Learning Movement Kinematics with a Targeted Sound

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Abstract. This study introduces an experiment designed to analyze the sensorimotor adaptation to a motion-based sound synthesis system. We investigated a *sound-oriented* learning task, namely to reproduce a targeted sound. The motion of a small handheld object was used to control a sound synthesizer. The object angular velocity was measured by a gyroscope and transmitted in real time wirelessly to the sound system. The targeted sound was reached when the motion matched a given reference angular velocity profile with a given accuracy. An incorrect velocity profile produced either a noisier sound or a sound with a louder high harmonic, depending on the sign of the velocity error. The results showed that the participants were generally able to learn to reproduce sounds very close to the targeted sound. A corresponding motor adaptation was also found to occur, at various degrees, in most of the participants when the profile is altered.

Keywords: gesture, sound, sensorimotor, learning, adaptation, interactive systems, auditory feedback, sound-oriented task

1 Introduction

There is growing interest in using tangible interfaces and motion sensing technology to interact gesturally with digital sound processes. In particular, a research community has been established over the last ten years around the development of gestural digital musical instruments (DMIs). The NIME conference (New Interfaces for Musical Expression) [3] has centralized several important research results. While the evaluation methodology of such interfaces is recognized as important, it has generally been considered from a user experience point of view, most often ignoring fundamental aspects of sensorimotor learning. Nevertheless, we believe that sensorimotor learning should be fully addressed for the development and evaluation of digital musical interfaces.

This research topic is close to applications using *movement sonification*, where digital sound processes are designed to react to movements, hence providing additional information about the movement/performance. Typically, the auditory feedback is thought to supplement other sensory modalities (such as proprioception and vision) and to facilitate sensorimotor learning. Such an approach has been proposed for example for the facilitation of skills acquisition in sports [28] or in physical rehabilitation [20]. Although there is a growing number of publications studying the mechanisms whereby auditory feedback can improve motor control and learning, there is still a lack of formalism and consensus on the use of such auditory feedback.

We have started to study sensorimotor learning in DMIs and interactive sound systems for movement training/rehabilitation, within a single research project[1]. We take advantage of the fact that these applications can share identical technology (motion sensing and processing) and also share similar questions about the action-perception loop involved in motion-sound interaction.

While the different applications might imply similar sensorimotor learning processes, they can still be categorized based on the different tasks they imply. In the case of DMIs, the task can be expressed as *sound-oriented*. The users adjust their movements in order to achieve a specific goal expressed in terms of sonic/musical characteristics. In the case of motion training (i.e. sport or rehabilitation), the task can be expressed as *motion-oriented*. The users get auditory feedback to adjust their movements and to achieve a specific goal in terms of motion characteristics. In Figure 1 we schematically describe the information flow of movement sonification in the cases of *motion-oriented* and *sound-oriented* tasks. The figure emphasizes that both concepts share the same architecture.

In this paper, we focus only on the first case: the *sound-oriented* task. In this case, the user's attention is drawn on the sound produced by the action and the auditory-motor loop is regulated by the perceived sound properties. We present an experiment where we evaluate the movement adaptation of subjects who are asked to control a specific sound quality.

The paper is structured as follows. First, we present a short overview of related works. Second, we describe the experimental setup, methodology and motion analysis. Third, we present the results, and fourth, we discuss our findings and their implications for further experiments.

2 Related Works

We first describe here the few studies that explicitly reported on a *sound-oreinted* task. We then report on other *motion-oriented* tasks that showed the interest of using auditory feedback.

