuschel et al. 2011). This flexibility in combining different sensory modalities to control reaching suggests that the motor system is arranged modularly, in the sense that error calculation systems apparently blend whatever sensory information is available relatively independently of the ensuing motor actions. The present results are consistent with this viewpoint. With little training, individuals were able to use novel auditory feedback to help them

adapt to the altered dynamic and kinematic environments in a way similar to when had standard visual feedback available. It is unlikely that they rapidly developed a new audio-motor arm control pathway to achieve this feat in only a few trials. Rather, this finding strongly suggests that the sensory motor adaptive control system is structured so that all available sensory inputs, including auditory information, feed into an error calculation system, the output of which is then used to control motor adaptation and is inconsistent with an alternate structure in which there exist dedicated pathways associated with each sensory modality. This viewpoint is consistent with the “flexible task machine” hypothesis of Reich et al. (2012), supported by functional brain imaging studies of sensory substitution, in which sensory processing brain networks usually associated with a particular modality (e.g., vision) readily use data from an alternate sensory modality that is presenting task-relevant information.

These results should be compared to a recent study by Kagerer and Contreras-Vidal (2009), in which subjects adapted to a visuomotor rotation and then, following adaptation, were asked to make blinded reaching movements to auditory targets. They made straight movements to the targets, indicating that the internal model formed during exposure to the visuomotor rotation was immediately available to the auditory-motor network used to control the movement to the auditory target. The present study is different in that auditory feedback of error was continuously provided to guide adjustments in an adaptation stage, but is consistent in that the motor system exhibited the capability of immediately incorporating auditory information to control movement. Kagerer et al. point out that several brain structures have been identified as being involved in polysensory convergence, in both early and later stages of sensory processing (Fu et al. 2003; Hyvarinen and Shelepin 1979; Pouget et al. 2002; Schroeder et al. 2003). They identify posterior parietal cortex as one area suited to process multiple sensory inputs and relay the processed information to dictate motor output, although other parieto-frontal networks could also serve this function.

One important feature of the present study to consider is that the reaching task was essentially a one-dimensional task, since subjects only needed to control left-right hand motion, because the mechanical hard limits of the joystick limited the forward-and-back motion of the hand to the targeted range. Thus, future studies should examine whether auditory feedback can drive adaptation of multi-dimensional arm movement. Based on the current results and the flexible task machine hypothesis, we speculate that it can, with the limiting factor being finding ways to provide multi-dimensional auditory input that is readily interpretable by the error processing network.

A possible limitation of the study is we did not systematically explore how the rate of introduction of the perturbation affected the motor system's ability to use auditory and visual feedback. In designing the protocol used here, we were inspired by the protocols of two classic motor adaptation studies, Shadmehr and Mussa-Ivaldi (1994), which abruptly introduced a dynamic perturbation, and Wolpert et al. (1995), which gradually introduced a visual distortion. Gradual and abrupt introduction of kinematic and dynamic perturbations produces comparable changes in motor commands (Klassen et al. 2005); change in motor command was a primary outcome measure in this study as well. However, recent studies suggest that the rate of introduction of a perturbation may affect the duration of after effects, the amount of retention, and the pattern of generalization (see concise review in Criscimagna-Hemminger et al. 2010), and may call into play different neural substrates to drive adaptation (Orban de Xivry et al. 2011). Thus, there is a possibility that the rate of introduction of the perturbation, and the type of feedback (auditory versus visual), may interact to affect these factors as well, a topic for future study. One might expect that they would not interact if the motor system is arranged modularly, as described above, blending available sensory information independently of the ensuing motor actions.

We also did not systematically explore different combinations of kinematic and dynamic perturbations. The decision to add the kinematic perturbation following adaptation to the dynamic perturbation was arbitrary; we could also have removed the dynamic perturbation and caused after effects to wash out before applying the kinematic perturbation. If anything, then the kinematic adaptation task was more demanding than those usually studied (as it was a "stacked" adaptation), and in its strictest interpretation, then, the data here show that the motor system uses auditory and visual feedback similarly when further adapting to a kinematic perturbation after adapting to a dynamic perturbation. Again, however, one might expect that the ordering of perturbation would not affect the results if the motor system is arranged modularly with respect to sensory input, a hypothesis that can be tested with further study.

Implications for sensory substitution and motor training

The results of this study further support the assertion that sensory substitution systems have significant potential to improve function of people with sensory impairment (Reich et al. 2012). Not only can auditory feedback facilitate pointing and reaching, but when designed appropriately it can allow people to adapt to altered dynamic and kinematic environments as they reach. The motor system's adaptive ability is likely important in dealing with muscle fatigue (Takahashi et al. 2006) and the various loads

encountered in life, as well as ongoing changes in limb dynamics or kinematics related to development (Takahashi et al. 2006), disease, weight changes, or aging in the motor system. The present study indicates that sensory substitution system should feed naturally into the normative motor adaptive processes used to deal with these circumstances.

Further, if auditory signals can readily be used to drive motor adaptation, this suggests they may be a viable means to enhance sensory feedback for motor training applications such as rehabilitation therapy and sports training. Auditory feedback is relatively underused in current rehabilitation technologies (Molier et al. 2011). However, it is the most frequently used form of feedback in rehabilitation therapy sessions (Molier et al. 2011). Several studies have shown its utility in facilitating learning, accuracy (Robertson et al. 2009), and attention and limiting compensatory movements (Thielman 2010) in re-training of reaching after stroke (Rath and Rocchesso 2005; Secoli et al. 2011; Secoli et al. 2009; Taylor and Thoroughman, 2007). The present study indicates that auditory feedback is readily incorporated into brain learning networks, supporting its use as adjuvant for helping neurologic patients and other motor learners improve their movements.

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