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SPATIAL ORIENTATION DURING LOCOMOTION FOLLOWING SPACE FLIGHT

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Abstract

To investigate changes in spatial orientation ability and walking performance following space flight, 7 astronaut subjects were asked pre- and post-flight to perform a goal directed locomotion paradigm which consisted of walking a triangular path with and without vision. This new paradigm, involving inputs from different sensory systems, allows quantification of several critical parameters, like orientation performance, walking velocities and postural stability, in a natural walking task. The paper presented here mainly focusses on spatial orientation performance quantified by the errors in walking the previously seen path without vision. Errors in length and reaching the corners did not change significantly from pre- to post-flight, while absolute angular errors slightly increased post-flight. The significant decrease in walking velocity and a change in head-trunk coordination while walking around the corners of the path observed post-flight may suggest that during re-adaptation to gravity the mechanisms which are necessary to perform the task have to be re-accomplished.

1. Introduction

Prolonged stays in weightlessness are known to cause adaptation to the new environment in both the vestibular and somatosensory systems. Several hypotheses have addressed the question how the changed sensory inputs are interpreted. For example, the otolithic system, which on earth measures a combination of head orientation re gravity and linear translational acceleration, is supposed to re-interpret all linear acceleration in weightlessness as being translational (otolith tilt-translation reinterpretation, [1]). This could lead to misperception of head tilt as translation in the first hours after return to earth. Similar adaptation to weightlessness can be seen for posture [2]. In the short re-adaptation period after return to normal gravity, those adaptation effects are still visible [3].

The new paradigm presented here aims at having the astronaut subjects perform a natural task involving both somatosensory and vestibular sensory inputs. Goal directed locomotion satisfies these requirements and furthermore provides information about the spatial orientation capabilities of the subjects. In contrast to former investigations, which required more artificial tasks like performing eye movements with the head fixed or walking on a treadmill, goal directed locomotion with or without vision is a simple everyday task. By measuring the movement of the head during the walk and reconstructing head position in all six degrees of freedom, it is possible to assess different questions : from the subject's performance in reaching a target over the head stabilization during the different phases of the walk to the question how we walk around a corner.

The data presented here will focus mainly on the question whether exposure to the microgravity conditions encountered during space flight is associated with impaired spatial orientation during locomotion following the return to Earth and what role vision plays in this process. To quantify the performance to orient during free walking after space flight, astronaut subjects were asked to walk preflight (10-15 days before launch) and post-flight (3-5 hours, 1 and 4 days after landing) a previously seen triangular path with normal vision and vision occluded. The path, marked on the ground by a cross at each corner, consisted of a right triangle with two legs of 3m in length. The subjects were asked to walk the path five times clockwise and counterclockwise in both conditions. The trajectories of three infrared-reflective markers fixed on a helmet were recorded using a video-based motion analysis system (Motion Analysis Corp. Santa Rosa, CA) and analyzed afterwards. Analysis included length of each leg walked, angle of turn at the corners, mean walking direction during each leg, mean walking velocities and distance errors to each corner. Additionally, the maximum angular head velocity at each corner was determined.

Up to now, seven subjects participated in the experiment. This paper will report a preliminary analysis of the last preflight and first post-flight data sessions.

2. Materials and Methods

7 astronaut subjects, 5 male and 2 female, were asked to perform two spatial orientation tasks that required them to negotiate a path by walking with and without the aid of vision. The path consisted of a right triangle with two sides 3 m in length. The three corners were marked on the floor with targets consisting of 7 cm x 7 cm crosses. (See Fig. 1) The subjects task was to walk the triangular path, starting at either corner 1 or corner 3. When the path was completed the subject was requested to turn and face the direction that he/she started. The verbal instructions given were, "Walk at a comfortable pace, as accurately as possible around the path. The motion should be continuous. The goal is accuracy, with accuracy defined as your ability to 'straddle' the path." For all experiment sessions, two spotters were in the room to prevent any collisions during the eyes closed tasks.

