Humans can separately perceive distance, velocity, and acceleration from vestibular stimulation

Markus von der Heyde, Bernhard E. Riecke, Douglas. W. Cunningham, and Heinrich H. Bülthoff

Max−Planck−Institute for Biological Cybernetics • Tübingen • Germany

email: Markus.von.der.Heyde@Tuebingen.MPG.de, web: www.kyb.tuebingen.mpg.de

Purpose

What spatial information can be derived from vestibular cues?

If the vestibular system is providing a spatial reference frame, one of the central questions is which motion parameters are used to specify the change in body position.

The vestibular system is known to measure changes in linear and angular position as acceleration. Can humans judge these vestibular signals as acceleration itself and integrate them to reliably derive velocity and distance estimates?

Methods

We asked for distance, velocity, and acceleration judgments.

Figure 1: **The Stewart-Platform motion simulator.** The subject is seated blindfolded and with headphones on the platform. The platform is able to move in all 6DOFs independently.

Twelve blindfolded naive volunteers (ages between 19 and 29) participated in three sessions of a psychophysical experiment using a Stewart−Platform (see Fig. 1). The subjects were seated on the platform and moved on predefined trajectories. Auditory cues were excluded during the entire experiment.

The vestibular stimuli consisted of Gaussian−shaped translatory or rotatory velocity profiles with a duration of less than 4 seconds (see Fig. 2). The movement was always confined to one degree of freedom per session (X: translation forward−backward, Y: translation left−right, H: turn around vertical body axis). The full two−factorial design covered 6 peak accelerations above threshold and 5 distances with 4 repetitions (see Fig. 3). In three separate blocks, subjects were asked to verbally judge on a scale from 1 to 100 the distance traveled or the angle turned, as well as the maximum velocity and maximum acceleration.

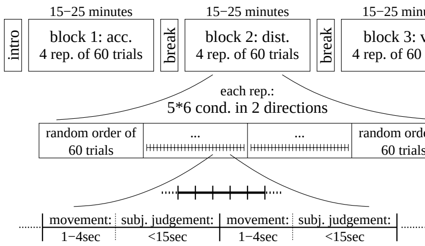

Figure 3: **Experimental design.** This example shows the order of blocks for the X (forward-backward) condition for one subject. After a short introduction to the purpose of the experiment and the task, this subject was asked to judge acceleration in the first block. These 240 trials (60 trials in 4 repetitions) were followed by a break and than the next two blocks with a break between them. The 60 trials of each repetition were randomized over the 5*6 conditions in both directions. Each individual trial had a maximum length of 4 seconds followed by a brief period during which the subject gave the verbal judgment to the experimenter.

Results

Judgments were correlated with distance, velocity, and acceleration.

Subjects judged the distance, velocity, and acceleration quite consistently, but with systematic errors (see Fig. 5). The distance estimates showed a linear scaling towards the mean response and were independent of accelerations. The histograms of the verbal responses reflect this tendency towards the mean (see Fig. 4).

The correlation of perceived and real velocity was linear and showed no systematic influence of distances or accelerations. High accelerations were drastically underestimated while accelerations close to threshold were overestimated, showing a logarithmic dependency (see Fig. 5(i)). The judged acceleration was close to the velocity judgment but clearly distinct from distance judgments.

A model, which assumes a linear combination of distance, velocity, and acceleration, was fitted to the individual data with minimal error (see Fig. 6 for an example of the subjects' responses, the model fit, and the difference (error) between them).

$$J_i = D_i * Distance + V_i * Velocity + A_i * Acceleration + Error_i$$

The coefficients (D_i, V_i, A_i) describe for each experimental condition the subjects' (i) response J_i across all 30 factorial combinations (see Fig. 7). There was no substantial difference between judgments of translational and angular movements.

Conclusions

One can derive distance and velocity from the vestibular cues.

Despite the fact that the vestibular system measures acceleration only, peak velocity and traveled distance can be obtained from it. Furthermore, it is particularly unclear why the acceleration judgment looks like a velocity judgment. One possible explanation is that since velocity is encoded at a very early stage (in the vestibular nerve), it may replace or mask the acceleration signal.

