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# An Experiment on Length Perception with a Virtual Rolling Stone

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## ABSTRACT

When an object rolls or slides inside a hand-held tube, a variety of cues are normally available to estimate its location inside the cavity. These cues are related to the dynamics of an object subjected to the laws of physics such as gravity and friction. This may be viewed as a form of sensorymotor coupling which does not involve vision but which links motor output to acoustic and tactile inputs. The theory of sensorymotor contingency posits that humans exploit invariants about the physics of their environment and about their own sensorymotor apparatus to develop the perception of the outside world. We report on the design and the results of an experiment where subjects held an apparatus that simulated the physics of an object rolling or sliding inside a tubular cavity. The apparatus synthesized simple haptic cues resulting from rolling noise or impact on internal walls. Given these cues, subjects were asked to discriminate between the lengths of different virtual tubes. The subjects were not trained at the task and had to make judgments from a single gesture. The results support the idea that the subjects mastered invariants related to the dynamics of objects under the influence of gravity that they were able to use them to perceive the length of invisible cavities.

**Keywords:** haptics, sensorymotor contingency, gravity invariants, perception.

## 1 INTRODUCTION

The experiment described in this paper was inspired by the ball catching experiments of McIntyre et al. and Senot et al. [6, 15]. They showed that subjects exposed to a variety of distortions of sensory inputs including the removal of gravity, or the up-down inversion of their retinal image, maintained a surprisingly robust, pre-establish notion of gravity that was manifest in their anticipatory motor behavior. We were also inspired by the work of Lenay et al. who attached a photo detector and a vibrotactile stimulator to one finger of blindfolded subjects and placed a bright point light source in their vicinity [4]. The system was so rigged that when the photo detector was pointing in the direction of the light source, the subjects experienced a single-pulse vibrotactile sensation. The authors report that during free exploration, typically, subjects progressively developed the perception of a distal, exterior object, that is, one which was not in contact with the skin.

O'Regan and Noe's theory of sensory-motor contingency provides us with a framework to investigate this type of phenomena [8]. A simplified account of this theory holds that perception arises when an organism discovers pre-existing invariants about the world and about itself and learns how to use them, something the authors call a *sensorymotor law* [9, 10]. In Lenay's experiment, the invariant was determined by the geometry of the propagation of light and by the *sensorymotor coupling device*, the properties of both of which were *a priori* unknown to the subject. It is easy to show that only one location of the source could explain a highly reliable correlation between specific finger pointing directions and the occurrence of a tactile pulse, hence the "exteriorization" of the stimulus as anticipated by Katz (see [2], "vibration has many of the capabilities of a far sense"). Robles-De-La-Torre and Sekuler showed that people could rapidly discover dynamic invariants despite the presence of an abstract and highly impoverished sensorymotor coupling [13].

In McIntyre's et al. experiments, gravity participated in the invariant behind the sensorymotor law linking visual input to hand movement, and eventually to the sensation of the ball hitting the hand. It is natural that learned gravity-related invariance in humans (and probably in most animals) be extraordinarily resilient to drastic perturbations of the sensorymotor couplings given the pervasiveness of gravity from the day we are born. It is also critical for survival that gravity and associated invariants be precisely established.

## 2 AN INTERESTING SENSORYMOTOR TASK

It will be easier for the reader to understand our experiment if she is kind enough to get hold of a tube, to place a small round object inside it and close the ends. It could be something as small as a drinking straw with a rice grain inside, but a cardboard tube to transport posters with a small wood, rubber, or metal ball will be more compelling. The reader can then appreciate how effortlessly she can predict the instant of collision between the ball and the cap. This is especially true if the eyes are kept open, although vision provides information about the tube but not about the object. Since the moving ball is not seen, predicting its collision entails estimating its position at all times. This requires solving its equation of motion from known initial conditions.

Since Galileo, we know that a ball rolling down a ramp inclined by angle $\alpha(t)$ travels a distance

$$d \approx d_0 + k \iint_0^T \sin\alpha(t)\, dt^2. \qquad (1)$$

This expression is independent from the mass of the objet if we ignore losses and neglect the acceleration due to the change of angle. Two cases arise in the experiment just described.

