GESTURAL EXPLOITATION OF ECOLOGICAL INFORMATION IN CONTINUOUS SONIC FEEDBACK — THE CASE OF BALANCING A ROLLING BALL

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ABSTRACT

Continuous sensory–motor loops form a topic dealt with rather rarely in experiments and applications of ecological auditory perception. Experiments with a tangible audio–visual interface around a physics-based sound synthesis core address this aspect. Initially dealing with the evaluation of a specific work of sound and interaction design, they deliver new arguments and notions for non-speech auditory display and are also to be seen in a wider context of psychoacoustic knowledge and methodology.

1. INTRODUCTION

The last decades have seen an overdue [1] but increasing recognition of, and interest in, sound as a source of information about our surroundings, perceived by the human auditory system[1]. A number of works have been occupied with questions of auditory perception of ecological attributes such as classes of everyday events (e.g. [2]), size of interacting objects (e.g. [3][4]) or material (e.g. [5]) etc.. In this field of research, a certain dominance can be spoted of experiments of comparisons of seperate discrete stimuli; hardly examined have been phenomena of continuous flows of information throughout the temporal extension and development of one continuous stimulus. At the same time, and this is surely a systematic coherence, evaluation of perceptual reactions is usually achieved through collecting discrete responses of test subjects, as in questionaires or rating or scaling tasks. Behind this remark lies a more principal problem in the examination of perceptual mechanisms: most psychoacoustic experiments rely on conscious reactions or answers of subjects — perceptual processes may however be in principle of unaware nature. Experiments based on conscious reaction provoke and rely on a chain of selfobservation and cognitive reflection of the experimental task (or request), which generally introduce sideeffects that put into question the value of the experimental responses in the light of the actual point of interest. It may occur that unconscious perceptual mechanisms generally resist any assessment relying on conscious selfobservation.

The experiment reported in this article sheds some concrete light on the previous general thoughts and exemplifies an approach of psychophysical examination that overcomes the described problems. By having subjects perform a task of gestural control, a "game", derived from a prototype of human interaction with the everyday world, and through registration and examination of their control movements under different sensory frame conditions, conclusions about perceptual processes can be drawn without interposition of conscious questions, reactions and introduction of related artefacts. The experiment is performed at the *Ballancer*, a tangible audio–visual device around a kernel of physics-based sound synthesis, whose development [6] resulted from notions of synthesis and exploitation of ecologically informative, *continuous* sonic feedback [7][8], parallel to the thoughts mentioned above. The following work thus initially forms an evaluation of the success of the design of the *Ballancer* and its underlying sound model but should be seen in a wider psychoacoustic context as described.

[1]...after a long tradition of psychoacoustic research focussing on abstract sound properties,

2. THE EXPERIMENT

2.1. The interface

The device used for the experiments described in this paper, the *Ballancer*, is based on a realtime sound model of rolling [9] and the control metaphor of balancing a ball on a tiltable track. The user, or here: test subject, holds a 1m–long wooden control-track as if balancing a small marble rolling along its upper face (compare the foto 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 a schematic representation on the computer screen and acoustically through the rolling model. Figure 1 depicts the use of the device. Details of the technical realization and the fundamental notions and motivations behind the development of the *Ballancer* are described in a dedicated overview article [6]. Another special paper [9] describes the architecture of the sound model of rolling.

2.2. Velocity information from sound?

As described in detail in previous articles [6][7], the general goal of the design of the *Ballancer* and the underlying sound model of rolling is the intuitive expression of ecological attributes through sound and the reactive dynamic behavior. The experiment reported here focusses on the specific parameter of the velocity of a rolling object. It is hypothesized that the (modelled) sound of the rolling object can convey information about the velocity of the virtual rolling ball in a more direct way and with higher perceptual resolution than the visual display. The most obvious way to assess this aspect would probably be by addressing subjects in direct questions about their perception of different stimuli, such as conventionally done in rating or scaling tasks. But this approach has the general disadvantage of possibly introducing artefacts by forcing conscious choices and reactions. As already remarked (section 1) it has to be assumed that mechanisms of perception may also be of unaware nature and can thus not be examined without bias through methods relying on conscious reaction. The following test is therefore based on a different strategy. In order to uncover perceptual mechanisms subjects are asked to perform a specific control task under different conditions of sensory feedback — without being given any information about the underlying scope in question. Possible differences in control behavior under different feedback conditions allow conclusions about perceptual mechanisms without influences of conscious reflection, knowledge or reaction.

