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Perceived radial translation during centrifugation

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Abstract.
BACKGROUND: Linear acceleration generally gives rise to translation perception. Centripetal acceleration during centrifugation, however, has never been reported giving rise to a radial, inward translation perception.
OBJECTIVE: To study whether centrifugation can induce a radial translation perception in the absence of visual cues.
METHODS: To that end, we exposed 12 subjects to a centripetal acceleration with eyes closed. To avoid confounding with angular motion perception, subjects were fist rotated on-axis, and were shifted out fast and slow only after rotation sensation had vanished. They were asked for translation direction and velocity right after the shift-out, as well as after about 60 seconds of constant centrifugation.
RESULTS: Independent of fast or slow shift-out, the vast statistically significant majority of trials yielded an inward radial translation perception, which velocity was constant after 60 seconds of constant centrifugation.
CONCLUSIONS: We therefore conclude that during centrifugation, an inward radial translation perception does exist in humans, which perception reaches a constant, non-zero value during constant rotation, lasting for at least one minute. These results can be understood by high-pass filtering of otolith afferents to make a distinction between inertial and gravitational acceleration, followed by a mere integration over time to reach a constant velocity perception.

Keywords: Human centrifuge, centripetal acceleration, self-motion perception, gravito-inertial resolution, tilt-translation disambiguation, path integration

1. Introduction

Knowledge on the perception of self-motion and -attitude is relevant for several reasons. Spatial disorientation in flight, for example, may lead to accidents [17], even in healthy pilots. In case of disease, such as Ménière, vertigo and nausea are also serious disabling phenomena. In vehicle simulation, furthermore, knowledge on self-motion and -attitude perception plays a key role in the design of motion filters squeezing real vehicle motion into the narrow envelope of a moving base simulator. Part of this knowledge concerns the organs of balance, that play a major role, as exemplified by the observations that labyrinthine defective patients do not suffer from motion sickness [18], while they have a poor situational awareness in the absence of appropriate visual cues and show a reduced oculo- and somatogravic illusion [15,19]. The latter illusion refers to a tilt sensation induced by linear inertial acceleration, and is a serious threat to aviators. In poor visual conditions it can lead to a controlled flight into terrain [13]. Analogous to the somatogravic illusion, oscillatory linear motion on a sled in the dark gives rise to a sensation as if moving over a hilltop [14].

Perceptions of translation and tilt have shown opposite behavior depending on the frequency of (oscil-

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latory) motion. Perception of tilt decreases with frequency and perception of translation increases with frequency [1,14,19]. Mayne [19] was probably the first to recognize the importance of Einstein's equivalence principle in this respect, which states that inertial and gravitational accelerations, although physically different, are yet indistinguishable [11]. The fact that our central nervous system (CNS) is capable of making a distinction, although not necessarily true, Mayne ascribed to frequency segregation. His basic idea was that gravity is constant, at least in an Earth-fixed frame of reference, and this perceived tilt may be the result of CNS low-pass filtering of otolith afferents. Because linear acceleration generally is variable, perceived translation may then be the result of high-pass filtering of otolith afferents, the two perceptions thus showing opposite behavior. Path integration then refers to the process that integrates the estimated inertial acceleration component over time into velocity and position or distance travelled. Seidman [23] studied path integration on a sled using eye movements and a joystick to estimate perceived velocity, concluding that velocity perception indeed follows integration of high-pass filtered otolith afferents. The integration, however, was assumed to be "leaky", because a lasting velocity percept after an initial acceleration seemed absent. From the late 1940's, the somatogravic illusion was studied most extensively using centripetal acceleration in human centrifuges [5], the inertial centripetal acceleration lasting as long as the centrifuge rotates. This has certain advantages over using a sled, which requires not only length for accelerating subjects, but also length to bring them to a stand-still in a preferably controlled and safe way. In a centrifuge, the centripetal acceleration experienced during onset may, however, also give rise to an inward sensation of translation. Path integration might then subsequently result in a persistent velocity percept, despite the experienced inertial acceleration having returned to zero during constant angular velocity centrifugation due to Mayne's high-pass filter. Leaky path integration would, however, result in a zero velocity percept after a while. Despite substantial information on centrifugation induced tilt perception (e.g. [3,6,24]) and human eye movements (e.g. [4,9,10], but see also [20,21]), subjective or cognitive translation responses, specifically along the radial direction during centrifugation have, to our knowledge, never been reported.

