Continuous Auditory Feedback in a Control Task

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Abstract

A tangible audio–visual interface based on the metaphor of balancing a rolling ball allows the examination of influences of continuous auditory feedback on human control actions. In measurement of control movements under different conditions of sonic feedback significant performance improvements through sound are found. Moreover, different types of auditory feedback, more "realistic" vs. more abstract, are seen to have significantly different influences on task performance and training curves.

Introduction

Background

The notion that sound may convey a seamless flow of information about the state of a system to a human user or operator and thus improve her or his control over, or interaction with, the system, may not be surprising. As an example, one may think about the common experience of driving a car where the continuous sounds of motor, brakes etc. may constantly influence the driver's behaviour. The question however seems to have received few attention as regards dedicated systematic examinations, technical implementations of auditory feedback in control interfaces or even concrete applications.

The *Sounding Object* European research project (SOb) has been dedicated to an enhanced use of the auditory perceptual channel for human–machine interaction, necessary technical advancements as well as underlying research on human auditory perception. In this context *sound models* of everyday sound-producing scenarios, such as of hitting, falling or breaking solid objects, were developed. (Rath 2004) These sound generation algorithms may form a basis for a use of sound in human–machine interaction adequate to the significance of continuous sonic information flows in everyday human environments (see e.g. (Gaver 1993)). They try to overcome the currently common restrictive use of sound almost solely in the form of short, pre-designed, repetitive signals of notification.

User experiments described in the following started off as an evaluation of one of the mentioned sound models, one of rolling interaction of solid objects (Rath 2003), and its capability to spontaneously convey ecological information such as velocity or physical attributes of the involved objects such as size or mass to a user. Results however have a wider psychoacoustic significance as they shed light on processes of auditory perception and the direct exploitation of sonic information in human control movements. These experiments were conducted with the "Ballancer" (Rath & Rocchesso 2005), a tangible audio–visual interface based on the metaphor of balancing a ball on a tiltable track.

Relevance of continuous sonic feedback?

It has been mentioned that sound is so far employed in Human–Computer interfaces mostly in the form of discrete signals of notification. One field where the question of a potential relevance of continuous sonic feedback for human performance in continuous interaction or control is of obvious importance is the one of manual control of robotic systems by a human operator such as in teleoperation tasks. Some work has been conducted dealing with auditory feedback in teleoperation (see e.g. (Apostolos *et al.* 1992)(Lcuyer *et al.* 2002)(Nagai *et al.* 2002)(Liu & Meng 2005a)(Liu & Meng 2005b)), yet it appears that also here discrete signals of notification and warning dominate. Apostolos et al. (Apostolos *et al.* 1992) have conducted an experiment of unbolting an electrical connector screw through a setup of teleoperation with acoustic feedback from microphones in the robot workspace. They found that test subjects concluded the task significantly faster when they were given the acoustic feedback in addition to visual or visual and force feedback. They however didn't systematically examine the nature of the information contained in the sound that is responsible for this noted performance improvement and its exploitation through the sensory–motor system. They report subjects' comments of the audio "indicating precisely when the task was completed", i.e. a noted (by the subject) effect of (temporally discrete) notification, as well as the observation of an "association of the sound with a visual position", i.e. a hint on a continuous information flow in the sound feedback. These remarks are however not deepened or followed further in their contribution. Similar comments may apply to Liu and Meng's experiment of navigating the SONY remotely controlled dog "AIBO" with auditory feedback from microphones in the robot dog's ears (Liu & Meng 2005a).

This question of the possible relevance of continuous information flows through sound for human control actions is the point of focus of the work reported in this paper. A first proof of (statistically) significant optimisation of human control behaviour has been found in an initial study that has been reported in some detail in previous publications (Rath & Rocchesso 2005)(M.Rath 2005)(Rath 2004). The experiment reported in this contribution is intended as a first continuation of this initial work that consolidates and refines the general results. It has so far been completed as a pilot study with only 6 subjects that however already has given statistically significant results. It is currently being continued with 12 additional subjects so that further insights may be expected.