2.3. The task

The task used to examine an effect of velocity information contained in the rolling sound consisted of moving (by balancing…) the ball from a resting position at the left end of the balancing-track, held horizontal at the start, to the target area of 15cm length slightly right of the middle of the track, and stopping it inside here. On the mechanical representation, the target area is marked with black adhesive tape (as seen in the photo of figure 1); its boundaries were located 10cm and 25cm right from the center, i.e. 60cm and 75cm from the left end of the track. In the graphical representation the task area was displayed in a lighter color (see figure 1) and acoustically through a different, rougher, slightly riffled, surface structure. Subjects were asked to try and accomplish the task as fast as they could and the movement of the control track (and thereby of the controlling subject) was recorded, as well as the "task time" needed to conclude the task.

2.4. Preparatory thoughts

Informal experience of the author and few other informal test subjects with the *Ballancer* had suggested that the control of the ball with active full–screen graphical display would not get notably easier or more efficient with additional sonic feedback from the rolling sound. On the other hand the target–reaching task showed to be generally solvable with purely auditory feedback. Since the control task further on naturally becomes more difficult and finally unsolvable for decreasing display sizes it was thus concluded that for displays below a certain limit size sonic feedback should help in performing the task.

Figure 1: *The* Ballancer *with the graphical display spanning the whole 21" monitor (display factor 12). The photo was taken during use of the device in a game application, thus the lighter target area on the screen is not in the same fixed position as during the performance task described here (slightly right from the middle, according the black mark on the mechanical track). Also, the real glass marble on the track only serves demonstration purposes in the photo.*

2.5. Experimental design

In individual sessions, the ten subjects were asked to perform the task described above (2.3) under different conditions of sensory feedback described below, and told to try and be as fast as possible. Subjects were not informed anyhow about their measured times needed in the trials, in order to minimize effects of conscious adaptation to the test conditions and isolate the effects of mechanisms applied by the subjects without awareness, trying to optimize (subjectively) their performance. Movements of control and ball, i.e. the changing angle of the rolling-track and the position of the (virtual) ball during trials, were recorded for later analysis.

Feedback about the movement of the virtual ball during the trials was given acoustically through sound from the rolling model [9] played over stereo headphones, and/or visually on the computer screen, as a schematic representation of the ball on the track (see figure 1). The graphical display, with the ball represented as a monochrome (red) sphere on a line representing the track and the target area marked by a different color (light green), was realized in 3 different sizes. Scaling factors for graphical display were ranging from 1, with the track horizontally filling the whole 21" computer screen (as in figure 1), to $1/3$ and $1/6$ of this size.

Each test started with 2×10 training runs (10 plus "pause" plus 10) with the largest display ("full screen", scaling factor 1) and sound feedback, to minimize possible training effects. Subjects were told that these first 20 trials could be used to get familiar with the setting and practice the task. In the following runs, the needed time was measured with display sizes of 1, $1/3$, $1/6$ and 1 (in this fixed order); again 20 measurements were made for each size, 10 times with and 10 times without sonic feedback. The order of the measurements "without–with sound" resp. "with–without" was switched after half of the subjects to test for, and eventually counterbalance, an effect of the order of performance on the results. At each change of the display size subjects had a short rest [2] and were afterwards given an additional 3 trials to warm up under the new conditions before the start of the actual measurement. Finally, the display was fully closed and subjects were asked to try and perform the task only with sonic feedback.

3. RESULTS

3.1. Task performance times with and without additional sonic feedback

Quite surprising after the preparatory considerations and informal expectations described above (2.4) is the first main result of the performance experiment: *For all display sizes*, the average time needed to perform the task improves significantly with the auditory feedback from the model. Table 1 shows the *average task times* for individual subjects (1, 2, …, 10), the two groups (1 – 5 ≙ "with sound first", and 6 – 10) and the set of all subjects (1 – 10) at the various display sizes, with and without sound. The two respective neighboring columns contain the relative difference, "no sound" to "with sound" (in %, δ) and the statistical p-value for the

[2] A short pause was needed by the experimenter to adjust the new display (and other connected) settings.