To control for directional preferences the task was performed alternating clockwise (cw) and counterclockwise (ccw) directions, but always approaching the right angle (corner 2) of the triangle first. Vision occluded trials were performed before the eyes open trials to minimise visual feedback. Also to minimise visual feedback, at the conclusion of each eyes closed trial, the subject was lead in a serpentine path, with eyes still closed, to the next starting point. The subject was instructed to look at the path before starting each eyes closed trial. The subjects performed 12 trials eyes closed (6 cw and 6 ccw) and 6

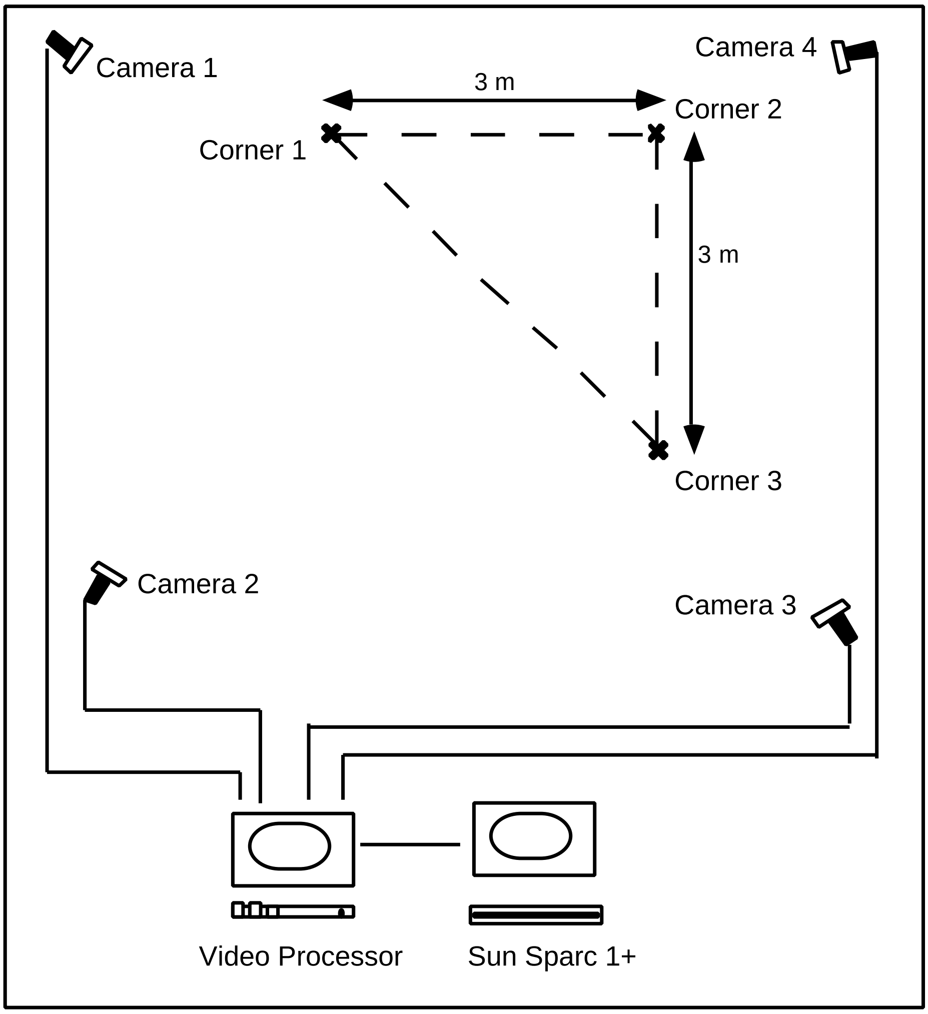

Figure 1 : Mapview of the experimental set-up. Four cameras connected to a videoprocessor were used to record the path of the subject. The three corners of the triangular path (dashed lines) were marked on the floor by white crosses.

trials eyes open (3 cw and 3 ccw). This protocol was performed 45 days and 15 days pre-space flight and 2 hours, 2 days, and 4 days post space flight. This paper will only present the data from 15 days pre-flight and 2 hours post-flight. All subjects were exposed to between 8 and 14 days of space flight.

The subjects wore a helmet with three retro-reflective markers located above the head in approximately the sagittal plane (See Fig. 2.). This helmet was also equipped with headphones that provided white noise to mask out spatial auditory cues and blackened goggles to occlude vision.

