

The importance of head-free gaze control in humans performing a spatial orientation task

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Abstract

The present study aimed at investigating how a specific instruction concerning gaze orientation, which involved active head motion, could influence the performance of human subjects in a self-controlled whole-body rotation task in the dark. Subjects were seated on a mobile robotic chair that they controlled using a joystick. They were asked to perform 360° rotations while maintaining, when possible, the gaze on the estimated position of an earth-fixed target. Subjects performed better when gazing at this target than when no target was shown. Furthermore, performance was significantly related to head stabilization in space. The results reveal the importance of head-free gaze control for spatial orientation in so far as it may involve spatial reference cues and sensory signals of different modalities, which may be beneficial to self-motion perception.

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Adequate orientation in space requires information concerning the position and movement of the different body segments (head, trunk, feet). In the absence of vision, head motion in space is perceived thanks to the vestibular system which detects both linear and angular head accelerations. Psychophysical experiments have demonstrated human subjects' capacity to store and retrieve the magnitude of passive whole-body rotations [2,3,6,14]. These experiments did not permit free head movement so that the vestibular system was stimulated by the exact imposed whole-body motion. However, the head is normally mobile with respect to the trunk. When it is the case, the perception of trunk motion in space requires the integration of neck proprioceptive signals and efferent copy of motor commands in addition to vestibular signals. Mergner et al. [10,11] have suggested that vestibular and proprioceptive signals are linearly summed for the perception of trunk in space. They proposed a "down-and-up channeling" principle, by which the body support is linked via coordinate transformations to the internal notion of physical space provided by the vestibular system. This model could explain

the conscious perception of passive horizontal rotations of the trunk, the head, or both, in the dark by human observers. In these psychophysical experiments as well as in other related works [4,9] on the interaction of vestibular and neck proprioceptive signals, subjects were asked to estimate *passive* motion of head, trunk or both, or the relative motion of a space-fixed target. Yet, it has been shown recently in monkeys that there is a differential processing of vestibular information at the level of vestibular nuclei when head motion is self-generated [12]. Therefore it is most probable that the passive/active modality has an influence on self-motion perception.

Our aim was to study how a specific gaze control task involving voluntary head motion could influence self-rotation perception. The present experiment differs from other studies on angular motion perception as subjects had to assess self-motion in order to orient themselves with respect to a space-fixed target. Furthermore, vestibular and neck proprioceptive signals resulted from 'active' motion. This experiment follows another experiment [13], which showed that cognitive processes, such as the use of mental images of the environment, influence self-motion perception in the dark.

After giving their written consent, 13 healthy volunteers (26.6 ± 3.1 years old) participated in the present experi-

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ment, which was accepted by the local ethical committee. All the subjects who participated in the present experiment had also participated in the experiment described in [13]. Subjects were seated on a mobile robot (Robuter™, Robosoft, France) that was programmed to rotate about the earth-vertical axis (see [1,14]). The robot's motion was controlled by subjects with a joystick and was recorded to a precision of 0.1° at a sampling rate of 25 Hz. Subjects wore a light helmet supporting the infra-red diodes (LEDs) that were part of the eye movement measurement system (IRIS, Skalar). The helmet was connected to the robot metallic frame by a mechanical device acting as a goniometer: linked rods and joints transmitted horizontal head rotations to a rotary potentiometer. This mechanical system allowed the three degrees of rotation of the head as well as translation in horizontal plane within a 5 cm radius from center of rotation with negligible horizontal and vertical forces. Horizontal head and eye movements were recorded at a sampling rate of 180 Hz. Before the experiment and once the subject seated, a calibration procedure of eye and head signals was carried out. However, eyes motion was not quantitatively analyzed since eye in orbit position during gaze saccades could exceed IRIS linear range, but was recorded to check afterwards that subjects had followed the instructions. During the experiment, subjects wore headphones delivering wide band noise to mask auditory spatial cues. They had to keep their eyes open during rotations and to hold their head in the most natural and comfortable erect position.

Subjects were asked to perform four times a complete clockwise turn (360°) in the dark by driving the robot. Before each rotation, subjects were shown an earth-fixed target positioned at eye level and 3 m in front of them. They were asked to memorize the location of target and to follow it as long as possible with the gaze while turning, i.e. to maintain gaze fixed in space. Subjects were pointed out that, since they had to produce a 360° -rotation, the target would disappear from the visual field on the left side and would come back shortly afterwards into the visual field from the right side. At this moment, they had to make a gaze saccade to the memorized target and to maintain gaze oriented on it till the end of the rotation. An example of head motion and other signals is given in Fig. 1. After each rotation, we positioned the subjects back to the starting direction by turning the mobile robot very slowly at nearly constant velocity in order to limit the feedback on performance.