We therefore performed an experiment to primarily observe whether an inward radial translation during centrifugation can be perceived in the absence of visual cues. Here, we rated translation perception in human subjects during and after the onset of a centripetal acceleration in a centrifuge. To avoid confounding with the angular motion sensation during the centrifuge angular motion onset [1], we used a paradigm equal to that used by Correia Gracio et al. [8], in which subjects were first rotated on axis. Only after their angular motion sensation had subsequently vanished, subjects were shifted out backward. The final constant centripetal acceleration not only resulted in the well-known somatogravic tilt illusion, but, as shown below, also in a lasting sensation of forward translation.

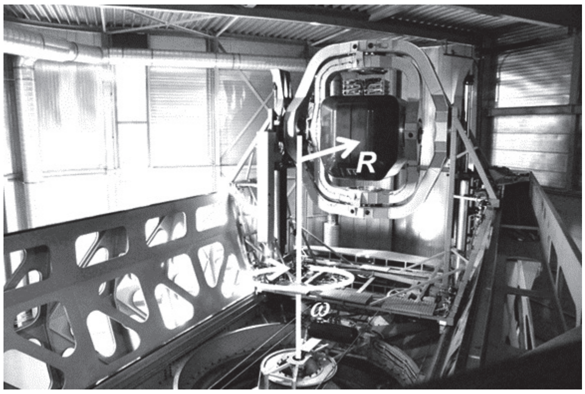

Fig. 1. The Desdemona facility. A 2 m diameter gondola seated for one subject can be rotated about all three gimballed axes unlimitedly, while moving vertically over 2 m and/or horizontally over 8 m, and being rotated about a central vertical axis to induce a centripetal acceleration when off-centre. In the present experiment we only used the central rotation (ω) in combination with the variable radius (R).

2. Methods

2.1. Centrifugation

To expose subjects to a centripetal acceleration we used the Desdemona facility in Soesterberg, Netherlands as shown in Fig. 1.

To avoid confounding with angular motion sensations, subjects were first rotated on-axis with an acceleration of $5^\circ/\mathrm{s}^2$ up to a constant angular velocity $\omega = 80^\circ/\mathrm{s}$, and stayed there for at least 1 minute. They were then shifted out backward as shown in Fig. 2, i.e., continuously facing the central rotation axis.

The centrifuge radius R was varied using a raised-cosine linear function according to Eq. (1):

$$R(t) = \left\{ \begin{array}{cc} 0 & t < 0 \\ \frac{-d}{T}\left(t - \frac{sin 2\pi t/T}{2\pi/T}\right) & 0 \leqslant t < T \\ -d & t \geqslant T \end{array} \right\} \quad (1)$$

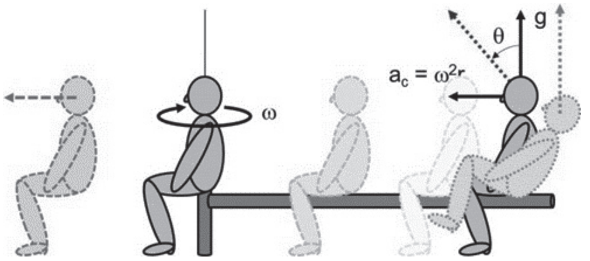

Fig. 2. Actual (solid black) and perceived linear motion (dashed grey) and angular position (dotted grey) during centrifugation. In this paper, subjects were first rotated on-axis to extinguish the angular motion sensation, after which they were shifted out.