Head kinematic data were collected with a video-based motion analysis system using four CCD video cameras with a sampling frequency of 60hz. (Motion Analysis Corporation, Santa Rosa, CA). Video signals from the four cameras were fed to a video processor. The outline of each target was extracted and passed to the Sun Sparc host computer for analysis. This system tracked the three reflective targets placed on the head, producing a three dimensional assessment of each marker. This data was then transferred to a PC for further analysis.

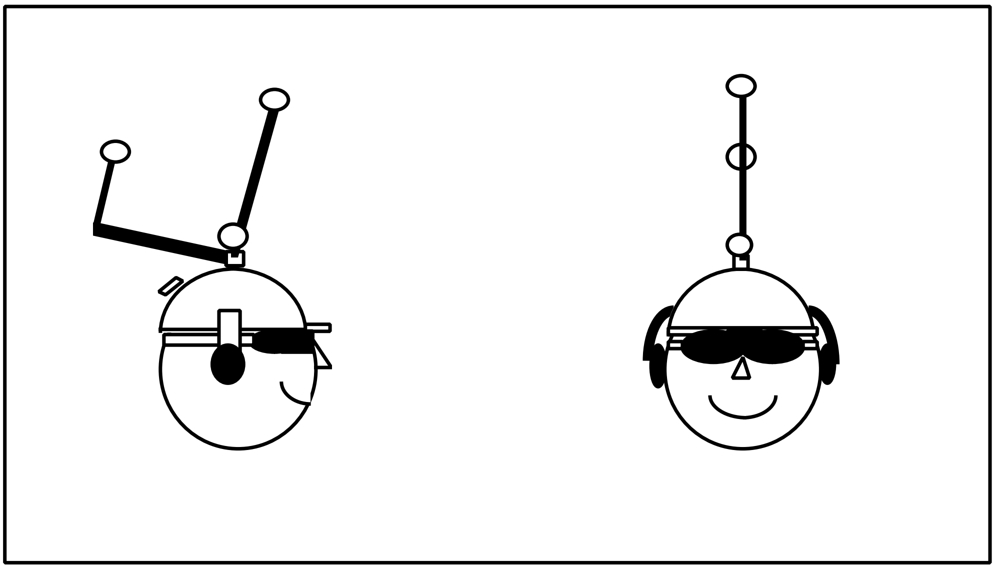

Figure 2 : Headset of the subject. Three infrared reflexive markers were fixed to the helmet. Headphones and blackened goggles were used to mask out auditory cues and occlude vision.

From the 3D-positions of the head markers the coordinates necessary to describe head position in all six degrees of freedom were computed. The three translational components were used to identify translational position and to compute linear velocity, the three rotational components to express tilt and to compute angular velocity of the head. The rotational head position was expressed as quaternions (see e.g. [4]). By means of an interactive graphical software package written by one of the authors (SG) the corners of the walked trajectory and the maxima of the angular head velocity were determined for each walk (see Fig. 3). The corner points were used to compute distance errors and mean walking velocity. To evaluate the mean walking direction for each leg of the triangle, lines of minimum least square distance were fitted to the trajectory between the corners. The angle between two lines then gives the amount of turn performed by the subject. The angular deviation from the desired trajectory (i.e. from the triangle’s leg) was computed as the difference between the angle turned and the required angle of turn at the respective corner.

Due to marker dropouts, not all parts of the trajectory were successfully recorded in all trials. The incomplete parts were marked as being invalid and not used for the statistical analysis.

Statistical analysis was performed on the mean parameter values of each subject. Hence, the analysis was based on a 3 segments x 2 directions x 2 visual conditions x 2 days repeated measures design.

3. Results

As described above, four points were determined for each walk : starting point, corner 1, corner 2 and the end point of the walk. The path trajectory is accordingly subdivided in three segments between these points.