[1] Legos project, http://legos.ircam.fr

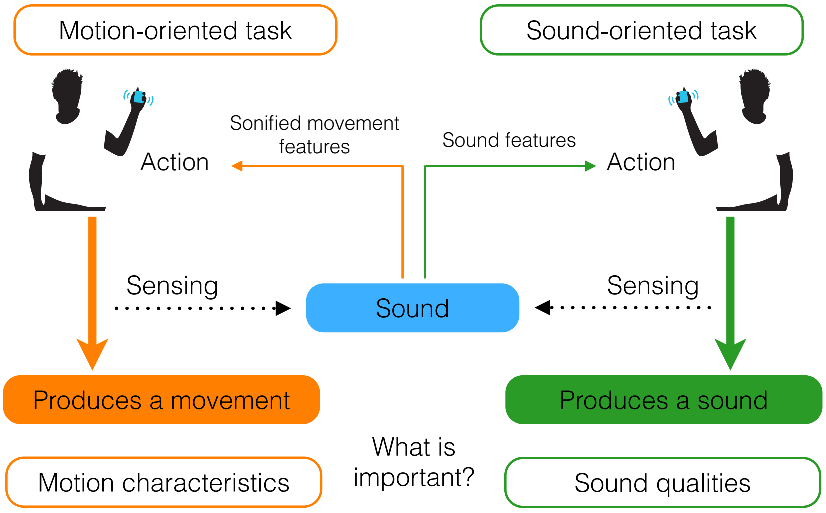

Fig. 1. Concept of Motion-oriented vs Sound-oriented task.

2.1 Sound-oriented Task

A small number of studies have examined the concept of *sound-oriented* task. Early works were performed focusing on the evaluation of gesture-sound mappings. Hunt et al. in [14] presented such an evaluation by asking subjects to reproduce a target sound using different mapping strategies. Only simple interfaces such as a mouse and sliders were used. It resulted that, while complex gesture-sound mappings were more difficult to master, they appeared to be more engaging for the subjects. This implies that the type of implicit learning involved in this case was perceived as beneficial.

Gelineck et al. [9] also studied input interfaces and compared knobs and sliders for a task consisting in reproducing reference sound samples. Subjects were musicians and were asked to reproduce four sounds with temporal timbral variations (synthesized with a physical model of flute and friction). A qualitative evaluation was performed showing that no significant difference was found between the use of knobs and the use of sliders. Note that these studies did not explicitly address sensorimotor learning or adaptation in their questionnaire-based evaluation.

Pointing towards auditory targets can also be considered as a sound-oriented task. Recently, we investigated the effect of sound feedback on blindfolded pointing movements towards auditory targets spatialized with HRTF binaural technique [4]. We found that the auditory target should last enough to be heard during the task. The potential advantage to additionally sonifying the hand was not apparent in such a case. Forma et al. [8] showed that blindfolded participants are also able to point towards targets in a auditory virtual environment using sound as sensory substitution. Interestingly participants succeeded in the task whether the virtual listener was congruent with their ears or placed on one of their hands.

The concept of a *sound-oriented* task can be linked to recent studies on the relationship between body motion occurring during various sound/music stimuli [11, 10, 5, 17, 18]. In particular, Godøy et al. [10] investigated motion trace that subjects performed on a 2-dimensional surface in response to a sound stimuli. Other studies were reported on hand gestures performed while listening to either abstract synthesized sounds [18], or stimuli derived from environmental sounds [5]. As expected these studies showed that the motion related to sound stimuli depends on several different sound aspects and varies greatly between subjects. Nevertheless, such studies offer novel perspectives in showing experimentally that some sounds can favor specific motions.

2.2 Auditory Feedback in Motion-oriented Task

The other types of related studies concern investigations of *motion-oriented* tasks to establish whether auditory feedback can be beneficial for learning and performance. Rath and Schleicher [19] studied a virtual balancing task under different feedback conditions, including auditory feedback to guide movements. They found that the auditory feedback was beneficial in terms of rapidity, the best results being found when sonifiying the ball velocity. They also found small differences between ecological and abstract sounds. More recently, Rosati et al. [22] showed that a tracking task can be improved using an auditory feedback (in addition to a visual feedback) related to the task achievement or, to a lesser extent, giving information about the error.

Vogt et al. [27] proposed a movement sonification system to improve perception of body movements. Sonification and "positive"sounds were beneficial for task understanding and increased the subject motivation. Effenberg [6] focused on an ecological approach, insisting there is a close relationship in kinesiology between movement kinetics and sound. He showed that supplementary auditory information improves the perception and reproduction of sport movements compared to vision alone. These results appeared independent from the qualitative assessment of the sounds qualities by the subjects. Takeuchi [25] previously pointed out that sound is a very useful information channel in sports. Avanzini et al. [2] insist on the role played by auditory information in multimodal interactions. Wolf et al. [28] and Effenberg et al. [7] showed that subjects can benefit from multimodal motor representation in a rowing-type task.