Interaction metaphor and control interface

In his classic experiments on human motor control (Fitts 1954) Fitts uses probably one of the most simple movement tasks to think of, that of moving a stylus from a given starting position into a target area. In this scenario the weight and size of the stylus are negligible with respect to the dimensions of the human body or arm. The stylus can thus be seen as a marker connected to the human body and in this sense Fitts' law applies to human movement as such rather than human interaction with the external world. Human control of an external system often differs from this situation in that inertia properties of the controlled objects are not negligible and body positions may relate more directly to occurring accelerations or velocities rather than controlled positions in the system. The already mentioned example of driving a car with the position of the driver's foot on the gas pedal or brake may serve as an example of this notion. Also, human movement as such usually generates low acoustic feedback and is in its control probably dominated by tactile proprioception [1] under support through visual confrontation of body position with respect to external targets or references. A related but extended metaphor is used here to include true interaction of user and an external system and reach a situation of stronger significance of auditory feedback. These objectives are reached by means of a scenario where the position of the controlling arm is not directly related to that of the controlled object but rather to a parameter of acceleration: in balancing a rolling ball on a track gravity acceleration along the track is approximately proportional to the sine of the angle of inclination which is in turn proportional to the vertical distance of the two hands holding the track. The balancing metaphor thus somewhat isolates "acceleration control" as it is found in many everyday situation, such as in driving a car, where the position of the gas pedal (or brake) is related to the acceleration of the car rather than its position. Also in the latter case of the car the felt feedback force is not directly related to the actually acting forces, and feedback through other sensory channels such as the auditory one gains in importance.

The control interface

Physically, the *Ballancer* consists of a 1m-long wooden control-track that the user, or here: test subject, holds as if balancing a small marble rolling along its upper face (compare the photo of figure 1). This virtual movement of such a controlled ball is simulated by the *Ballancer* software according to the measured angle of the track and the simplified equations of the scenario. The virtual ball is displayed graphically in schematic representations of various size on the computer screen (compare figure 1) and acoustically through the rolling model (Rath 2003).

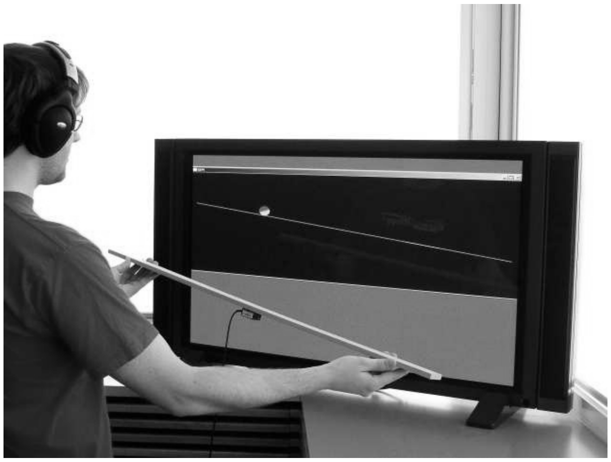

Figure 1: *The* Ballancer *with the large-screen, full-size display.*

Sonic feedback

Two sound models are used to sonify the movement of the virtual ball along the track. The first (Rath 2003), whose development and evaluation also forms the original starting point of the setup of and experiments at the Ballancer, follows a physically-based approach to sound synthesis and generates acoustic feedback that has been shown to represent fairly well the intended scenario of a rolling object (Rath & Rocchesso 2005).

Second, a rather abstract sound model has been derived from the first one in the aim of allowing a possibly clearer expression of the main parameter of interest, the velocity of the moving object, on the cost of losing any realistic connotation of its auditory appearance with a scenario of rolling. This sound model is based on a metaphor of an "ideal record-player-needle", i.e. produces acoustic feedback as if tracing perfectly the profile of the surface along the trajectory of the rolling object. Hereby a sawtooth-shaped surface profile is used, such that the resulting sound is of a clear pitch directly proportional to the velocity of virtual ball and of large bandwidth.

The Experiment

A general task analogous to the one in Fitts' classic experiments is used to examine effects of ecological information

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[1] I here use the really superfluous adjective "tactile" to stress the fact that I'm not referring to any perception of the own body through other senses…

contained in the rolling sound. It consisted of moving (by balancing…) the virtual ball from a resting position at the left end of the balancing-track, held horizontal at the start, into a small target area and stopping it inside here. In the graphical representation the target area was displayed in a lighter colour (see figure 1). Subjects were asked to try and accomplish the task as fast as they could under different conditions of sensory feedback. The movement of the control track (and thereby of the controlling subject) and the controlled virtual ball was recorded, as well as the "task time" needed to conclude the task.