Two motion profiles were used with differing times T required for shifting out: $T = 5$ (fast) and $T = 20$ s (slow). The final distance d of the shift itself was always fixed at $d = 2.15$ m, its minus sign in Eq. (1) denoting a backward shift. The final resulting centripetal acceleration $a_c = \omega^2 R$ accordingly was 4.2 m/s^2 and the final tilt of the gravito-inertial acceleration (i.e., the vector sum of the gravitational and centripetal acceleration) was 23° with respect to true gravity. The total acceleration at issue (**a**), is then given by Eq. (2), the x-axis pointing nose-out, the y-axis to the left, and the z-axis up. The two variable components are plotted in Fig. 3.

$$\mathbf{a} = \begin{pmatrix} a_x \\ a_y \\ a_z \end{pmatrix} = \begin{pmatrix} \ddot{R} - \omega^w R \\ -2\omega\dot{R} \\ g \end{pmatrix} \quad (2)$$

where the dots represent time derivatives, a_y the linear Coriolis acceleration, and $g = 9.81$ m/s^2 the free-fall or gravitational acceleration. Note that while the true motion was backward (i.e., $d < 0$), R, $\dot{R}$, and $\ddot{R}$ are all negative, the final for-aft acceleration is positive again. Note that the centripetal acceleration also results in a backward (somatogravic) tilt-sensation, and the linear Coriolis acceleration in a combined lateral translation and (somatogravic) tilt sensation.

2.2. Subjects and procedures

After approval by the local ethical board, 12 subjects participated in this experiment, 2 females and 10 males with an average age of 40 ± 11 years. All were informed about the experiment dealing with motion perception, but naive with respect to the Desdemona device and the actual motions to which they were about to be exposed. They were furthermore free of any vestibular-related disease or medication as known by themselves, and had not been drinking alcohol for at least 12 hours. After signing an informed consent form, they were seated in the dimly lighted Desdemona gondola, strapped in with a five point safety belt, and provided with a headset with active noise reduction, the latter also used for communication purposes. They were instructed to keep their heads still in a head rest for the remainder of the experiment. Although not explained to them, they were asked to do so to minimise possible nauseating angular or cross-coupled Coriolis effects. The central yaw rotation was then started, and after one minute all subjects confirmed being subjectively stationary, after which they were first exposed to a familiarization run (always the slow shift-out). This run allowed for an open conversation between the subject and experimenter about possible translation and tilt sensations, again, without the subject being informed about the true motion. After about two minutes, they were shifted back in to the centre position while the central yaw motion continued for the rest of the experiment. During the interval lasting from shift-out to shift-in, subjects were furthermore instructed to keep their eyes closed, as could be confirmed by infrared video. At this point, subjects were instructed to only focus and report on their perceived for-aft linear translation, ignoring all other motion and tilt sensations. They were also explicitly instructed to report on their experiences, rather than to rely on cognitive inferences possibly based on assumed simulator capabilities and limits.

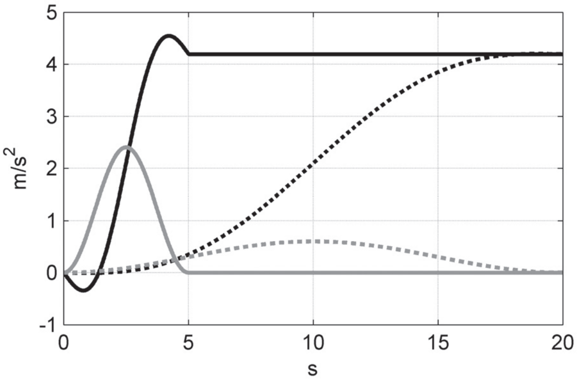

Fig. 3. Forward (a_x, black lines) and lateral (a_y, Coriolis, grey lines) accelerations for the two motion profiles used in this experiment: fast ($T = 5$ s, solid lines), slow ($T = 20$ s, dotted lines).