Wolf et al. also report that auditory feedback can reduce spatial error and improve synchronization when the feedback is related to the internal representation of the task rather than short-time features of the movement. Karageorghis and Terry [15] suggested as well that sound feedback can improve mood, hence performance, in sports and leisure activities.

Sport and musical control are not the only domains where auditory interaction can improve motor learning. Thoret et al. [26] studied the sonification of drawings to investigate whether subjects could recognize a drawn shape from recorded and synthesized friction sounds. They noticed that people were able to identify gesture trajectories with the friction sound they produced and the model-generated sounds which used movement velocity as input.

A recent review by Sigrist et al. [23] presents experimental studies of sonification techniques. The authors formalize the different type of auditory feedback in the framework of motor learning theories. They insist on the fact that, despite important applications, several questions on auditory feedback for motor learning remain insufficiently explored.

Recent studies show that an additional feedback can improve physical rehabilitation processes and there is growing interest in using additional auditory feedback to guide movements of impaired or stroke patients [20, 24, 1, 21]. For instance Huang et al. [13] designed a multimodal biofeedback with musical tracks in a reaching task with stroke patients and found that visual and auditory feedback together helped patients producing smoother and more accurate movements.

3 Materials and Methods

3.1 Experimental Setup

The *sound-oriented* task is based on the manipulation of a specific motion interface that allows for the continuous control of sound synthesis. Subjects are seated in front of a table on which two spots are drawn, named 1 and 2, marking the spatial starting and ending areas of the movement they will have to make. Subjects carry in their hand the motion interface, consisting of a small object containing 3D accelerometers and a 3-axis gyroscope. Figure 2 depicts schematically the setup. Data are transmitted wirelessly to a receiver through the IEEE protocol 182.15.4 (2.4 GHz Band), that transmits them to the computer using Open Sound Control (through the UDP protocol). A software programmed using the Max environment (Cycling '74) includes real-time data processing, sound synthesis and data logging (data, sound and video recordings of each subject). The subjects listen to the sound using headphones.

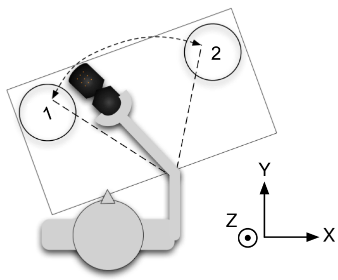

Fig. 2. Experimental setup. The subjects move the tangible interface from 1 to 2 in order to continuously control the sound and aim the targeted sound.

The angular velocity around the Z axis of the interface is used as input. The sound is synthesized from the difference between the performed velocity profile and a defined velocity profile, the *reference profile*, that varies between different conditions. This profile is a bell shape curve (derived from a Gaussian profile), corresponding roughly to the velocity profile typically found while moving the hand between two points [16], with a maximum peak velocity around 70 $deg.s^{-1}$.

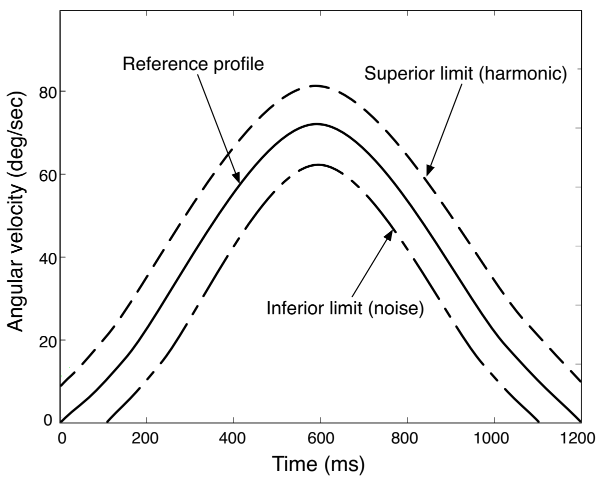

Fig. 3. Reference profile and the associated thresholds enabling the change in the sound qualities (noise or loud higher harmonic).