sub-ject(-s) no.	average task time (ms) at various display sizes, with (+) and without (–) sound, percentual difference (δ) and statistical significance (p)											
	scale factor 1				scale factor $1/3$				scale factor $1/6$			
	+	–	δ (%)	p	+	–	δ (%)	p	+	–	δ (%)	p
1	6206	6828	10.0	0.282	7041	8437	19.8	0.276	7313	8441	15.4	0.323
2	4257	4295	0.9	0.933	4706	4370	−7.1	0.460	4539	5621	23.9	0.042
3	5795	7351	26.8	0.067	7009	9455	34.9	0.137	6782	8457	24.7	0.264
4	4767	5262	10.4	0.222	5009	6114	22.1	0.082	5599	6965	24.4	0.083
5	5908	5288	−10.5	0.433	6074	5480	−9.8	0.473	6551	7479	14.2	0.446
6	5478	5289	−3.4	0.701	4246	5700	34.2	0.004	5631	8291	47.2	0.027
7	4592	4599	0.1	0.987	4523	4685	3.6	0.741	4994	5668	13.5	0.314
8	5175	5516	6.6	0.554	6143	6430	4.7	0.732	6615	7844	18.6	0.513
9	5132	6846	33.4	0.037	6131	7241	18.1	0.298	8451	7793	−7.8	0.551
10	4862	5475	12.6	0.244	5558	5650	1.7	0.902	5446	6273	15.2	0.416
1 – 5	5387	5805	7.8	0.203	5968	6771	13.5	0.135	6157	7392	20.1	0.015
2 – 6	5048	5545	9.9	0.063	5320	5941	11.7	0.086	6228	7174	15.2	0.095
1 – 10	5217	5675	8.8	0.031	5644	6356	12.6	0.029	6192	7283	17.6	0.004

Table 1: *Average times needed to complete the "target matching"-task at the various display sizes, with and without sound. The additional columns contain the relative difference of the values δ, "without sound" to "with sound" in % and the statistical p-value for the two compared groups of measurements.*

according set of measurements. Relative differences with p-values of (≤ 0.05) or near (≤ 0.1) statistical significance are underlined. It can be seen that the average task time for the set of all subjects as well as for both subgroups improves (i.e. gets shorter) with the auditory feedback for all display sizes, corresponding to only positive δ-values (task time is longer without sound) in the last 3 lines (of table 1). These performance improvements, ranging from around 9% for the largest to around 18% for the smallest display, are always statistically significant for the whole set, while they reach statistical significance for the subgroups only for the smaller displays. Since significance is reached for the whole set of subjects, it can be expected that it would be found also for both subgroups, i.e. independently of the order of presentation with a sufficiently large set of measurements, using more subjects or more trials per subject.

Individual cases, (10–trial-) sets of single subjects at a fixed display size, that contradict the general performance improvement are easily recognized as negative δ-values in table 1. It is seen that all these (rather few: 5 out of 30) cases of decrements of performance with sound are not statistically relevant, which justifies the expectation that these outliers are not systematic [3] and would tend to decrease in number and level with longer testing sessions. On the other hand, all individual differences of, or close to, statistical significance (underlined in table 1) are positive δ-values, i.e. cases of improved performance with sound.

The slightly stronger performance improvement for group 2 at the largest display size (scale factor 1) together with the smaller p-value, 0.0063 versus 0.203, might suggest that despite the training session of 2×10 trials we still have a slight learning effect that amplifies the positive difference of performance for group 2 and diminishes the effect for group 1. A direct comparison of the performances however, shows no significant difference between the results of the two groups, i.e. no significant influence of the order of presentation: Table 2 presents again the average task times for groups 1 and 2 in flipped orientation with the according p-values (well above 0.05).

[3] ...i.e. not consistent signs of any regular mechanism of control behavior,

	average task time group1	average task time group2	p
+ sound	5387	5048	0.209
– sound	5805	5545	0.425

Table 2: *Average time needed by subjects 1 to 5 and 6 to 10 to complete the task, with and without sound, and the statistical significance.*

3.2. Mechanisms of performance improvement?

The results presented in the previous section (3.1) are strong arguments for the potential of auditory display to support human–machine interaction. Of course the question arises of what responsible perceptual or sensory–motor mechanisms stand behind this measured preformance improvement. One motivation behind the development of the rolling model and *Ballancer* has been the conveyance of velocity information through the sound. It is thus important to ask if the found phenomenon is really explainable by, and even a proof for, the perception and exploitation of (additional) velocity information by the human sensory–motor system. In particular must we consider the possible hypothesis that the average time to complete the task is shorter with sound, only because the controlling subject is additionally notified acoustically when the ball enters the target area, through the change in the rolling sound. If this was the case, the dynamic quality of the sound feedback might appear as irrelevant for user performance; even more, no continuous sound feedback at all (at least outside the target area) might be necessary to gain the same auditory support of performance, just a short notification "ping" at the moment of entering the target area might have the same effect on the task times. It is therefore relevant to ask if the sonic feedback has an optimizing influence on the control movements already before the ball enters the target area. As no immediate clue in this respect is found just from a direct look at the graphs of measured movements — figure 2 depicts the situation — several indices are developed, whose derivation and analysis is described in the following.

