Guiding Motion using a Sound Target

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Abstract. We report on an experiment designed to evaluate sensorimotor adaptation in a motion-based sound synthesis system. We propose to investigate a *sound-oriented task*, namely to reproduce a targeted sound. The system is a small handheld object whose motion drives a sound synthesizer. In particular, the angular velocity is captured in real-time by a gyroscope and transmitted wirelessly to the sound engine. The targeted sound is obtained when the motion matches a given reference velocity profile. If the velocity profile is performed with sufficient accuracy, a specific sound is heard, while a incorrect velocity profile produces either noisier sound or sound with a louder high harmonic (depending on lower or higher velocity values). The results show that subjects are generally able to learn to reproduce the target sound. Motor adaptation is also found to occur, at various degrees, in most subjects when the profile is altered.

Keywords: gesture, sound, sensorimotor, learning, adaptation, interactive systems

1 Introduction

There is growing interest in using tangible interfaces and motion sensing technology to interact gesturally with digital sonic 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) [1] has centralized several 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 other another type of application, where digital sound processes are designed to accompany movements, hence providing information about the performance (either about knowledge of performance or on the knowledge of result). Such a case is often referred to as *movement sonification*. Typically, the auditory feedback is sought to supplement other sensory modalities (such as proprioception and vision) and facilitate sensorimotor learning. Such an approach has been proposed for example for the facilitation of skills acquisition in sports [2] or in physical rehabilitation [3].

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 this paper, we focus only on the first case: the *sound-oriented task*. Our general goal was to design an experiment allowing us to assess movement adaptations in subjects continuously controlling sound. Specifically, the subjects were asked to move a small tangible interface containing motion sensors. The motion is used to control sound synthesis in real-time. This experiment represents a first step to design more complete investigations of sensorimotor adaptation driven by sound-oriented tasks.

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

A small number of studies have examined this concept of *sound-oriented task*. Early works were performed focusing on the evaluation of gesture-sound mappings. Hunt et al. in [4] 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.

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

Gelineck et al. [5] 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 were 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 [6]. 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.

The concept of a sound-orientied task can be linked to recent studies on the relationship between body motion occurring during various sound/music stimuli [7–11]. In particular, Gody et al. [8] 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 [11], or stimuli derived from environmental sounds [9]. 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.

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 [12] 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 by sonifiying the ball velocity. They also found small differences between ecological and abstract sounds. More recently, Rosati [13] 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 [14] 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 [15] 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 [16] previously pointed out that sound is a very useful information channel in sports. Avanzini [17] insists on the role played by auditory information in multimodal interactions. Wolf [2] and Effenberg [18] showed that subjects can benefit from multimodal motor representation in a rowing-type task. 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, Wolf adds. Karageorghis and Terry [19] also suggest 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 [20] studied the sonification of drawings to investigate whether subjects could recognize a drawn shape from recorded and synthesized friction sounds. He 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.

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 [3, 21–23]. Huang [24] 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. The main features of the setup are shown in Figure 1. 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 motion. Subjects carry in their hand the motion interface, consisting of a small object containing 3D accelerometers and a 3-axis gyroscope. Data are transmitted wirelessly to a receiver through the IEEE protocol 182.15.4 (2.4 GHz Band), that transmits the data to the computer using the Open Sound Control protocol (using 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.

The angular velocity around the Z axis of the interface is used as input. The target 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 [25], with a maximum peak velocity around 70 deg/s^{-1}.

The velocity profile produced is mapped to a sound synthesizer using Modalys in Max[2]. A resonator, modeled as a string, is used to filter three types of input sound signal: one square sound signal at a fundamental frequency equal to 260Hz

[2] Modalys (Ircam), http://www.forumnet.ircam.fr/product/modalys

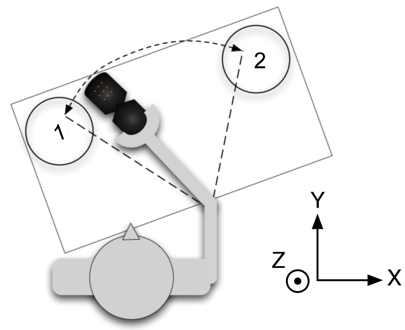

Fig. 1. Experimental setup. The subject moves the tangible interface from 1 to 2 in order to continuously control the targeted sound.