The velocity signal is mapped to a sound synthesizer using Modalys[2] in Max. A resonator, a string model, is used to filter three types of input sound signal: one square sound signal at a fundamental frequency equal to 260 Hz (corresponding to C4), matching the second harmonic of the string, one square sound signal at a fundamental frequency equal to 910 Hz, matching approximately the 7th harmonic and pink noise (constant power per octave). The difference between the performed profile and the reference profile modulates the intensity of the higher harmonic or the noise inputs: positive values boost the higher harmonic, negative values boost the noise sound. This choice is motivated by the analogy with the velocity/pressure adjustments in bowing a string in a violin: low velocity might produce a noisy sound (with sufficiently high pressure), while increasing the velocity produces higher frequencies.

The sound level of the added effect is effective only when the difference reaches a given threshold, of constant value over the whole profile of velocity, as illustrated in Figure 3. Once the threshold is reached, the intensity of the

[2] Modalys (Ircam), http://www.forumnet.ircam.fr/product/modalys. The object used is “MONO-STRING”, see documentation for details.

effect depends linearly on the difference between the performed and reference velocity values. Our interest was to investigate how the subjects can learn a specific movement without guessing it directly from the sound morphology of the reference sound. As shown in Figure 4, the intensity morphology of the target sound does not match the reference profile.

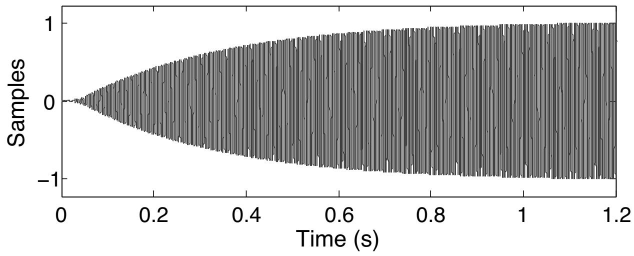

Fig. 4. Waveform of the target sound.

3.2 Experimental Procedure

The subjects first listen to the target sound and to typical sounds associated to incorrect movements: one with noise referring to a lower angular velocity movement and one with an extra harmonic note referring to a higher angular velocity. All the sounds are 1.2 seconds long. The subjects can listen to the sounds as many times as they wish until they feel comfortable distinguishing the different sound characteristics. Figure 5 shows the spectrogram of the three example sounds, which are chosen to be easily discriminated by the subjects according to their frequency content.

Subjects are then instructed to move the object with their dominant hand between areas 1 and 2 to produce the target sound. Their motion should last as long as the sound (1.2 s). The subjects do not have control anymore on the sound produced beyond 1.2 seconds.

During the first phase, we call *Exploration*, subjects perform 60 movements (30 rightward and 30 leftward) with the normal symmetrical profile called E as a reference for feedback generation. Between each movement, they must wait until a *beep* is emitted, which occurs randomly between 2.5 and 3.5 seconds. This random start is set to avoid the creation of a rhythmic pattern in chaining the movements.

In the second phase, *Adaptation*, subjects are blindfolded and asked to perform three blocks of 50 movements. For each block, the reference velocity profile was changed following the sequence A - B - A, without informing the subjects. As illustrated in Figure 6, the profiles A and B were obtained from profile E by shifting the temporal position of the maximum velocity. Figure 6 also shows the

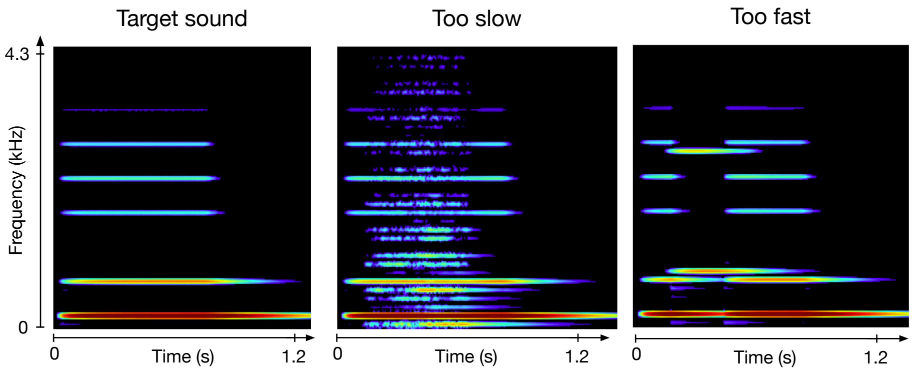

Fig. 5. Sonograms of the three example sounds; left: target sound produced if the movement matches exactly the target velocity profile *i.e.* the plain line in Figure 3; middle: sound containing noise produced by a slow movement; right: sound with the higher harmonic produced by a too fast movement.