Either the subject has access to $d_{\text{cavity}}$, the length of the cavity, say by seeing and touching the tube (which is another thorny sensory motor problem! Let's assume this problem to be solved), and the subject must solve the above equation for $T$ to predict the collision. Evidently, the problem is simplified if the subject keeps the tube at a constant inclination, in which case there is a simple expression for $T$. The task corresponds to the solution of an inverse problem, provided that $k$ was known from another inverse problem.

A second experimental condition is created when the distance $d_{\text{cavity}}$ is unknown from the subject, for example if an experimenter placed invisible walls inside the tube to limit the travel of the ball. The task is then to guess the distance over which the object is limited to travel. This is feasible only if the subject can solve a direct problem where the unknown is $d_{\text{cavity}}$ as well as an inverse problem for $k$. It is the case that we investigate in this paper because testing subjects is simple since the task is to guess the rolling length.

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## 3 A MORE DETAILED ANALYSIS

### 3.1 Physics

The constant $k$ in Eq. (1) takes specific values according to the mass distribution of the rolling object. Write $L = mgh + \frac{1}{2}m\dot{x}^2 + \frac{1}{2}I\dot{\theta}^2$, where $x$, $\theta$, and $h$ are the position, angle, and height of the object, $m$ and $I$ are its mass and moment of inertia, and $g$ is the intensity of the gravity field. If $r$ is the rolling radius then $dx = r\,d\theta$, and Lagrange's equation gives $k = g/[1 + I/(mr^2)]$. Without learning, this can make the sensorymotor tasks described in the previous section very difficulty indeed. For instance, Figure 1a shows a rolling object designed to have a malicious behavior. The rolling radius $r$ is such that $I/(mr^2)$ is a number much greater than 1. On the other hand, the case of solid ball, Figure 1b, is such that $1 + I/(mr^2) = 1.4$ since $I_{\text{ball}} = \frac{2}{5}mr^2$. This case is admittedly very common to us (marbles, pinball machines, and golf balls) and is, again, invariant with mass. Later in our simulations, we will make a virtual rolling ball obey:

$$\ddot{x} = \frac{g}{1.4}\sin(\alpha(t)) \approx 7.0\sin(\alpha(t)). \tag{2}$$

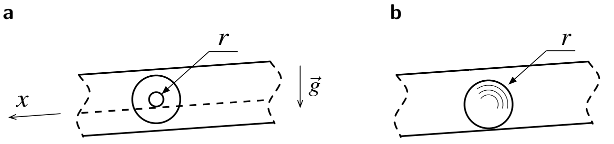

Figure 1: **a**) Unusual case. **b**) Usual case.

Another case of related interest is that of an object sliding down the tube. Assuming that both Coulomb's and Amonton's laws are good enough to apply, if $\mu$ is the coefficient of friction between the two sliding surfaces, then the object's motion is governed by

$$\ddot{x} = \begin{cases} g[\sin(\alpha(t)) - \mu\,\text{sgn}(\dot{x})\cos(\alpha(t))], & \text{if } \tan(\alpha(t)) > \mu \\ 0 & \text{otherwise.} \end{cases} \tag{3}$$

This is still invariant with mass but now at least one additional unknown quantity, $\mu$, participates in the resulting displacement of the invisible object. Without prior knowledge this makes the task of finding the sliding length more difficult.