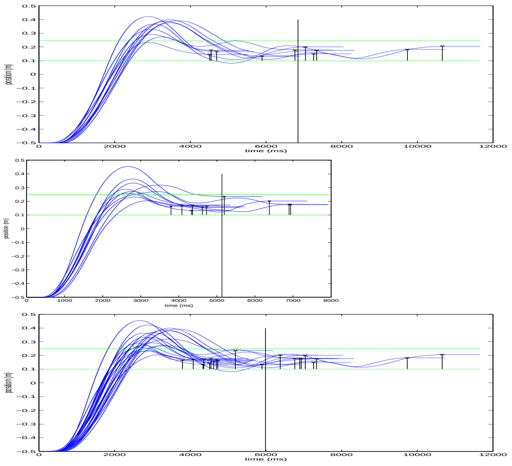

Figure 2: *Trials of subject* 9 *at the largest display, without sound (*10*, above), with sound (*10*, below, left) and all* 20 *trails (below, right). Clear, quantifiable mechanisms responsible for the improved average performance are not found from such overviews. In particular, the two groups of trials, with and without sound can not be separated in the (lower) overall view.*

3.2.1. Target reaching times *and* Maximal velocity

Searching for possible systematic differences in the behavior of control and ball before the target area is reached, the probably most obvious first step is to survey the times for the virtual ball to reach (enter) the target area from its starting position, the "*target reaching times*". The dash-dotted black line in figure 3 represents this index. Extracted values are not clearly revealing in themselves, so they are not displayed here; only the main observations are sketched. (Detailed results and discussion can be found in [7].) It was found that the average *target reaching time* for the

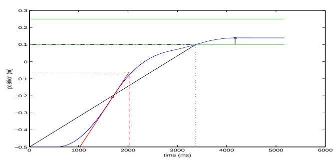

Figure 3: Target reaching time *(ms, black dash-dotted line), average velocity and maximal velocity (m/s, length of the red dash-dotted line) for one example trial.*

set of all subjects does not significantly (statistical p-values between ca. 0.25 and 0.95) change with or without sound for any display size. However, statistically significant differences of average *target reaching time* with and without sound were found for several single subjects. In contrast to the overall averages, these individual cases form a hint that the sonic feedback may have a systematic influence on control behavior already before the target is reached. The partly opposite behavior of these significant individual changes — i.e. shorter times with sound for some, longer for other subjects — within both subgroups 1 and 2, contradict the suspect of a pure effect of order of presentation, i.e. of a training effect.

The *target reaching time* t_{target} defined above is in each trial equivalent (exactly: antiproportional) to the ball's average velocity $\bar{v} = 0.6\text{m}/t_{\text{target}}$ before reaching the target area (see the black triangle in figure 3). Another similar value to observe for the ball moving towards the target area is the maximum velocity that it reaches along the way (compare figure 3). Average values extracted from the measurements are again not displayed or discussed in detail here since they show a behavior of similar quality as the *target reaching times* [4]: the average maximum velocity of the ball before reaching the target area for the set of all subjects is only slightly (relative difference between -2% and 1.5%), and not significantly (by far: p-values between ca. 0.55 and 0.95), different with or without sonic feedback. Again, some contradicting individual cases of significant differences seem to hint on systematic influences of the sonic feedback on subjects' control behavior through the whole phase of the task, also before the target area is reached.

Summing up the observations so far, certain hints but no clear picture of the influence of the continuous sonic feedback and its connection to the performance improvement is not gained from observing *target reaching times* and *maximum velocities*. In the wish to reveal mechanisms of perception and cognition involved in the course of the experiment further examinations are necessary.