In sum, the vestibular system is providing a good spatial reference frame, which does enable spatial updating.

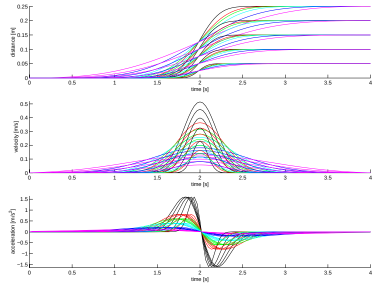

Figure 2: **The vestibular stimuli.** The translation profiles were created from the Gaussian-shaped velocity profiles. The acceleration describes a function close to a sinusoidal profile. The plot shows the factorial combination of 5 distances (5, 10, 15, 20, 25 cm) and 6 accelerations (0.1, 0.2, 0.4, 0.6, 0.8, 1.6 m/s^2). Profiles with the same maximum peak acceleration are plotted in the same color.

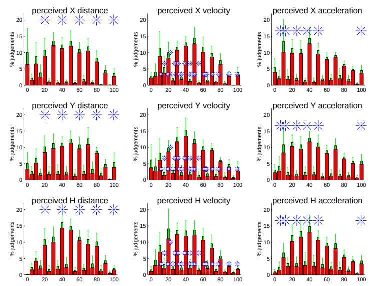

Figure 4: **Histograms of subjects' responses.** The red bars represent the mean percentage of the subjects' responses. The green bars refer to the standard error of the mean, with the "whiskers" depict one standard deviation. The blue "stars" show the right answer percentages.

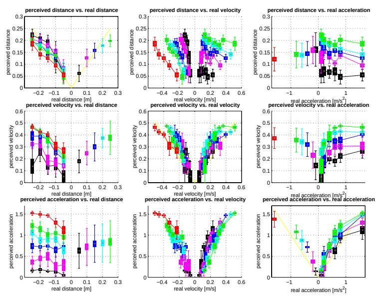

Figure 5: **Perceived values vs. physical stimulus.** The nine graphs show the data of one typical subject in the Y (left-right translation) condition. The rows contain the data for distance, velocity, and acceleration judgments, respectively. Each column plots those data against the physical distance, velocity, and acceleration of the stimulus. Therefore, the diagonal displays the subject's answers correlated to the physical stimuli. Each plot displays the data twice: the left-hand side groups the data for identical peak acceleration and the right-hand side groups the same data for identical distance.

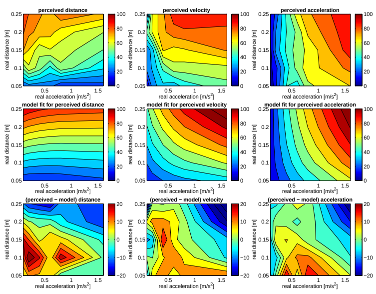

Figure 6: **Model fit to the data.** The nine graphs show the same data as Fig. 5. This time, each plot in the first row displays one block of the experiment. The color encodes the mean of the subject's judgments across all factorial combinations. The second row is the result of the fitted model to the individual data of the first row. Finally, the last row depicts the difference between the model and the actual data.

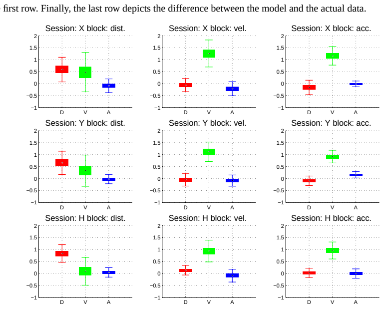

Figure 7: **Coefficients of the model.** The nine graphs display the mean of the coefficients from the model (see Fig. 6) for all nine experimental conditions. The rows show the three sessions: X (forward – backward translation), Y (left – right translation, and H (turn around the body's vertical axis). The columns show the different experimental blocks of each session (distance, velocity and acceleration judgment). The bars refer to the standard error of the mean, and the "whiskers" depict one standard deviation.