changes in the initial slope, which is approximated between start point and maximum of the profile. Profile A thus exhibits a higher acceleration and a slower deceleration. Profile B exhibits the opposite variation: a lower acceleration and higher deceleration.

The subjects are asked to fill in a questionnaire at the end of the experiment. It contains questions about their musical abilities, whether they are used to manipulate digital interfaces, asks whether they noticed modifications in the system in both phases, and invites them to rate the difficulty and the degree of control they experienced.

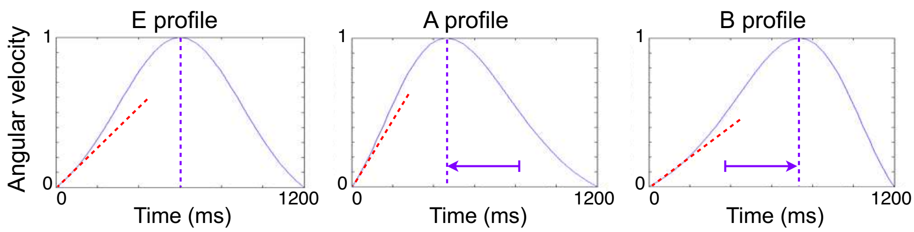

Fig. 6. Reference profiles of angular velocity used in the different phases of the experiment, showing initial slopes and peak shifts; amplitudes are normalized.

3.3 Subjects

Fourteen subjects volunteered for the experiment. All were healthy and reported normal hearing. They were 23.6 ± 1.9 years old and three of them were left-handed (21%). All were familiar with digital interfaces such as computers, and were familiar with music from recreational to professional levels (1 to 20 years of instrumental practice). All subjects gave written informed consent for the experiment.

3.4 Data Analysis

The analysis is based on the comparison between the angular velocity time profile performed by the subjects v_i and the reference profile u_i, where i is the i^{th} time sample (50 Hz sampling frequency). The recorded profiles are low-pass filtered with a 10 Hz cutoff Savitsky-Golay filter. As described below, different measures are estimated to capture specific features of the performed profiles. In a second step, the time evolutions of these measures were examined to find trends over the series of the subjects' trials, using t-tests and ANOVAs.

3.5 Angular Velocity Profile Parameters

The different measures described below were considered:

First, the mean error can be evaluated for each trial by taking the standard deviation of the difference between performed angular velocity v_i and the reference profile u_i :

$$mean\ error = \frac{1}{(N-1)}\sqrt{\sum_{i=1}^{N}[v_i - u_i]^2} \tag{1}$$

N being the total number of samples.

Second, the mean or first order moment of the profile was computed. It allows us to characterize where the largest velocity values are reached.

$$first\ moment = \Delta t \frac{\sum_{i=1}^{N} v_i i}{\sum_{i=1}^{N} v_i} \tag{2}$$

Δt being the time interval between two samples.

Third, we computed an approximation of the initial slope of the velocity profile. The changes in dynamics to A and B profiles come from the modification of the last two parameters, it is thus natural to compute these measures to evaluate subjects adaptation to the changes in the mapping. Table 1 gathers the parameter modifications in profiles E, A and B.

Table 1. 1^{st} order moment and initial slope of the different reference angular velocity profile phases.