### 3.2 Cues

During tasks with a ball rolling inside a tube a variety of acoustic and haptic cues are available to the subject. First, rolling causes the tube to vibrate, yet not periodically since the ball's velocity is generally not constant. The pseudo-period of the vibration, or its spectrum, which can be felt and heard, is related to the ball's velocity. But velocity cannot be directly observed given the many unknown factors contributing to the signal. Nevertheless, it is plausible that this signal can be processed to estimate the change of velocity, i.e. the acceleration, by autocorrelation in the time domain or by spectral shift estimation. A second basic cue is the plain duration of the roll which is also a bimodal cue. A third bimodal cue is the intensity of the impact felt when the ball hits the wall. The energy dissipated by an inelastic collision is $E_{\text{loss}} = \frac{1}{2}mv_a^2(1-e^2)$, where $v_a$ is the approach velocity of the ball just before it hits the wall and $e$ the coefficient of restitution. The product $\frac{1}{2}m(1-e^2)$ is another invariant that may be estimated after several trials to eventually give access to $v_a$ from which $d$ can deduced. A fourth cue that is purely haptic is the transfer of weight caused by the movement of the ball. It can be subtle or prominent according the relative masses of the tube and the ball. Other monomodal or bimodal cues probably exist, such as the intensity of the vibration growing with the ball's velocity, that are probably exploited during the tasks described. For the case of an object sliding without rolling, access to the change of velocity through spectral shift no longer is available or in a greatly weakened form, but the other three cues remain.

In all cases subjects must have also access to the angle $\alpha(t)$. Interestingly, it is likely that they can estimate it from at least four distinct sources of information. The first are motor commands issued to incline the tube at a desired angle, the second are proprioceptive cues arising from the posture of the entire body, including limbs and extremities, the third are visual cues allowing the subject to compare the viewed tube with surrounding structures, and the fourth is the static loading caused by the tube which may be picked up proprioceptively or cutaneously and which is proportional to $\cos(\alpha(t))$. It is also plausible that vestibular cues participate in reporting the direction of the ambient gravity field.

A related case of particular relevance is when the velocity of the ball is proportional to $\sin(\alpha(t))$ instead of its integral. This actually happens with a musical percussion instrument called the "rain stick". It is made of a dried, hollowed branch of a cactus in which many horns are nailed to cross the inner compartment along many diameters. The inner maze cause pebbles that have been placed inside to descend in a "pachinko game" fashion, the many collisions causing their *average* velocity to be low and steady (resulting in a steady rain-like sound). This is highly relevant to the foregoing discussion because a very first encounter with the instrument typically results in wonder and amazement owing to the fact that the vibrations emanating from the tube grossly violate the invariance rules that we have outlined earlier.

## 4 EXPERIMENTAL APPROACH & QUESTION

The abundance of cues available to a subject wielding a tube containing a ball or a sliding object makes it hard to design well controlled experiments, but by employing haptic technology, it possible to reproduce the essential aspects of the tube and ball dynamics, while having freedom in the construction of desired sensorymotor couplings.

An apparatus, Figure 2, was constructed by inserting a powerful electromagnetic recoil actuator and an accelerometer inside a tube. These elements were connected to a microprocessor. This way, we could create any type of sensory feedback, haptic or acoustic, in response to the movement of the tube with respect to the ambient gravity field.

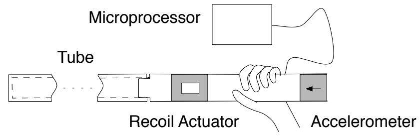

Figure 2: System.

To good approximation, it is possible to make this apparatus behave like a tube containing an object by simulating the physical principles set forth in the previous section and by programming it to produce desired sensory cues. It is also possible to endow the device with nonphysical behaviors such as objects having unusual inertial behaviors, to decouple the haptic response from the acoustic response, to add or remove dry friction, viscous friction, etc., etc., (including making it behave like a rain stick).

In the present study we restricted ourselves to imitating the ordinary response of a ball rolling or sliding in a tube under the normal gravity field but without transfer of weight. We asked the subjects to handle the tube within shallow angles only, lest they suspect something abnormal at steep angles where a real ball would no longer roll but slide or free-fall. Also, they could not hear the sound it produced, but they could see the tube normally.

We hypothesized that under these conditions, naive subjects *without any kind of practical or theoretical training*, could use either the balling-rolling-rumble cue, or the time-to-collision cue, as sole source of information in a spontaneous, one-shot, length estimation task. From the above discussion, the task was feasible only if the rolling ball or sliding object invariants were available to the subjects before the trials.