The actual experiment consisted of four trials, the two shift-out/shift-in motions repeated once each, presented in a random order, balanced over subjects. During the shift-out within these four experimental trials, as well as after about 60 seconds of stationary centrifugation, subjects were asked the following: "Are you sitting still, i.e., Earth-fixed? If not so, are you then moving forward or backward with a decreasing, constant or increasing velocity?". Their verbal responses thus led to a final data set with a maximum of 12 (subjects) $\times$ 2 (fast, slow) $\times$ 2 (repetitions) $\times$ 2 (during shift-out and after 60 s) $=$ 96 combinations of perceived translation directions (no, for, or aft motion) and velocity estimates (decreasing, constant, increasing). The latter categorical data yielded contingency tables with relatively small numbers, allowing Fischer's exact test to calculate the chance that the observed outcomes were due to coincidence.

3. Results

During the fast shift-out ($T = 5$ s), subjects perceived 17 times a forward and 7 times a backward increasing velocity. This distribution would occur due to coincidence with a chance $p = 0.021$ ($0 \leqslant p \leqslant 1$). During slow shift-out ($T = 20$ s), subjects perceived 18 times a forward acceleration and 5 times a backward acceleration. One subject could not indicate in which direction he was moving in one condition. The chance p of finding 18 equal incidences out of 24 is 0.008. The combined distribution, i.e., 35 out of 48 conditions showing a forward motion, would only occur with a chance $p = 0.0007$ when due to coincidence.

After about 60 seconds, perceived motion remained in the same direction as perceived during the shift-out in all cases. A stand still (i.e., feeling Earth fixed), was reported one time after the fast shift-out, and two times after the slow shift-out. A decelerating motion, i.e., a decreasing velocity, was reported two times after all shifts. A constant nonzero velocity was reported 18 times after the fast shift-out and 17 times after the slow shift-out, where after both shifts; two subjects did not know in which direction they were moving. An increasing velocity was reported 2 times after both shift times. The vast majority of conditions therefore resulted in a forward translation perception, the velocity of which remained constant even after 60 seconds of centrifugation. The probabilities ($0 \leqslant p \leqslant 1$) of the observed outcomes if occurring by mere coincidence are $p = 0.008$ (fast shift), 0.021 (slow shift) or 0.0007 (pooled data, i.e., 35 out of 48 conditions).

Table 1 summarizes the observed numbers of each perceived translation.

4. Discussion and conclusions

In the absence of concomitant angular motion sensations, and despite an initial *out*ward radial translation, the data of the experiment show that during centrifugation subjects by far most often perceive an *in*ward radial translation. Also constant centrifugation usually results in a constant velocity that lasts for at least one minute, independent of the onset of the centripetal acceleration. The following issues lend further support to these conclusions.

One issue concerns the lack of reports on the topic of interest here, i.e., whether a perception of radial translation during centrifugation exists or not. Partly, this lack may be explained by the assumption that the illusion of translation is not that obvious, especially when attention is focused on other issues like tilt sensations or anti-G straining maneuvers. It is the authors' experience, for example, that during centrifugation, radial translation is certainly not the first thing to notice. It therefore makes sense to assume that just because it is not that obvious, and that to our knowledge researchers have never explicitly asked their subjects about it, the radial translation perception implicitly has been assumed to be non-existent [2]. This assumption may further be assisted by the observation that the perception of complex motion is difficult to describe. Moreover, the most common type of centrifuge used for human experiments had a fixed radius and a free swinging gondola, resulting in complex six degree-of-freedom motion sensations during centrifugation motion onset (start) and offset (stop).

It may furthermore be argued that the total radial shift-out acceleration in our experiment, especially for the fast shift, was not monotonically increasing, but did show a negative dip at motion onset for 1.5 s, with a minimum of -0.3 m/s^2. The minimum of the slow shift-out was only -0.007 m/s^2. Griffin [16] assumes perception improbable below 0.1 m/s^2, and the lowest threshold we could find in the literature is 0.01 m/s^2 [12]. If this negative peak had contributed substantially to the current observations, it would have been expected that backward translation had been noticed more often during the fast shift-out than during the slow shift-out. Because the data do not show a difference in this respect, we assume this effect can be ignored.