Profil	1^{st} moment [ms]	initial slope [deg]
E	600	34.6
A	536	41.0
B	684	28.4

4 Results

We first investigated the evolution of the performance by comparing average error values at the beginning (8 first movements) and at the end (8 last movements) of each block (E, A, B, A). A general statistical analysis (ANOVA) was performed with three factors: the 4-level 'block' factor, the 2-level 'beginning/end' factor and the 8-level 'trial' factor. The analysis revealed a significant effect of the 'beginning/end' factor alone ($F_{(1,13)}$=26.3, p<0.005) which was not the case for the 'trial' factor. The interaction of 'beginning/end' and 'block' factors interestingly presented a significant effect on the performance ($F_{(3,39)}$=9.2, p<0.005), but the post-hoc tests indicated significant error reduction only within the first block (the Exploration phase). This shows that there is significant learning occurring in the Exploration phase which we further examined using individual t-tests.

4.1 Exploration Phase

During the Exploration phase, each subject starts with a spontaneous motion from area 1 to 2. By listening to the auditory feedback, they are able to adapt their movement to reach, more or less, the reference profile. A typical example is shown in Figure 7, where the first and last profiles are plotted along with the reference profile. In this case, the ending profile is clearly closer to the reference profile than the initial one.

The mean error values of the velocity profile are shown in Figure 8 for each subject. Error bars indicate the standard deviation across the profiles for a given subject. A large variability between the subjects can be observed on the initial movements (dark grey bars). This was expected since no specific instruction was given to the subjects about the dynamics of the movement they had to perform. These differences can thus be directly linked to the variability of the spontaneous movements performed by the subjects. After more than 45 trials, the variability between the subjects is largely reduced (by 50%), which indicates they were able to use the sound feedback to constraining their motion towards the reference profile.

Importantly, Figure 8 also shows that for all subjects the mean error is lower in the last trials than in the first trials, which is also a strong indication of the positive effect of the auditory feedback. To characterize this quantitatively, we performed t-tests to determine which subjects exhibited statistically significant improvements ($p < 0.05$ shown with an asterisk in Figure 8). This result confirms

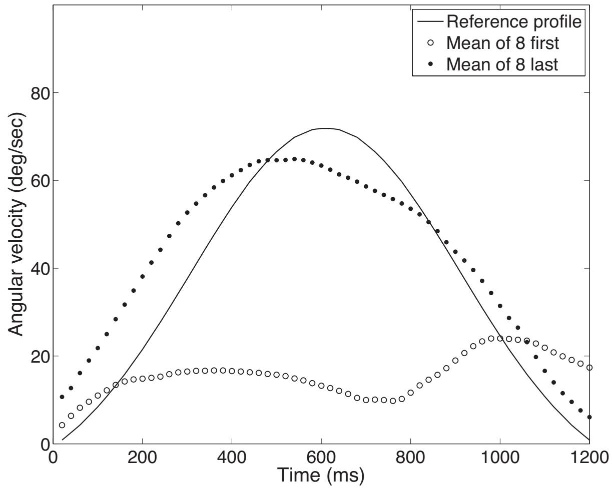

Fig. 7. Example of angular velocity profiles during the exploration phase (subject #7). The comparison between the first and last profiles clearly shows that the subject modified his movement towards the reference profile.

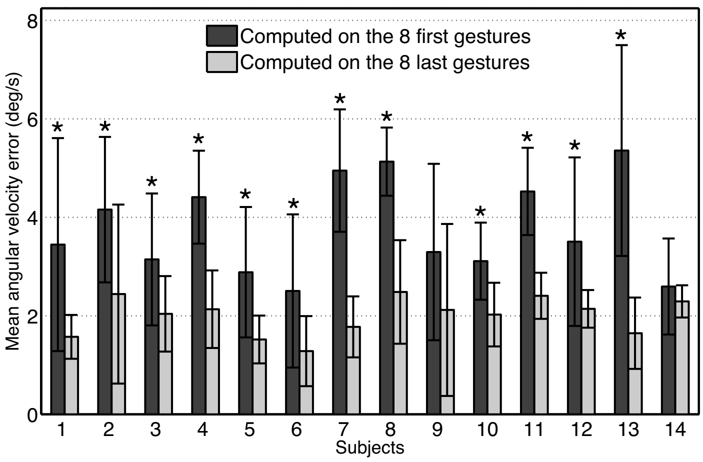

Fig. 8. Mean error results on angular velocity profile for each subject during the Exploration phase E; error bars indicate standard deviation; the asterisks indicate significant error reduction at the end of the Exploration phase ($p \leq 0.05$).

the general ANOVA performed previously, and provides us with more detailed information: 12 subjects out of 14 significantly adapted their motion during phase E. Among the two subjects who did not show significant improvement, subject #14 spontaneously performed motions with errors relatively close to that of last profiles for the other subjects, which might explain why the improvement was less significant. Subject #9 exhibited large standard deviations which also explains why the improvement is not statistically significant. The Adaptation phase discussed in the next section provides more information about the performance of these subjects.