(corresponding to C4), matching the second harmonic of the string, one square sound signal at a fundamental frequency equal to 910Hz, matching 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 sound obtained when scratching an object on a surface: 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, as illustrated in Figure 2. Once the threshold is reached, the intensity of the effects depends linearly on the difference between the performed and reference velocity values.

3.2 Experimental Procedure

The subjects first listen to the target sound and to typical sounds associated to incorrect movements : one with an extra harmonic note referring to a higher angular velocity movement and one with noise referring to a lower 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.

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).

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

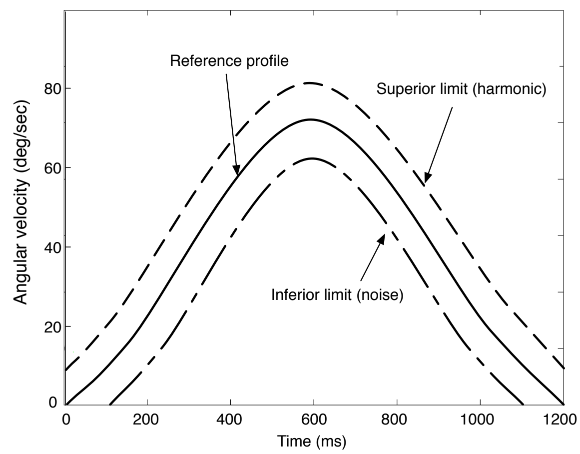

Fig. 2. Reference profile and the associated thresholds enabling the change in the sound qualities (noise or loud higher harmonic).

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 3, the profiles A and B were obtained from profile E by shifting the position of the maximum velocity. Profile A thus exhibits a higher acceleration and a slower deceleration. Profile B exhibits the opposite variation: a lower acceleration and higher deceleration.

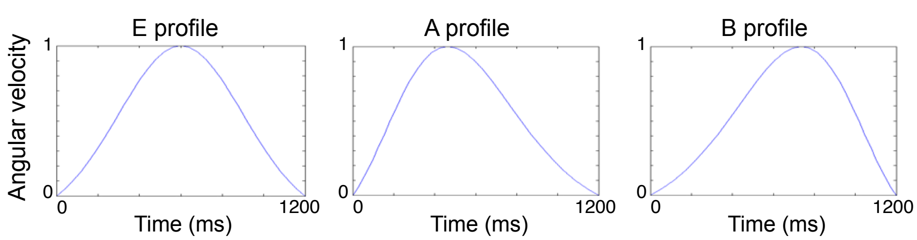

Fig. 3. Reference profiles of angular velocity used in the different phases of the experiment ; amplitudes are normalized.

A questionnaire is given to the subjects at the end of the experiment. It comprises questions about their musical abilities, 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.

3.3 Subjects

Fourteen subjects volunteered for the experiment. All were healthy and had 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 musical controllers, 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 subject 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 $v(t)$ and the reference profile $u(t)$:

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

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. This is an interesting measure since the first order moment varies between the reference profiles E, A and B as shown in Table 1.

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

Δt being the time interval between two samples.

Third, we computed the initial (ending) slope, by considering the first (last) point and the maximum velocity point.

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

Profil	1^{st} moment [ms]
E	600
A	536
B	684

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 16-level 'movement' factor. The analysis revealed a significant effect of the 'beginning/end' factor alone ($F_{(1,13)}$=26.3, p<0.005). 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 examine using individual t-tests.

4.1 Exploration Phase

During the exploration phase, each subject starts with a spontaneous motion from point A to B. 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 4, 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 5 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%, light grey bars), which indicates that the sound feedback was responsible for constraining the motion towards the reference profile.