## 5 METHODS

### 5.1 Apparatus

The apparatus comprised a 60 cm-long, 1.3 cm diameter fiber-glass tube which weighted about 300 g, and a sensor/actuator subassembly unit rigidly attached to the tube. This unit was connected to a custom-made, single-board microprocessor subsystem, see Figure 2.

An accelerometer (Model ADXL210, Analog Devices, Norwood, MA), gave readings that were acquired by the microprocessor (MSP4301612, Texas Instrument, Dallas, TX). An on-chip 12-bit digital-to-analog converter drove an audio amplifier that powered a custom-made actuator. It had a magnet suspended by two membranes inside a pair of coils, see Figure 3. The geometry was such that current generated a Lorentz force between the magnet and the coils. By conservation of momentum, acceleration of the magnet was matched by acceleration of the case held by the subject.

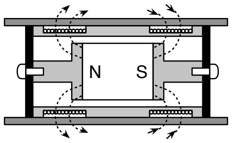

Figure 3: Actuator.

The weight of the sensor and of the actuator was such that the apparatus felt like an ordinary hollow tube. It had the visual appearance depicted by Figure 4. The beginning of the hollow section was indicated by the visible connection between the sensor/actuator unit and the tube.

Figure 4: Apparatus used in the experiment.

The microprocessor ran software to simulate the key aspects of the physics discussed earlier and generated specific cues, thus creating desired sensorymotor couplings. The accelerometer measured the component of the acceleration vector that was in the direction aligned with the main axis of the tube and rejected the others. What the accelerometer measured was the acceleration of a frictionless point mass that would be located where the measurement was made. In the apparatus, the virtual object moved but the accelerometer was fixed with respect to the tube. Provided that the subjects subjected the apparatus to movements that were sufficiently slow, to good approximation the sensor returned a measurement directly proportional to $g\sin(\alpha(t))$.

For the case of the simulation of a rolling ball, the software solved a finite difference version of Eq. (2) using the trapezoidal integration rule, and reset $\dot{x}$ to zero whenever $d$ met one of the two ends of the virtual tube.

$$\begin{aligned} \ddot{x}_k &= 7.0 sin(\alpha_k), && \ddot{x} \text{ directly from the sensor,}\\ \dot{x}_k &= \begin{cases} 0 & \text{if } (x_{k-1}<0)\vee(x_{k-1}>d_{\text{cavity}}),\\ \dot{x}_{k-1}+h\dfrac{\ddot{x}_{k-1}+\ddot{x}_k}{2}, & \text{otherwise} \end{cases}\\ x_k &= x_{k-1}+h\frac{\dot{x}_{k-1}+\dot{x}_k}{2}, \end{aligned}$$

where the system's sampling period was $h = 1/256$ s.

To synthesize rolling noise, an "artificial source-natural filter" approach was adopted. The source waveform was generated by repeating the positive arch of a sine wave. This waveform has a strong fundamental component and both even and odd harmonics. The filter was simply the natural dynamics of the actuator and the tube. Thirty samples of the sinusoidal arch were stored in a "wavetable" that was looked up by the index $i = x_k \bmod 30$. This way, if $x_k$ was expressed in millimeters, the waveform repeated itself every 30 mm, which corresponded to a ball of about 1 cm diameter. Figure 5a shows the spectrogram of the generated source waveform when the virtual ball was made to roll at an inclination of 27°, and Figure 5b shows the resulting measured acceleration. Figure 5a clearly shows the linear increase in velocity of the virtual ball and the corresponding shift of the spectrum linearly with time. Figure 5b shows the filtered version of the signal where the actuator's natural resonance (see Figure 6) enhanced the 100 Hz band and where the multiple violations of the Nyquist's condition created much high frequency noise. This resulted in a plausible rolling noise that was partly deterministic and partly stochastic.

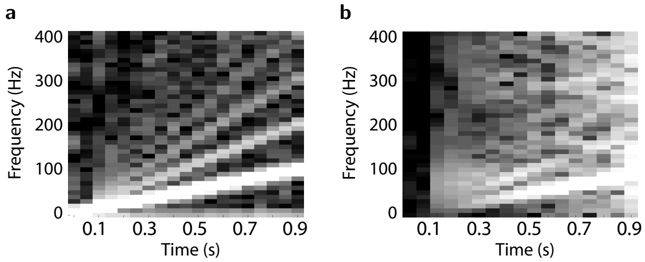

Figure 5: **a**) Spectrogram of source signal. **b**) Spectrogram of the filtered recorded acceleration.