4.2 Adaptation Phase

During the Adaptation phase, the A and B profiles are alternated, which allows for a more detailed investigation of the subject performances. We emphasize that the subjects were not informed of the change between the A and B profiles. The main difference between these profiles can be characterized by the variations of the first moment, or by the initial slopes (see Table 1). The first moment is actually close to the relative time to peak velocity (rTPV). Nevertheless, we found the computation of rTPV less robust, due to irregularities sometimes occurring in the velocity profiles. Therefore, we focused on the first moment and the initial slopes and performed statistical tests to examine whether significant adaptation can be observed within the transitions A to B and B to A. The results are reported in Table 2.

Table 2. Significance of the parameter variations during the Adaptation phase, between the 14 last trials of each block ($p \leq 0.05$)

Subject	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1^{st} moment A $\rightarrow$ B	$\star$	$\star$		$\star$		$\star$	$\star$		$\star$	$\star$	$\star$		$\star$	$\star$
1^{st} moment B $\rightarrow$ A	$\star$	$\star$	$\star$			$\star$	$\star$				$\star$		$\star$	
initial slope A $\rightarrow$ B		$\star$		$\star$		$\star$	$\star$			$\star$	$\star$	$\star$	$\star$	$\star$
initial slope B $\rightarrow$ A		$\star$	$\star$	$\star$		$\star$	$\star$			$\star$	$\star$	$\star$	$\star$	

The individual t-test results show that we can separate the subjects into three groups. First, 5 subjects show significant adaptation for all blocks (#2, #6, #7, #11, #13). Two subjects show no significant adaptation (#5, #8). The other 7 subjects show some adaptations depending on the considered parameters. This can be explained by the fact that subjects adopt different strategies. For example, subject #1 adapted his profile globally as shown by the significant variation of the 1^{st} moment. On the contrary, subject #12 principally adapted the beginning of the profile, as evidenced by the significant variation of the initial slope.

We performed a general statistical analysis (ANOVA) over the three blocks of the Adaptation phase for the 1^{st} moment and initial slope parameters, respectively left and right on Figure 9. The analysis revealed a significant effect of the phase factor for both parameters: $F_{(2,26)}=6.7$, $p<0.005$ and $F_{(2,26)}=11.5$, $p<0.005$ respectively. Post-hoc tests indicated a significant change between transitions A-B and B-A for the 1^{st} moment and only for A-B transition for the initial slope. Therefore, these results show that subjects adapted their movement between the ends of each block, and this adaptation appeared more significant on 1^{st} moment. Interestingly, subjects tend to underestimate the adaptation of the 1^{st} moment position, indicating it might be difficult to modify that much this dynamic property of the movement. They also overshoot the initial slope towards small values, indicating they generally initiated their movement too slowly.

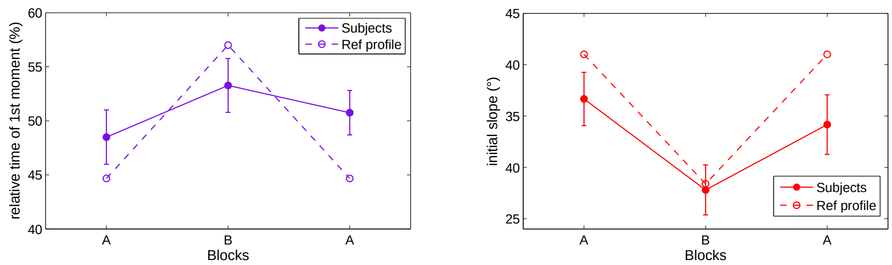

Fig. 9. Evolution of the relative time to 1^{st}moment (left) for the 14 last trials averaged for all subjects (plain lines) showing an underestimation of this parameter, and initial slope (right) showing the overshoot. Error bars indicate 95% confidence interval.