6 subjects participated in this first pilot, four male and two female, all students at Berlin University of Technology aged between 21 and 27. They were asked to perform the described target reaching task under the three different feedback conditions, of

- purely visual, "no sound (*no*)"
- additional acoustic feedback from the rolling model (Rath 2003), "rolling sound (*rs*)"
- additional acoustic feedback from the abstract sound model based on the record–needle metaphor, "abstract sound (*as*)".

The different conditions appeared in *sets* of 20 *games* (trials) each. The order of the sets/conditions was counterbalanced by distributing the $3! = 6$ possible orderings of the 3 feedback conditions across the 6 subjects. The whole series of all conditions was repeated once for each subject so that the whole test consisted of six sets, e.g. for subject 1 of the form: "*rs, as, no, rs, as, no*", subject 2: "*rs, no, as, rs, no, as*"… Due to the repetition of the whole series, each condition appeared twice for each subject, as one set in a less "trained" state and again in "trained" circumstances in the second half of each test. Together with counterbalancing the order of conditions we can thus assume that any training effect during performance of the test should not introduce artifacts in the comparison of performance values at different conditions of feedback measured through all subjects.

Results

As in the initial experiment (Rath & Rocchesso 2005)(M.Rath 2005), subjects on average performed the task faster with sonic feedback than without. Table 1 shows the times subjects needed to complete the task on average — over all subjects and games — under the different conditions of feedback, in the first ("untrained") and second ("trained") series. One interesting new observation with respect to the initial experiment (Rath & Rocchesso 2005)(M.Rath 2005) is the fact that a training effect, i.e. the improvement of performance in doing the task over time — here depicted in line 3 of table 1 is comparatively small with the rolling sound and does not reach a statistical significance of 5%. The training effect is however much higher and about equally strong under the conditions of abstract sound and without sound feedback. In accordance with this phenomenon, average performance in the trained series gets better with the abstract sound than with the rolling sound, while it is best with rolling sound in the untrained series. Table 2 shows a comparison of these different values in the form of relative difference and according statistical significances, i.e. p-values resulting from t-test comparison of the two respective sets of measurements. It can be seen that in the untrained series task performance is significantly faster with rolling sound than without sonic feedback and still faster with abstract sound than without but the latter improvement does not reach statistic significance. In the trained series rolling sound and abstract sound somewhat "switch roles". Of course these interesting first observations will have to be rechecked with a larger set of subjects.

Table 1: "Average task times", i.e. times subjects needed to complete the task on average — over all subjects and games — with rolling sound (*rs*), abstract sound (*as*) and without sound (*no*). The third line shows the relative difference of task times in the "trained" series with respect to the respective "untrained" set of equal feedback condition. Line 4 gives the p-value resulting from t-test comparison of these according sets.

	Average task times (ms)		
	rs	*as*	*no*
"untrained"	7623	8388	9286
"trained"	7149	6613	7366
δ(%)	-6.21	-21.16	-20.67
p	0.261	0.000	0.001

Table 2: Differences in average task times (in %) under the different conditions in the untrained and trained set. Below each difference value the according statistical significance, p, is given.

	Differences in performance, statistic significance			
	"untrained"		"trained"	
	as	*no*	*as*	*no*
rs				
δ(%)	10.04	21.83	-7.50	3.04
p	0.134	0.005	0.141	0.598
as				
δ(%)		10.71		11.40
p		0.183		0.021

Discussion

While an initial experiment at a previous version of the Ballancer (Rath & Rocchesso 2005)(M.Rath 2005) interface had already proven the significance of continuous sonic information for control behaviour the experiment reported here complements the previous results in several points. First, it is seen that the positive influence of additional acoustic feedback is still present even for the full-size large-screen display of the same width as the physical control stick, a graphical structure of the virtual ball that allows the recognition of the rolling movement (compare figure 1) and without any positional information contained in the sound.

The results thus don't leave any doubt that the measured improved performance with sound must be ascribed to velocity information contained in the auditory feedback. It is seen that auditory feedback may allow significant performance improvements even under very good conditions of visual feedback. While these observations may be considered rather refinements of the original results, the recent experiment offers new insights with respect to the different types of acoustic feedback and accompanying effects of training. It is seen that with feedback from the rolling model performance is highest (significantly) for untrained subjects. For the conditions of purely visual display and additional feedback through the abstract sound model a significant effect of training is found, such that after some training performance is strongest with abstract sound (again significant).