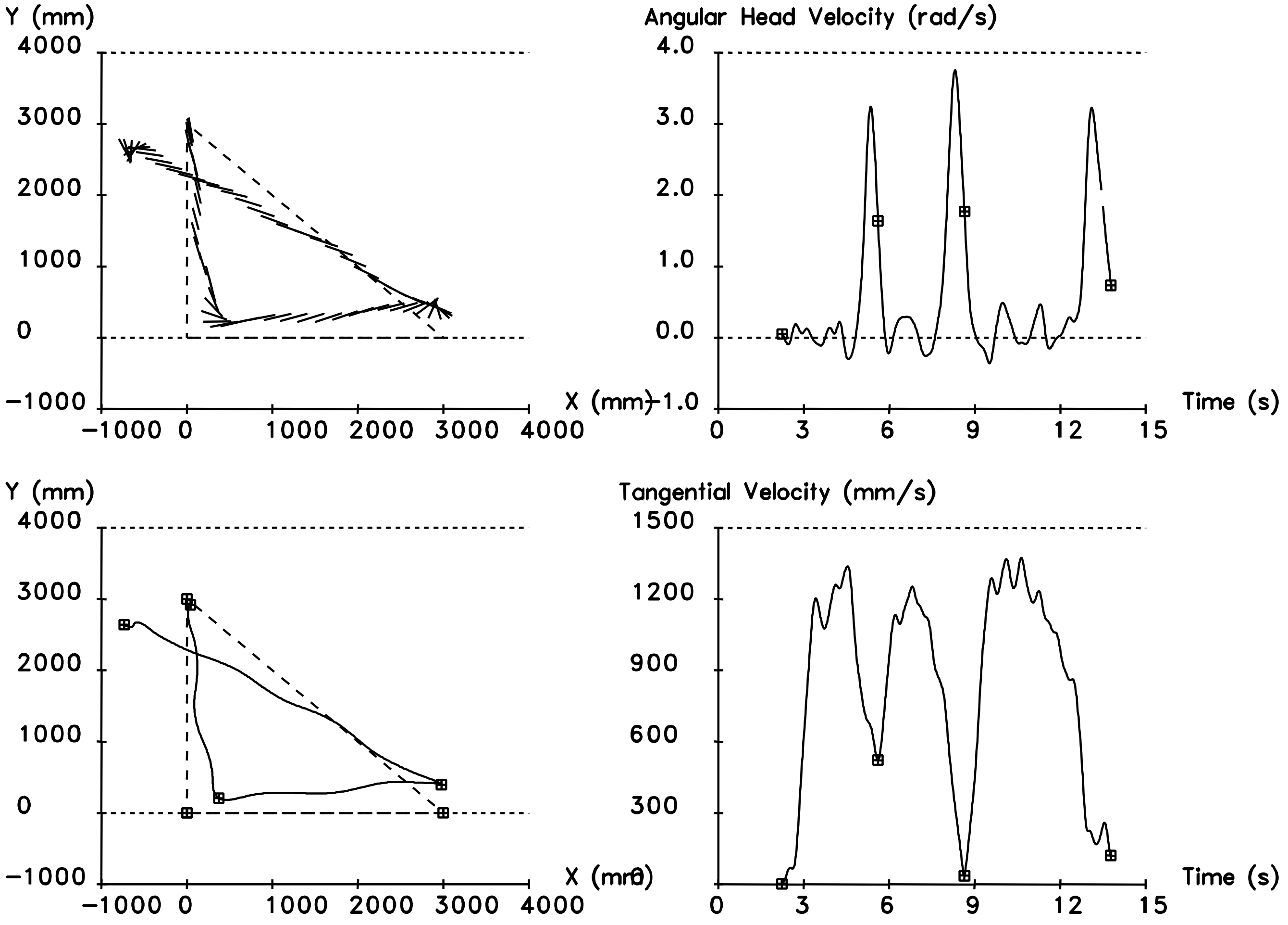

Figure 3 : Example of raw data of one walk (eyes closed). Lower left : Mapview of the path , dashed line : required path, solid line : trajectory performed by the subject, squares : corners of the path. Lower right : Tangential velocity profile during the walk, squares : corners as in lower left. Upper left : Mapview with head orientation. Upper right : Angular head velocity profile, squares : corners as in lower left. Note that the head turns prior to the corner, which can be seen in the map view of head orientation and the angular head velocity profile.

3.1 Distance errors

Two different ways of describing distance errors were applied : 1) the 2D distance error of each cornerpoint to the required corner at the end of a segment (arrival error), 2) the difference between required length of a segment and actual distance covered (length error). The arrival error gives an absolute estimate of both directional and longitudinal deviations from the required path, while the length error shows purely longitudinal errors in reproducing the segments. Thus, arrival error is cumulative over the walk, while length error is not.