4.3 Qualitative Comments of the Subjects

The questionnaire filled by each subject offers additional information about the experiment. Concerning the Exploration phase, 8 subjects (out of 14) were positive that no change occurred in the system and 6 were unsure. Concerning the Adaptation phase, 8 subjects noticed that some changes occurred in the system, 5 were certain that no changes occurred, and 1 subject was convinced that the changes he perceived were solely due to his motion.

The subjects rated the difficulty of the task as 3.1 ± 0.9 and 3.1 ± 0.8 for the Exploration and Adaptation phases respectively (from 1-easy to 5-difficult). Subjects were also asked to evaluate the level of control they experienced over the system (from 1-no control at all, to 5-complete control). The results are close to the median : 2.3 ± 0.7 for the exploration phase and 2.8 ± 0.7 for the adaptation phase. Finally, they were asked questions concerning the system design. Subjects reported neither particular physical nor auditory fatigue (1.4 ± 0.6 and 1.2 ± 0.4 respectively, rated from 1 to 5). The perceived quality of the sounds produced was rated as 2.9 ± 0.9 over 5.

The performances of the subjects were not correlated with their sensation of control or success. Despite the fact that they all declared to be familiar with digital interfaces and practicing music (at a recreational level for most of them) we obtained quite heterogeneous results in terms of adaptation. It appears as though musical abilities or non-professional training is not a particular natural tendency to obtain better results in this particular adaptation task.

5 Discussion and Conclusion

We investigated the concept of *sound-oriented* task and questioned whether sound qualities could guide motion, and, in particular, its velocity profile. We proposed an experimental procedure to quantify how subjects adapt their gesture to produce a specific sound by avoiding either the presence of noise or of a loud higher harmonic.

Overall the results show that sensorimotor adaptations were found in both the Exploration and Adaptation experimental phases. In particular, 12 out of 14 subjects significantly adapted their movement to match the reference velocity profile during the Exploration phase. During the Adaptation phase, 12 out of 14 also showed some adaptation to the reference profiles, even if they were not informed of the sudden changes.

Nevertheless, important differences were noticed between subjects, which require further investigation. Several explanations can be put forward. First, participants, even musicians, appeared not to be used to manipulate sound with such a digital interface. The qualitative assessments of the subjects confirmed that the task was relatively difficult, which also indicates that the sensorimotor adaptation should be designed as more gradual. It is also noted that some subjects who obtained positive results did not notice the reference profiles variations. These observations are in favor of the presence of a strong implicit learning.

The type of extrinsic auditory feedback we developed in our experiment cannot be simply described using the well-known categories knowledge of result *KR* and knowledge of performance *KP* [12]. Knowledge of result provides user with information on the success of the task, as a score for instance. Knowledge of performance provides user with information on the performance itself, such as information about kinematics or joint angles. In our case, the auditory feedback is used to adjust the angular velocity profile (faster or slower). In particular, it leads to corrections occurring in two steps, first during the motion to adapt it, and second, after the motion when planning for the next trial. The first role of the auditory feedback here is thus to provide information during the motion, which could be considered as KP. Nevertheless, the subjects also make use of the general auditory feedback during one trial in order to plan the next trial. The quantity of noise or harmonic they heard during a movement informs them on the success of their trial. Such a feedback could be considered to be similar to KR. This might explain why we did not observe a smooth improvement rate during the trials, but rather improvements based on trials and errors corrections.

From a sensorimotor loop perspective, the auditory feedback we propose is continuous. Moreover, the auditory feedback is designed as the task itself (as opposed to a motion-oriented task). This experiment served us as a first step to design more complete investigations of sensorimotor adaptation driven by *sound-oriented* tasks. In particular, it shows the limit of using standard feedback categories for continuous auditory feedback. Additional formal investigation and experimental works is thus necessary to establish a new framework to describe interactive auditory feedback and the regulation of the auditory-motor loop using these systems.

In conclusion, our results establish that learning movement kinematics is possible in a auditory task and allow us to support the notion of *sound-oriented* task for the study of sensorimotor learning. They open up towards new experiments which we are being pursued.

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