For the case of an object sliding down the tube, the microprocessor solved a finite difference version of Eq (3) by the trapezoidal rule also. Approximating $g$ by 9.8, assuming $\mu = 0.2$, and replacing the sign of the velocity by the sign of the inclination angle to avoid spurious switching, we had:

$$\begin{aligned} \ddot{x}_k &= \begin{cases} 0, & \text{if } \sin(\alpha_k)^2 < 0.2(1-\sin(\alpha_k)^2)\\ 9.8\,\sin(\alpha_k) - 1.96\,\mathrm{sgn}(\sin(\alpha_k))\sqrt{1-\sin(\alpha_k)^2}, & \text{otherwise} \end{cases}\\ \dot{x}_k &= \begin{cases} 0, & \text{if } (x_{k-1}<0)\vee(x_{k-1}>d_{\text{cavity}}),\\ \dot{x}_{k-1}+h\dfrac{\ddot{x}_{k-1}+\ddot{x}_k}{2}, & \text{otherwise} \end{cases}\\ x_k &= x_{k-1}+h\frac{\dot{x}_{k-1}+\dot{x}_k}{2}. \end{aligned}$$

To synthesize the impact of an object hitting the end of the tube, we set the actuator signal at a fixed amplitude during one sample

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period and made the amplitude of the pulse proportional to the virtual impact velocity. This way, the energy dissipated in the hand of the subject was directly proportional to the square of the virtual impact velocity which was consistent with the physics of an impact as seen earlier. The sensor/actuator unit was housed in a 10 cm tube section that was attached to a 60 cm extension. Recordings were made when the sensor/actuator unit was disconnected from the tube and when it was attached to it. The results are reported in Figure 6 where the 100 Hz natural resonance of the actuator can be noticed as well as the attenuation brought by the heavier tube. During preliminary trials with several volunteers, we found this response realistic enough.

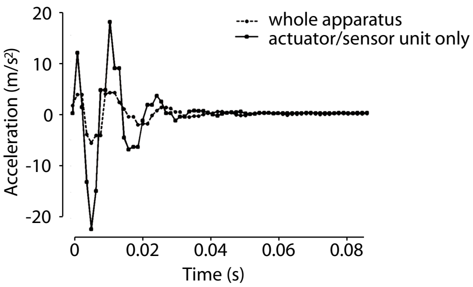

Figure 6: Impulse Responses with tube attached or removed.

We validated the simulation by measuring the time required for a real irregular ball to travel 60 cm on an inclined surface and did the same with the apparatus. The measurements were made 12 times for a 10° inclination and again 12 times for 30°. Table 1 summarizes the results for each case.

Table 1: Mean rolling durations, real and virtual.

| | 10° | 30° |
|---|---|---|
| Real | 0.9987 s, $\sigma = 0.1458$ | 0.4512 s, $\sigma = 0.0999$ |
| Simulation | 1.1354 s, $\sigma = 0.1304$ | 0.4082 s, $\sigma = 0.0125$ |

### 5.2 Procedure and Subjects

Eight students from McGill University's Electrical and Computer Engineering department kindly volunteered for the study. They were asked to guess the length of the tube by tilting it and experiencing the hidden object's dynamics. To avoid any possibility of learning, the subjects were divided in two groups. Four subjects experienced only the rolling noise cue produced by simulating the rolling dynamics and there was no simulated impact as if the tube had soft internal walls. Four other subjects experienced the impact cue only by simulating the sliding dynamics, but did not experience the rolling noise cue as if the object slid very smoothly.