The 4-way ANOVA revealed a significant effect of segment (F(2,6)=8.74; p=0.017) and a segment-vision interaction (F(2,6)=5.86; p=0.039) on the length error. Length error was increasing from segment 1 to 3 for the eyes closed condition, while it was largest for segment two in the eyes open condition due to fact that subjects tended to walk around corner 1 and 2 with open eyes. The segment effect can partly be explained by the different length of segment 3, while the interaction illustrates the fact that in the eyes closed condition the errors increased more from one segment to the next than with eyes open.

2D distance error was slightly larger post-flight (0.74±0.53 m) than pre-flight (0.61±0.42 m), but the difference was far from being significant. Only vision (F(1,3)=12.66; p=0.038) and the segment-vision interaction (F(2,6)=12.83; p=0.006) had significant effects. The effect of vision is due to the much smaller errors in the eyes open condition (0.22±0.11 m pre-flight, 0.27±0.12 m post-flight).

3.2 Directional error

The directional error is described as the difference between the mean walking direction during each segment with respect to the previous segment and the required angle of turn from one segment to the next. Therefore, the directional error of the first segment only gives the heading error towards corner 1, while the directional errors during segments 2 and 3 give the errors of angular turn with respect to the preceding segment of the path. Note that directional error as defined here is not cumulative, as it is computed in relative coordinates. The mean absolute directions are evaluated from the lines of minimum least square distance described above.

Directional error was tested only for segment 2 and 3. Mean errors for the eyes closed conditions were -7.01±9.77 deg pre- and -9.28±8.23 deg post-flight, which shows a trend to underestimated the turns. The vision factor (F(1,3)=14.45; p=0.031) and the interaction segment-direction (F(1,3)=36.72; p=0.009) turned out to be significant.
To assess the absolute errors, the absolute mean directional error was tested as well, here day was found to be a significant factor (F(1,3)=15.25; p=0.030) caused by larger absolute errors in the post-flight testing. The two way interactions segment-direction and segment-vision were also significant.
The segment-direction interactions are due to individual differences between the clockwise-counterclockwise conditions, the effect of day on absolute directional error shows that post-flight directional deviations were larger than pre-flight.

3.3 Mean walking velocity

Mean walking velocity was computed by dividing the walked length by time needed for one segment to walk.

Subjects walked slower post- than pre-flight for both eyes closed (0.73±0.10 m/s pre-flight, 0.66±0.10 m/s post-flight) and eyes open (0.84±0.08 m/s pre-flight, 0.81±0.10 m/s post-flight) conditions.
All main factors except of direction turned out to be significant, i.e. segment (F(2,6)=21.68; p=0.002), vision (F(1,3)=28.28; p=0.013) and day (F(1,3)=12.26; p=0.039). The interaction direction-day (F(1,3)=10.62; p=0.047) was the only significant two-way interaction. Slower walking velocity was found for segment 3, with eyes closed, and post-flight.

3.4 Corner parameters

We tried to describe the way how subjects walk around a corner by several parameters. The tangential linear velocity turned out to be a minimum at the cornerpoint which is preceded by a maximum of angular head velocity. The maximal angular velocity of the trajectory coincides with the minimum of the tangential velocity. This means, that prior to walking around the corner the subjects turn their head in the new direction. The angular velocity vector was computed from the angular position of head in space. The maxima of its vertical component, which express the yaw angular velocity, were determined for the head turns at corner 1 and 2. Additionally, the time between those maxima and the corner point were evaluated. This parameter is supposed to show the coordination between head and trunk for walking around a corner.

Angular head velocity (eyes closed : 137±38 deg/sec pre-flight, 124±29 deg/sec post-flight) showed significance for corner (F(1,3)=227.8; p=0.0006), direction (F(1,3)=15.33; p=0.030) and corner-vision interaction (F(1,3)=35.47; p=0.009).
Time between max. head velocity and min. tangential velocity was always negative, showing that the head turned always before the body went around the corner. It increased from pre- to post-flight (eyes closed : -0.35±0.27 sec pre-flight, -0.47±0.27 sec post-flight; eyes open : -0.25±0.10 sec pre-flight, -0.28±0.11 sec post-flight). None of the main factors, but direction-vision (F(1,3)=26.15; p=0.014) and vision-day (F(1,3)=49.10; p=0.006) interactions were found to be significant. The vision-day interaction was caused by the significantly larger increase of head lead in the eyes-closed condition compared to the eyes-open condition.
Tangential walking velocity had significant effects for segment (F(1,3)=62.31; p=0.004) and for day (F(1,3)=11.30; p=0.043).