Importantly, Figure 5 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 5). This result confirms the general ANOVA performed previously, and provides us with more detailed

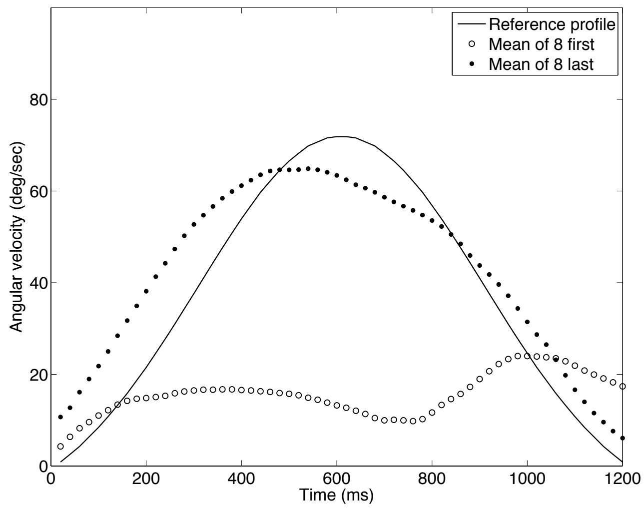

Fig. 4. Example of angular velocity profiles during the exploration phase (subject #7). The comparison between the first and last profiles clearly shows that the subject modified his movement towards the reference profile.

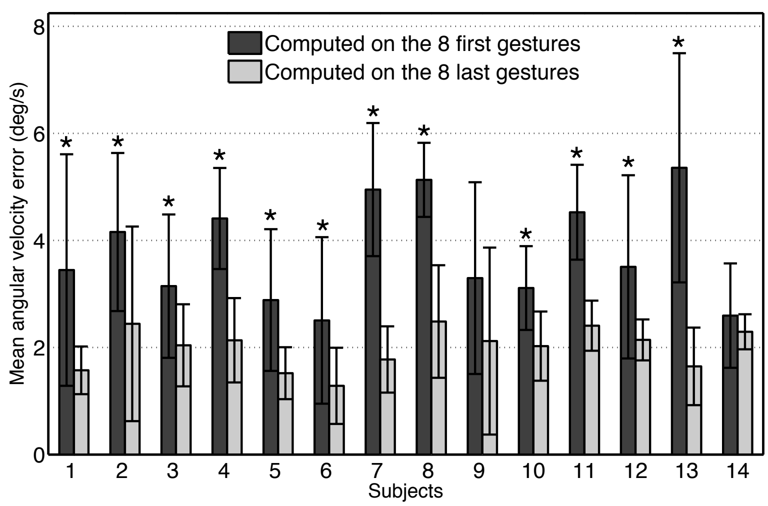

Fig. 5. Mean error results on angular velocity profile for each subject during the exploration phase E; error bars indicate standard deviation across all movements of each subject; the asterisks indicate significant error reduction at the end of the exploration phase ($p \leq 0.05$).

information: 12 subjects out of 14 significantly adapted their motion during phase E. In particular, subject #14 spontaneously performed motion relatively close to the average last profiles of 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. 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.

We performed a general statistical analysis (ANOVA) over the three blocks of the adaptation phase for the 1^{st} moment and initial slope parameters. 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 initial slope and only for A-B transition for the 1^{st} moment. 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.

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.

4.3 Qualitative Comments of the Subjects

The questionnaires filled by each subject offer 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,

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	⋆	⋆		⋆		⋆	⋆		⋆	⋆	⋆		⋆	⋆
1^{st} moment B $\rightarrow$ A	⋆	⋆	⋆			⋆	⋆				⋆		⋆	
initial slope A $\rightarrow$ B		⋆		⋆		⋆	⋆			⋆	⋆	⋆	⋆	⋆
initial slope B $\rightarrow$ A		⋆	⋆	⋆		⋆	⋆			⋆	⋆	⋆	⋆	

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 that 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 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.

5 Discussion and Conclusion

We investigated the concept of *sound-oriented task* and questioned whether sound qualities could guide motion, and, in particular, the angular velocity shape. 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*, 12 out of 14 also showed some adaptation to the reference profiles, even if they were not informed of the sudden changes of the reference profiles.