As a final remark it shall be said that in the initial study subjects were seen to accelerate and stop the controlled virtual ball more efficiently with sonic feedback, represented by significant differences in the characteristic indices. Figure 2 depicts these phenomena at example data of the initial study. In the recent pilot reported in this publication the same effects could only be assigned statistical significance for the sets of measurements of some single subjects, not for the set of all subjects. This is one of the motivations for our current continuation of the study with more test subjects. The same remark applies to other indices of the experimental data that we are currently analysing, such as the number of oscillations in the movement trajectories of the virtual ball before being stopped inside the target area.

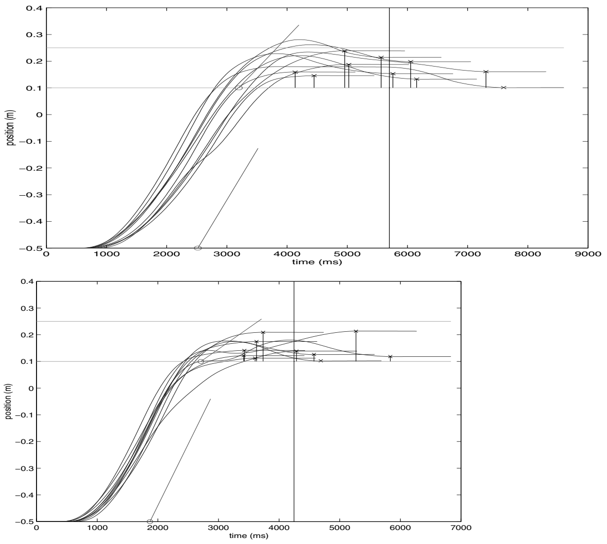

Figure 2: *Twenty trials of one subject, above without, below with sound. The maximum velocity, indicated by the first (lower) rising red line, is in average reached earlier with sound. Simultaneously the ball enters the target area with lower average velocity, as seen from the less steep second (upper) red line, and the task is completed faster.*

References

Apostolos, M.; Zak, H.; Das, H.; and Schenker, P. 1992. Multisensory Feedback in Advanced Teleoperations: Benefits of Auditory Cues. In *Proceedings of the Sensor Fusion V, SPIE Vol. 1828*, 98–105.

Fitts, P. M. 1954. The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology* 47:381–391.

Gaver, W. W. 1993. What in the world do we hear? an ecological approach to auditory event perception. *Ecological Psychology* 5(1):1–29.

Lcuyer, A.; Megard, C.; Burkhardt, J.; Lim, T.; Coquillart, S.; Coiffet, P.; and Graux, L. 2002. The effect of haptic, visual and auditory feedback on an insertion task on a 2-screen workbench. In *Proceedings of Immersive Projection Technology Symposium (IPT).*

Liu, P. R., and Meng, M. Q.-H. 2005a. Acoustic display for navigation in internet based teleoperation. In *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 05)*, 2181–2185.

Liu, P. R., and Meng, M. Q.-H. 2005b. Acoustic display for navigation in internet based teleoperation. In *Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 05)*, 2181–2185.

M.Rath. 2005. Gestural exploitation of ecological information in continuous sonic feedback — the case of balancing a rolling ball. In *Proceedings of the 8th International Conference on Digital Audio Effects (DAFx'05)*, 98 – 103.

Nagai, Y.; Tsuchiya, S.; Iida, T.; and Kimura, S. 2002. Audio feedback system for teleoperation experiments on engineering test satellite vii system design and assessment using eye mark recorder for capturing task. *IEEE Transactions on Systems, Man and Cybernetics, Part A* 32:237–247.

Rath, M., and Rocchesso, D. 2005. Informative sonic feedback for continuous human–machine interaction — controlling a sound model of a rolling ball. *IEEE Multimedia Special on Interactive Sonification* 60–69.

Rath, M. 2003. An expressive real-time sound model of rolling. In *Proceedings of the 6th "International Conference on Digital Audio Effects" (DAFx-03).*

Rath, M. 2004. *Interactive Realtime Sound Models for Human–Computer Interaction — A Sound Design Concept and Applications.* Ph.D. Dissertation, Department of Computer Science, University of Verona. available online under <http://www.di.univr.it/dol/main?ent=pubbdip>, "research reports".

The Sounding Object (SOb). European research project (IST-25287, < http//:www.soundobject.org >) as part of the *Disappearing Computer (DC)* proactive initiative (< http://www.disappearing-computer.org/ >).