All subjects were told that there were three inner tubes inside the apparatus. Two were short: 18 cm and 24 cm in length, and one was long: 60 cm in length. There were also told that, inside, there was a free-moving object which could fall randomly into one of the three inner tubes. The subjects had to guess in which inner tube the object fell by **tilting the tube only twice: first tipping downward, then lifting upward**. They had no further instruction nor any feedback, before or during the trials. They reported their answer by pointing to one of the markings on the tube (Figure 4). They were instructed to use only shallow angles and were asked to wear sound blocking ear muffs. Each subject performed the task 30 times where each of the three simulated length was presented 10 times in randomized order. Typically they completed the 30 trials within a few minutes. After the trials, they were debriefed and the nature of the apparatus was revealed to them.

## 6 RESULTS

### 6.1 Scores

The total numbers of guesses for each length category are collected in Figure 7. For both the impact and the rolling cue, the subjects' guesses for the shortest and medium lengths (18 cm and 24 cm) were very similar. By and large, they were not able to distinguish between them and performed nearly at chance between these two cases. On the other hand, for the longest length (60 cm) they were generally very good at guessing it apart from the medium and shortest ones. The simulation and the cues provided enough information for most subjects.

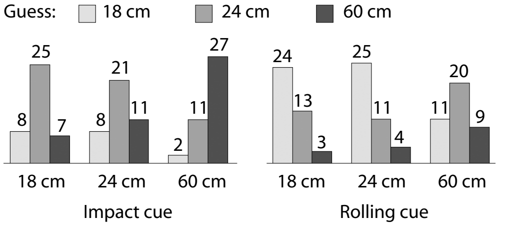

Figure 7: Total number of estimation for each simulated length

With only the impact cue available, most subjects chose *medium* for the two short cases, and *longest* for the long case. However, when only the rolling cue was available, most subjects chose *shortest* for the two short cases, and *medium* for the long one. This seems indicates a slight tendency to overestimate length given the impact cue only and a more marked tendency to underestimated the simulated length given the rolling cue only. The subject pool was too small however to be able to collect statistically meaningful results.

In both experimental conditions, because of the absence of training the performance varied greatly among subject. Some were very consistent and successful at guessing correctly, but some performed nearly at chance. Figure 8 and Figure 9 give examples of such cases. It is worth mentioning that the two subjects with the worse performance *spontaneously offered* that they were "not good at this" even before starting the trials. The subjects with the best performance, however, represent the general trend very well indeed.

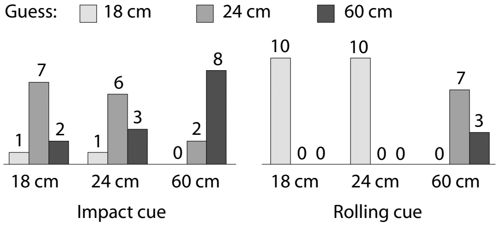

Figure 8: Scores of subjects with best performance.

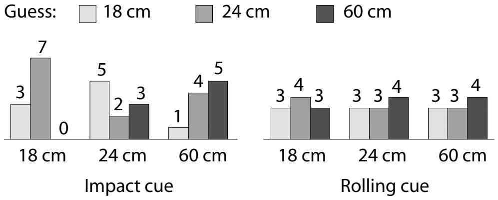

Figure 9: Scores of subjects with worse performance.

### 6.2 Subjective Comments and Observations

The subjects did not know how the sensation of a moving object was created but said that they could visualize the object without problem. In fact, it was quite interesting to observe their typical posture and behavior while attending to the task. Figure 10 attempts to capture this. Most remarkably, what subjects appeared to do was to "track" the virtual object with their eyes. This seemed to help them to locate the invisible wall inside the tube, although some noticed that something was "not exactly right."

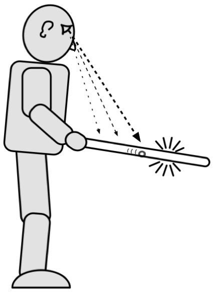

Figure 10: Typical posture during the experiment.

Most subjects agreed that the rolling haptic noise or the haptic impact were realistic. Some were extremely surprised to learn there was no rolling ball inside the tube. When only the impact cue was provided, some subjects commented that since they were unable to feel an object roll, it must have been be light, but the impact was strong, creating a conflit. This comment was given once the mechanism of the apparatus was revealed.