Here, the most interesting result is the day-vision interaction for the time between max. head velocity and min. tangential velocity. It is caused by a larger post-flight head lead in the eyes closed condition which means that post-flight subjects turned their head earlier before reaching the corner than pre-flight.

4. Discussion

Repeating a previously seen trajectory without vision has been examined since Thomson's [5] experiment on locomotor pointing. However, most of the work concentrated on walking towards one target. For two different segments, one straight ahead and the second perpendicular to it, [6] showed that subjects are able to reproduce previously seen distances correctly by walking.

A similar task to the one presented here is called "triangle completion". The subject is guided over two legs, and then he/she attempts to return directly to the point of origin [7,8]. Length of the walked segments and their sustaining angle are varied, the measured parameters are : the error in subject's turn toward the origin after walking the first two legs, and the error in the distance that the subject subsequently walked to complete the third leg. Both of these errors show a pattern of systematic regression to the mean: subjects tend to overrespond when the required distance or turn is small and to underrespond when it is large, similarly for both blind and normal subjects [9].

However, triangle completion has one major drawback in indicating disturbances in complex spatial understanding in blindfolded individuals : some errors that are made during the guided walk and the return walk will not be seen in the results. Imagine a subject overestimating his walked distance by a certain factor, but making no other errors : this subject will perfectly perform the triangle completion, but will fail in reaching the first and second corner in our task.

Therefore, we have chosen the reproduction of a previously seen path by means of locomotion. Hence, the performance of the locomotor pointing allows to quantify misperception of linear and angular self-displacement.

Astronauts have reported anecdotally about problems in walking straight paths or going around corners when visual information is suppressed. However, little is known about the influence of these modifications on spatial orientation during free locomotion following space flight. The experiment reported above tried to asses this question by having subjects walk a triangular path pre- and post-flight with and without visual information.

The subjects showed inter-individual differences especially for directional deviations from the path in the vision occluded condition even pre-flight; the characteristics of these differences persisted throughout all experimental sessions. However, the absolute directional errors turned out to be larger post-flight, which means that subjects had larger directional errors but in different directions. There was, however, a trend to a larger underestimation of the angle turned at each corner in the post-flight condition. In contrast to directional errors, the length of the legs walked was similar pre- and post-flight. If this trend is verified within additional subjects, it would suggest that the perception of self-displacement during turning, but not during linear motion, has been changed due to the stay in microgravity. A possible explanation could be the development of a mismatch between information from otoliths and semicircular canals during whole-body turns in microgravity. This change in canal-otolith interaction may underlie the disturbances in locomotion experienced by returning astronauts.

However, due to the changes in walking velocity, all results have to be interpreted carefully, since previous experiments [10] showed that angular as well as linear path integration performance heavily depends on velocity. All changes found could be caused by the most significant finding, the lower walking velocity during post-flight testing. The found correlation between angular and linear velocity suggests that post-flight decrease in velocity as found for example for saccades [11] seems to be a general effect of space-flight.

The question remains, however, why subjects walk slower during the post-flight experiments. One explanation, which relates to other findings like decrease in saccade velocity, could be that slower motor performance is caused by fatigue due to the prolonged stay in weightlessness and return to earth.

Another possible explanation might be that a task as simple as walking towards a previously seen target needs a larger cognitive effort after spaceflight, which would slow down motor performance. This implies that mechanisms like computing self-displacement from somatosensory and/or vestibular inputs and updating of spatial information are disturbed by the stay in weightlessness and have to be re-acquired after return. The found changes in the time between head turn and turning around the corner also point towards a disturbed head-trunk coordination, which would corroborate the hypothesis that even the basic motor program of walking around a corner may have to be re-learned during the re-adaptation period.

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