Nevertheless, important differences were noticed between subjects, which require further investigation. Several explanations can be put forward. First, as the sound-oriented task is not common, such an experiment should be designed considering several difficulty levels (as typically designed in video games). 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 that obtained positive results did not notice the reference profiles variations. This can be linked to the notion of agency as reported for example by Knoblich and Repp in the case of tapping [26], and should be further investigated.

In sensorimotor learning studies, additional feedback is often depicted in two categories: knowledge of result (KR) which informs the subject about the goal to achieve and knowledge of performance (KP) which gives information about how to access that goal. Typically, a simple KR could be in the form of a binary information related either to the positive or negative accomplishment of a given task. The KP could give quantitative information about the correction that must be brought to the wrong movement. The experiment we describe here encompassed these two categories. As the motion is relatively short, the very beginning can be considered as ballistic, while the subsequent motion can be modified continuously according to the sound produced (presence of noise or of a loud harmonic).

The first role of the auditory feedback is thus to provide information during the motion, which can 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 hear during a movement inform them on the success of this movevment, and this feedback can be considered as KR. In our case, the auditory feedback can thus be considered as both a quantitative KR and KP that is used to adjust the angular velocity profile (faster or slower). In particular, the auditory feedback leads to corrections occurring in two steps, first during the motion to adapt it and second after the motion in planning the next trial. This explains that we did not observe smooth improvement during the trials, but rather improvements based on trials and errors corrections. Nevertheless, significant improvements were found taking into account the average of several trials.

In conclusion, our results allowed us to validate the notion of *sound-oriented task* for the study of sensorimotor learning, and open up towards new experiments which we are currently performing.

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References

1. Bevilacqua, F., Fels, S., Jensenius, A.R., Lyons, M.J., Schnell, N., Tanaka, A.: Sig nime: music, technology, and human-computer interaction. In: CHI '13 Extended Abstracts on Human Factors in Computing Systems. CHI EA '13, New York, NY, USA, ACM (2013) 2529–2532
2. Wolf, P., Sigrist, R., Rauter, G., Riener, R.: Error Sonification of a Complex Motor Task. BIO Web of Conferences **1** (December 2011) 00098
3. Robertson, J.V.G., Hoellinger, T., Lindberg, P.v., Bensmail, D., Hanneton, S., Roby-Brami, A.: Effect of auditory feedback differs according to side of hemiparesis: a comparative pilot study. Journal of neuroengineering and rehabilitation **6** (January 2009) 45