After the trials, we also let the subjects experience the rolling noise cue together with the impact cue. Most felt that this was indeed a lot more realistic, and that having both cues would make the estimation task easier. Some subjects were surprised when they used the apparatus without the impact cue and when it was later turned on. The channel suddenly appeared to be a lot longer.

Almost all subjects commented about the absence of weight transfer as the virtual ball rolled down the tube. Their comments were different depending on whether they had the impact cue or the rolling cue. Those who received only the impact cue noticed the absence of weight transfer, but those who received only the rolling cue were amazed to find out there was no weight transfer whatsoever. The rolling noise was sufficiently convincing to create the illusion of weight transfer which perhaps is a case of a "pseudo haptic" sensation [3]. In addition, because the experiment required them to tilt the tip first downward and then upward, they tended to use a larger inclination angle when they tilted the tube upwards, as if they tried to compensate for the higher torque due to the mass being at the extremity of the tube in a form of anticipatory movement [1, 15]. Some subjects even reported that the length seemed to be shorter when the ball rolled back (perhaps because of the larger tilt angle), even though the apparatus was well calibrated.

We observed that sometimes the subjects were able to give a definitive answer without hesitation, even after tilting the rod downward only once. Sometimes, however, they seemed confused and took several seconds to make a choice. Some users appeared to hesitate more than others, and this occurred both in the rolling and impact cue conditions.

## 7 DISCUSSION

The results suggest that even with an impoverished sensorymotor coupling, most subjects were able to perform much better than at chance in guessing the size of an inner cavity inside which an object moves under its own dynamics. Given the conditions in which the trials were administered, the results cannot be explained by cognitive factors although this possibility cannot be entirely excluded at this stage. It is conceivable that the subjects might have used the recall of previous trials to discriminate between virtual tube lengths, even if this was difficult to do within a small number of trials. This suggests that the subjects must have had several invariants available to them and that they were able to use them spontaneously, something O'Regan and Noe call the "mastery of patterns of sensorimotor contingency" [8].

We also observed that different haptic cues contributed differently to the task. The results suggest that the impact cue provides the subjects with better estimates around the real value, it is however somewhat ambiguous. With the rolling noise cue the subjects tended to be more consistent, but they under-estimated the distance covered by the virtual object. Estimating the elapsed time *between* two events (roll onset and subsequent impact) seems to be harder to use than estimating the *duration* of one event (rolling noise). It is also possible that subjects also used information related to spectral shift in the rolling cue which was not available for those who experienced the impact cue only.

The large performance gaps from one subject to another is rather interesting. One explanation is the variability in background experience. Without specific training, some people may not be particularly good at, or even unable to, using these cues to judge distances. They may normally rely on cues not made available to them during the experiment, such as weight transfer, acoustic feedback or prior knowledge of the material and inertia of the moving object.

Sufficient realism of the simulation was confirmed by the surprise expressed by most subjects upon debriefing. Although most subjects suspected that there was something unnatural about the apparatus, they had no trouble developing mental imagery associated with a rolling or a sliding object.

## 8 CONCLUSION

Future experiments could explore additional haptic cues or cues from other modalities, and explore their interactions. With the addition of well designed acoustic cues specifically, more interesting results may be obtained. In [12], the audio synthesis of the sound made by a rolling ball is suggested to be sufficient to enable the creation a new kinds of human computer interfaces. Systems similar to our apparatus may have applications in human-compurer interaction and several other areas. For example in [11], additional haptic feedback in portable devices is said to be useful to functions other than just alerts such as data input. Oackley et al, as well as Linjama et al, have applied the principle of *tilting* a hand-held device and combined it with haptic feedback to devise new human-computer interfaces techniques [7, 5]. In computer music performance, the use of tactile feddback coupled with movement was proposed to aid the execution of gestures in "thin air" [14]. In all these examples, the authors observed that a number of interesting perceptual effects occurred for certain sensorymotor couplings which are not unlike that explored in the present paper.

## 9 ACKNOWLEDGMENTS

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