3.2.2. Differences of movement with and without sound

While the survey of maximum velocities was not really revealing, the first clear statements about an influence of the continuous sonic feedback on the control movements while solving the task can be made after the extraction of the *time at which* this maximum velocity of the ball (before reaching the target area, as measured from the start of each trial) occurs. In figure 3 this is the temporal location of the red cross, referred to in the following as "*max. velocity time*". From table 3 holding the results (in the previously used format) it can be seen that in average over all subjects the ball reaches its maximum velocity earlier when the controlling subjects receive sonic feedback. This effect is present for all display sizes and always clearly significant (for the whole group). It is further seen that all individual cases (single subjects in table 3) of statistic significance [5] are supporting the rule, i.e. cases of earlier reached maximum velocity — subject 3 at display factor $1/6$ is the only exception (out of 12 significant cases for the three largest displays). Vice versa, all other (than the latter) outliers, negative δ-values are not significant.

Summing up "in plain words" the observed *max. velocity times*, it can be said that subjects tend to accelerate the ball faster when they also *hear it*. More exactly, what I call "faster acceleration" is not simply a side effect of an overall faster movement since the maximum velocity itself was seen not to change significantly in average. It is seen that subjects use the additional information at their disposal in the sound to optimize their control movement. In particular, the phenomenon of more efficient acceleration shows that the continuous sonic feedback outside the target area *does* have an influence on performance and can surely not be

[4] I again refer to [7] for details.

[5] . . . or even all cases close to significance, underlined p-values,

sub-ject(-s) no.	average max-vel.-time (ms) at display size, +/– sound, δ, p: 1				1/3				1/6			
	+	−	δ (%)	p	+	−	δ (%)	p	+	−	δ (%)	p
1	1772	1927	8.8	0.055	1875	1840	−1.9	0.656	1667	1776	6.5	0.243
2	1446	1330	−8.0	0.375	1333	1516	13.7	0.091	1641	1701	3.7	0.620
3	2282	2210	−3.2	0.686	2453	2646	7.9	0.446	2411	2101	−12.9	0.038
4	2306	2440	5.8	0.311	2058	2389	16.1	0.003	2046	2242	9.6	0.012
5	2103	2137	1.6	0.799	1819	1910	5.0	0.257	1723	1929	11.9	0.094
6	2340	2432	4.0	0.584	1870	2519	34.7	0.000	2167	2323	7.2	0.322
7	1548	1649	6.5	0.589	1441	1613	11.9	0.151	1605	2045	27.4	0.044
8	1987	2260	13.8	0.060	2510	2436	−3.0	0.754	1963	2063	5.1	0.606
9	1547	1854	19.8	0.001	1461	1659	13.5	0.023	1756	1946	10.8	0.131
10	1642	2184	33.0	0.020	1658	1841	11.1	0.110	1873	1937	3.4	0.538
1 – 5	1982	2009	1.4	0.767	1907	2060	8.0	0.120	1898	1950	2.7	0.454
6 – 10	1813	2076	14.5	0.005	1788	2013	12.6	0.024	1873	2063	10.1	0.014
1 – 10	1897	2042	7.6	0.027	1848	2037	10.2	0.007	1885	2006	6.4	0.020

Table 3: *Averages of the time values at which the ball reaches its maximum velocity before entering the target area. Columns are of the same format as in previous tables.*

substituted by a short momentary notification signal. Naturally, more efficient acceleration in the beginning of the control task will lead to faster task completion if the gained temporal benefit is not lost later in the movement. The latter can be assumed, since the maximal velocity (in average) is not influenced through the sonic feedback. It can thus be claimed that one, first reason for the better task-performance with sound has been found.

After the previous results of improved motion of acceleration with sonic feedback it is obvious to ask whether subjects also use the additional information in the rolling sound to optimize their movement while finally stopping the ball (or trying to…). Also, from the earlier (section 3.2.1) observation of unchanged average (overall) *target reaching times*, the presence of another systematic change in control movements while the ball is approaching the target can be deduced: if the improved task performance found its sole cause during the acceleration-phase, parallel significant changes in *target reaching times* as in the average task performance times should be found. With the aim of gaining more information about the stopping-movement, the velocity of the ball at the moment of entering the target area, referred to in the following as "*entry velocity*" is extracted from the recorded trajectories. Average values for the two groups and the set of all, subjects at the various display sizes with and without sound are shown, in table 4. It is seen that in average over all subjects the ball enters the target area slower when auditory feedback is present. This difference of average *entry velocity* with and without sound is statistically significant for all display sizes but the largest. [6] Again significant differences are found also for several individual cases (not displayed in table 4 for reasons of space, please refer to [7]), all of which support the overall rule and are highly above average in their value.