When using fixed radius centrifuges, yet another issue concerns the possible interaction between the centrifuge angular motion and the perceived somatogravic tilt and translation illusions. Bos and Bles [1], for example did show that angular motion can have a large effect on the tilt illusion, especially the temporal characteristics thereof at high angular velocities. To avoid a possible confounding with this angular motion, in the

Table 1
Numbers of observed perceptions

	During shift-out			After shift-out				
	For	Aft	Missing	Still	Decel.	Const. vel.	Accel.	Missing
$T = 5$ s	18	5	1	1	2	18	2	1
$T = 20$ s	17	7	0	2	2	17	2	1

present experiment we therefore chose to rotate subjects on-axis first, and only shift them to an off-axis position after the angular motion sensation had vanished. As a consequence, it remains a question whether perceived angular motion in a centrifuge affects or even kills the perception of linear radial translation, thus offering an additional explanation of why radial translation may stay unnoticed. The other way round, centripetal acceleration may as well affect or even kill angular motion perception, as may have been the case in a study by Cohen et al. [7], for example. They rotated subjects only for 3 s with a peak acceleration of about 4 Gx, reporting no problems or confounding with the angular motion. Concurring with the previous paragraph, they, however, neither reported having asked their subjects about perceived angular motion, nor for any other perception of translation.

Our second conclusion is about the constant velocity still perceived after one minute of constant centrifugation. If Mayne [19] is right, assuming that our central nervous system does apply high-pass filtering to estimate inertial acceleration from the specific force as sensed by the otoliths, then, a simple integration of the high-pass filtered otolith afferents over time would indeed yield a lasting velocity percept. This percept would then remain constant from about 20 seconds onwards in both shift-out conditions as shown in Fig. 4. Note that this conclusion, apart from the final velocity reached, is independent of the filter time constant, and the integration from acceleration to velocity does not need to be "leaky" as assumed before [2,23]. Whether this finding holds for periods longer than 1 minute remains uncertain.

Lastly, not all subjects gave the same results, and in some cases even within-subjects results varied between equal conditions. This may be attributed to the assumption that not only idiothetic information is taken into account by the CNS, i.e., information gained by inertial sensors or information such as efference copies, but also certain pre-existing knowledge or cognitive information [22,23,25]. Especially these latter cues are likely to vary between subjects, and become more important the less idiothetic information is available. The absence of visual, auditory, and airflow information may therefore account for any variability in translation perception observed in general and the intra-subject variability observed here in particular.

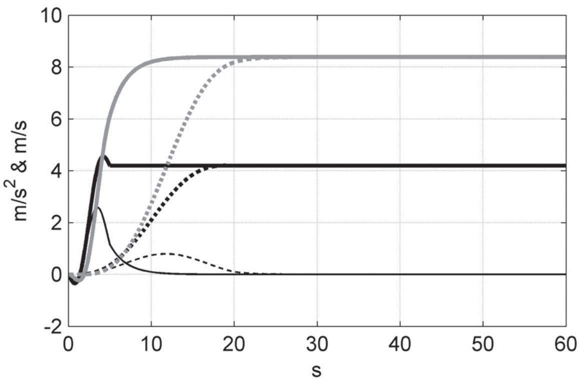

Fig. 4. Actual (thick black lines) and high-pass filtered (thin black lines) centripetal accelerations, and assumed perceived velocity (grey lines) obtained by integration of the high-pass filtered accelerations over time for the two motion profiles used in this experiment: fast ($T = 5$ s, solid lines), slow ($T = 20$ s, dotted lines).

For these reasons we conclude that during human centrifugation, an inward radial translation perception does exist. This perception reaches a constant, nonzero value during constant rotation, lasting for at least one minute.

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