Mean rotation magnitude (\pm SD) was $326.5 \pm 78.5^\circ$. Performance in the present experiment can be compared to the performance of the same subjects in the experiment of Siegler [13]. This former experimental session will be referred to as 'No Target Condition (NoT)': subjects were simply asked to keep their eyes open and to gaze far ahead in front of them in the dark while performing the 360° whole-body rotations on the same set-up. Responses in the present experiment are closer to the expected 360° than

those executed by the same 13 subjects in NoT ($277.1 \pm 65.1^\circ$). A *t*-test showed that the difference between both experimental conditions was significant [$N = 52$, $t = -5.1$, $P < 0.0001$]. In [13], it had been observed that subjects spontaneously adopted different orientation strategies when no target was shown. From subjects' verbal reports following the experiment, they were categorized into two groups depending on their preferred orientation strategy, either an egocentric (body-centered subjects) or an allocentric strategy (environment-centered subjects). In the present experiment, like in NoT, the mean performance of environment-centered subjects ($355.3 \pm 75.0^\circ$) was significantly better than the mean performance of body-centered subjects ($308.56 \pm 76.3^\circ$) [$F(1, 50) = 4.7$, $P = 0.03$].

Head motion was analyzed (Fig. 2) during both gaze stabilization phases (Fig. 1). We studied the latency between

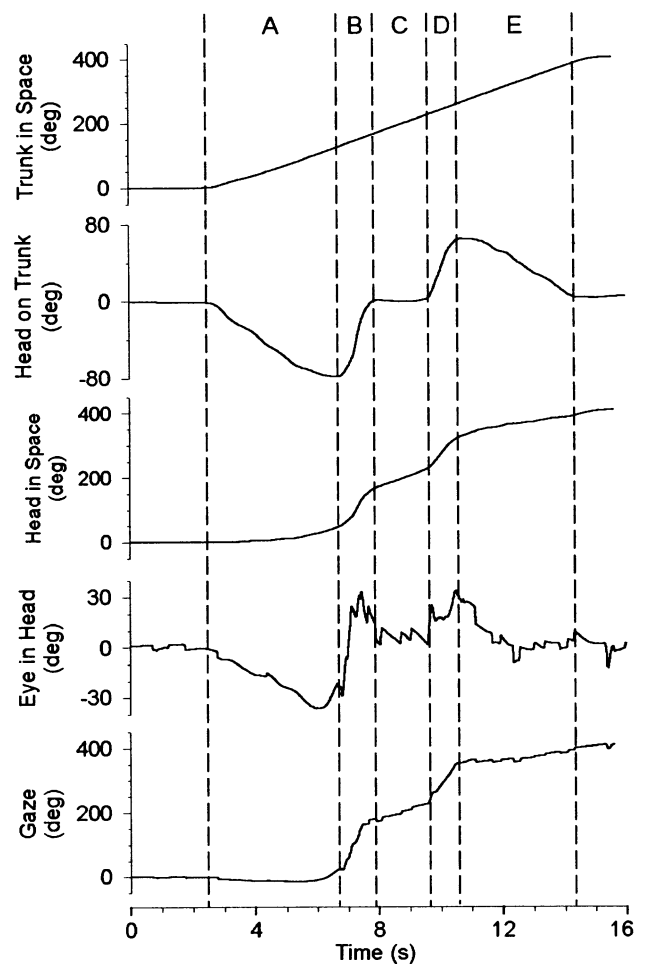


Fig. 1. An example of raw and calculated tracings during one trial, which was divided into five different time stages. (A) First gaze stabilization phase. (B) Subject brings the head back to the primary position. (C) Subject maintains his/her head stationary on trunk. Eye exhibits a vestibular nystagmus. (D) Anticipatory gaze saccade towards the estimated position of the memorized target. (E) Second gaze stabilization phase. Gaze = eye + head + robotic chair position.

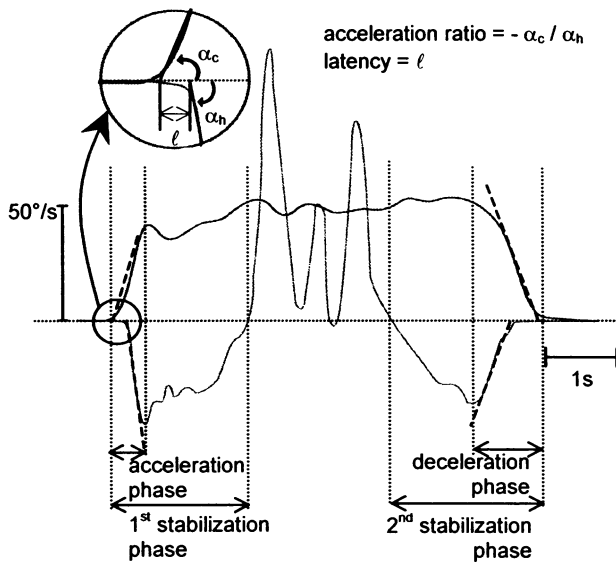


Fig. 2. Angular velocity of the robotic chair (thick line) and head angular velocity (thin line) during one trial. The stabilization phases correspond to the time periods during which the subject tries to fixate the memorized target at the beginning (1st) and the end of the motion (2nd). Latency, ℓ , was the delay between the onset of the robotic chair and head motion onset. Mean head acceleration α_h and robotic chair acceleration α_c were calculated through first order linear regression analyses of head angular velocity and chair velocity, respectively.