How, if at all, is this lower average *entry velocity* related to other previously noted effects of sonic feedback, in particular to performance improvement, i.e. shorter average task times? Generally, it can be said that for fast task performance it is desirable to stop the ball possibly shortly after it has entered the target area. To that end, any action aimed at stopping the ball should start already while approaching the target area. Starting from a fixed velocity outside the target area and assuming a given, fixed stopping-trajectory, task performance gets better, the closer to the left target boundary (after entering) the ball comes to rest; i.e. the slower the ball enters the target area, and vice versa. From the average values in table 4 (lowest line), it has to be assumed that generally subjects exploit the additional information available from the rolling sound to optimize their stopping-manoeuvres in the sense just stated. With sonic feedback, in average subjects appear to be able of stopping the ball earlier without increased risk of "stopping too early". This is the first notion suggested by the parallel phenomena of improved task performance and slower *entry velocities* with auditory feedback. The latter idea can also serve to explain why improved task performance overall is not connected to shorter *target reaching times*, as asked in the beginning of this paragraph: earlier stopping-motion with the ball coming to rest earlier after entering the target area can also increase the time span of reaching the target area. Such an effect would counteract the "headstart"-effect of more efficient acceleration with auditory feedback.

3.2.3. Summary

From the previous considerations the following picture is gained of how the movement of control and thus of the ball during the task changes when auditory feedback is added: In average, subjects use the additional information about the reaction/motion of the controlled ball conveyed through the sound, to optimize their control movements such that the ball **1.** accelerates faster in the beginning and reaches its maximum velocity earlier and **2.** slows down earlier, indicated through lower average *entry velocity* and stops earlier after having entered the target area. As a side-effect, the *target reaching time* stays basically unchanged in average, while task performance times improve with sound. The overview of results of subject 6 at display size $1/3$, figure 4, (a) with and (b) without

[6] With the general difference of averages for the largest display not far from values of other display sizes, one statistically relevant individual case (see the following lines) and a overall p-value of 0.156 it is reasonable to believe that statistical significance could be reached for a larger set of subjects.

sub-ject(-s) no.	average entry velocity (mm/s) at display size, +/– sound, δ (%, p)											
	1				1/3				1/6			
	+	–	δ (%)	p	+	–	δ (%)	p	+	–	δ (%)	p
1 – 5	263	304	15.6	0.136	308	310	0.5	0.958	266	325	22.3	0.081
6 – 10	229	246	7.8	0.562	195	286	46.8	0.001	183	222	21.3	0.088
1 – 10	246	275	12.0	0.156	251	298	18.5	0.032	225	274	21.9	0.022

Table 4: *Average velocity of the ball at the moment of entering the target area. The format is identical to previous tables.*

sonic feedback serves well to exemplify the proposed principle. Of course this picture is to be seen as a model for the average tendency of control movements, not as an exhaustive strict rule.

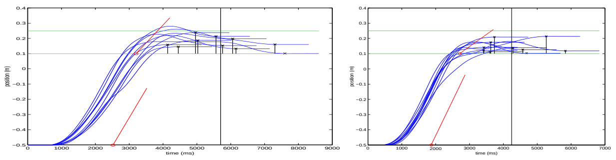

Figure 4: *Overview over the ten trials of subject* 6 *at the second largest display, above without (left), below with sound (right). With sonic feedback, in average the maximum velocity is reached earlier, the ball enters the target area with lower average velocity and the task is completed faster.*

3.3. Purely auditory feedback

All 10 subjects were able to perform the task with purely auditory feedback only. This fact is of interest in the light of possible applications of the *Balancer* interface and idea for the support of users with special needs. It would surely be interesting to plan and execute more thoroughly, comparative measurements with purely auditory and purely visual feedback in future tests. A deeper analysis of control movements in those two cases might further support the general insight from the tests, that subjects perceive and exploit different information through the two different sensory channels — visually mainly position, velocity auditorilly — and possibly reveal more details.

4. CONCLUSIONS

The results of the experiment and their analysis, reported in this article, demonstrate the intuitive (in the sense of without preliminary explanations and training) perception and exploitation (in optimized control movements) of continuous sonic feedback. They prove the success of the design of the used sound model of rolling [9] and the tangible interface with a simple everyday control metaphor as its basis. The work presented gives an example and strong new arguments for the use of ecologically-based sonic feedback in human–computer interaction. It also forms a wider contribution to psychoacoustic knowledge, as effects of performance improvement and optimization of control gestures through continuous acoustic information, comparable to the ones of this experiment, don't seem to have been demonstrated nor systematically examined before.

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