4. Hunt, A., Kirk, R.: Mapping Strategies for Musical Performance. In Wanderley, M.M., Battier, M., eds.: Trends in Gestural Control of Music. Ircam - Centre Pompidou (2000) 231–258
5. Gelineck, S., Serafin, S.: A Quantitative Evaluation of the Differences between Knobs and Sliders. In: New Interfaces for Musical Expression (NIME 2009). (2009)
6. Boyer, E.O., Babayan, B.M., Bevilacqua, F., Noisternig, M., Warusfel, O., Roby-Brami, A., Hanneton, S., Viaud-Delmon, I.: From ear to hand: the role of the auditory-motor loop in pointing to an auditory source. Frontiers in computational neuroscience **7**(April) (2013) 26
7. Godøy, R.I., Haga, E., Jensenius, A.R.: Playing "air instruments": Mimicry of sound-producing gestures by novices and experts. In: Lecture Notes in Computer Science. Springer-Verlag (2006)
8. Godøy, R.I., Haga, E., Jensenius, A.R.: Exploring music-related gestures by sound-tracing: A preliminary study. In: Proceedings of the COST287-ConGAS 2nd International Symposium on Gesture Interfaces for Multimedia Systems (GIMS2006). (2006)
9. Caramiaux, B., Susini, P., Bianco, T., Bevilacqua, F., Houix, O., Schnell, N., Misdariis, N.: Gestural embodiment of environmental sounds: an experimental study. In: Proceedings of the International Conference on New Interfaces for Musical Expression, Oslo, Norway (2011) 144–148
10. Nymoen, K., Glette, K., Skogstad, S., Torresen, J., Jensenius, A.: Searching for cross-individual relationships between sound and movement features using an svm classifier. In: Proceedings, New Interfaces for Musical Expression, NIME 2010 Conference. (2010)
11. Nymoen, K., Caramiaux, B., Kozak, M., Torresen, J.: Analyzing sound tracings: a multimodal approach to music information retrieval. In: Proceedings of the 1st international ACM workshop on Music information retrieval with user-centered and multimodal strategies. MIRUM '11, New York, NY, USA, ACM (2011) 39–44
12. Rath, M., Schleicher, R.: On the Relevance of Auditory Feedback for Quality of Control in a Balancing Task. Acta Acustica united with Acustica **94** (2008) 12–20
13. Rosati, G., Oscari, F., Spagnol, S., Avanzini, F., Masiero, S.: Effect of task-related continuous auditory feedback during learning of tracking motion exercises. Journal of neuroengineering and rehabilitation **9**(1) (January 2012) 79
14. Vogt, K., Pirro, D., Kobenz, I., Höldrich, R., Eckel, G.: Physiosonic - Movement sonification as auditory feedback. In: ICAD 2009. (2009) 1–7
15. Effenberg, A.: Using Sonification to Enhance Perception and Reproduction Accuracy of Human Movement Patterns. In: Internation Workshop on Interactive Sonification 2004. (2004) 1–5
16. Takeuchi, T.: Auditory information in playing tennis. Perceptual and motor skills **76**(3 Pt 2) (June 1993) 1323–8
17. Avanzini, F., Rochesso, D., Serafin, S.: Friction sounds for sensory substitution. In: Proceedings of ICAD 04. (2004) 1–8
18. Effenberg, A., Fehse, U., Weber, A.: Movement Sonification: Audiovisual benefits on motor learning. In: BIO Web of Conferences, The International Conference SKILLS 2011. Volume 00022. (2011) 1–5
19. Karageorghis, C.I., Terry, P.C.: The psychophysical effects of music in sport and exercise : a review. Journal of Sport Behavior **20**(1) (1997) 54
20. Thoret, E., Aramaki, M., Kronland-Martinet, R., Velay, J.L., Ystad, S.: Sonifying drawings: characterization of perceptual attributes of sounds produced by human gestures. In: Proceedings of the Acoustics 2012 Nantes Conference. (April 2012) 23–27

21. Subramanian, S.K., Massie, C.L., Malcolm, M.P., Levin, M.F.: Does provision of extrinsic feedback result in improved motor learning in the upper limb poststroke? A systematic review of the evidence. Neurorehabilitation and neural repair **24**(2) (February 2010) 113–24
22. Avanzini, F., De Götzen, A., Spagnol, S., Rodà, A.: Integrating auditory feedback in motor rehabilitation systems. In: Proceedings of International Conference on Multimodal Interfaces for Skills Transfer (SKILLS09). (2009)
23. Rosati, G., Oscari, F., Reinkensmeyer, D., Secoli, R., Avanzini, F., Spagnol, S., Masiero, S.: Improving robotics for neurorehabilitation: enhancing engagement, performance, and learning with auditory feedback. In: 2011 IEEE International Conference on Rehabilitation Robotics (ICORR). (2011) 1–6
24. Huang, H., Ingallas, T., Olson, L., Ganley, K., Rikakis, T., He, J.: Interactive Multimodal Biofeedback for Task-Oriented Neural Rehabilitation. In: Annual International Conference of the IEEE Engineering in Medicine and Biology Society. (2005) 3–6
25. Mitrovic, D., Klanke, S., Osu, R., Kawato, M., Vijayakumar, S.: A Computational Model of Limb Impedance Control Based on Principles of Internal Model Uncertainty. PLoS One **5** (2010) e13601
26. Knoblich, G., Repp, B.H.: Inferring agency from sound. Cognition **111**(2) (2009) 248 – 262