the onset of the robot rotation and the onset of head movement on the trunk. Mean latencies were 0.48 ± 0.46 s and -0.79 ± 0.57 s during the first and second stabilization phases, respectively. The first was the ratio of mean head acceleration to mean chair acceleration (see Fig. 2 for more details). This variable will be referred to as the ‘acceleration ratio’. The second variable was a ‘velocity ratio’, i.e. the ratio of maximal head angular velocity to maximal robot velocity during each of the gaze stabilization phases. During the first stabilization phase, the mean acceleration ratio was 1.00 ± 0.41 , thus indicating a very good average matching between head and robot initial accelerations. Mean velocity ratio was 1.45 ± 0.60 , meaning that maximal head velocity was on average 45% higher than robot velocity. During the second stabilization phase, mean acceleration ratio was 1.00 ± 0.72 , again indicating a perfect average matching between robot acceleration and head acceleration, yet with a very high variability. Velocity ratio was 1.35 ± 0.52 . This high variability is not too surprising since it is known that subjects do not have the same head movement propensity [5]. Furthermore, subjects were not explicitly asked to stabilize head in space. However, this large variability enabled us to perform a multiple linear regression test (Table 1) in order to analyze which of the involved variables were specifically related to rotation magnitude. There was a significant correlation between rotation magnitude and the subjects’ ability to stabilize the head in space during the first stabilization phase, characterized by the velocity ratio. As mentioned above, maximal head velocity was on average

45% higher than robot maximum velocity, but this multiple linear regression showed that the closer to unity the velocity ratio was, the better the performance. In other words, the better the head stabilization, the better the performance. Maximal head amplitude during the trial was also significantly related to rotation magnitude. The second stabilization phase, which gave more trouble to subjects, as shown by an increased variability, was not significantly correlated to performance. However, it should be noted that mean latency was negative, exhibiting therefore an anticipatory behavior of head motion with respect to robot motion. This stems from the active modality of the involved motions.

The present experiment shows that subjects performed better a 360° whole-body rotation in the dark when asked to stabilize gaze in space than when no specific instruction was given (NoT). Both conditions differ on the cognitive and sensory levels. When subjects are asked to stabilize gaze on a earth-fixed target, they have no other choice than using an environment-centered strategy, which has been shown to improve performance in a whole-body rotation task [13]. In order to assess whether subjects could use vestibular information for the estimation of self-rotation, we measured to what extent subjects stabilized the head in space when asked to stabilize gaze. We wanted also to look for a possible relationship between the robot rotation magnitude and the subjects’ propensity to stabilize the head. It is already known that subjects are able to stabilize the head in space when asked to do so [8,7]. In the present experiment, subjects were not required to stabilize head in space. However, the computation of acceleration ratios showed that head stabilization was good on average, especially during the first gaze stabilization phase. What could be the advantage of head stabilization when executing the rotation task? When the head is stable on the trunk, the perception of whole-body rotations is mediated by vestibular signals, which decay with a time constant of 15 s when velocity is constant [15]. This decrease is non negligible in the case of the rotations performed in the present experiment (Fig. 1, Fig. 2). On the other hand, when the head is maintained stable in space, vestibular signals are close to inex-

Table 1
Multiple linear regression analysis for variables predicting performance^a

	Adjusted $R^2 = 0.47$, $P < 0.0001$	
	β	P
Strategy group	0.24	0.054
Gender	-0.24	0.035
Head amplitude (1st stabilization phase)	0.40	0.05
Velocity ratio (1st stabilization phase)	-0.54	< 0.001
Head amplitude (2nd stabilization phase)	-0.03	0.83
Velocity ratio (2nd stabilization phase)	-0.12	0.32

^a Partial correlation coefficients (β) and P -values are given for each of the six independent variables.

istent. Therefore the perception of trunk orientation in space results from the integration of efferent copy signals and neck proprioceptive signals, which have been shown to indicate almost perfectly head orientation relative to the trunk [10]. When subjects stabilized the head in space for some time, the duration of the vestibular system stimulation was reduced compared to the NoT condition, increasing at the same time the ‘weight’ of neck proprioceptive and motor command signals. The integration of these sensory signals of different modalities most probably enabled a better perception of trunk rotation in space, and consequently a better performance. This hypothesis is supported by the results of the multiple linear regression analysis. Indeed, this test showed that one of the variable characterizing head stabilization was significantly correlated to performance. The maximum head amplitude during the first stabilization phase was also a significant factor: the more the subject moved his/her head, the larger the rotation magnitude. The head stabilization was in a way a space calibrating factor. To conclude, the results of the present study suggest the importance of head-free gaze control for spatial orientation in so far as it may involve spatial reference cues and sensory signals of different modalities which being associated may be beneficial to self-motion perception.

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