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Mental rotation of a letter, hand and complex scene in microgravity

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HIGHLIGHTS

- ▶ The study compared three typical mental rotation tasks in weightlessness and 1 G.
- ▶ We provided visual and tactile vertical cues to provide a more realistic surrounding.
- ▶ Reaction time and error rate of all stimuli showed typical behavior.
- ▶ Reaction time and error rate were equal in microgravity and 1 G.
- ▶ Allocentric and egocentric mental rotation were both not impaired in microgravity.

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ABSTRACT

Previous studies showed egocentric but not allocentric mental rotation tasks to be impaired in microgravity when feedback cues about vertical surroundings were restricted. Those studies are difficult to reconcile, however, since they were limited not only to small subject groups, but also differed dramatically in design. According to this lack, the present study was conducted in order to compare three typical egocentric and allocentric mental rotation stimuli in microgravity within a single experiment and using the same subjects and setup conditions. In order to simulate astronauts' working conditions in space, visual and tactile vertical references were provided. Six subjects mentally rotated letters, body parts, and complex scenes in parabolic flight during near-weightlessness and level flight conditions. Subjects viewed letters and judged whether they were mirror-reversed or not (task LETTER), viewed pictures of a hand and assessed whether it was a right or a left hand (task HAND), and viewed drawings of a person at a table that contained both a weapon and a rose and had to decide whether the weapon was on the right or left side of the table (task SCENE). Material could be in canonical orientation or rotated from 0° up to 180° in ±60° steps. We calculated reaction times and error scores for each task, orientation in each condition, and performed additionally intra-subject correlations between reaction times of both conditions for each task. We found typical reaction times and error scores for each stimulus category with increasing rotation level. More importantly, response time and error score were not impaired in microgravity, independent of stimulus type and orientation. This finding is further confirmed by correlation analysis. We conclude that the mental rotation of letters, hand shapes, and complex scenes is not affected by short periods in microgravity when visual and tactile vertical references are provided. This finding is relevant for astronauts who are normally aware of their surroundings, and it is in accordance with previous findings, where only egocentric stimuli were impaired in microgravity when sensory cues about the vertical reference were restricted.

1. Introduction

The detailed understanding of cognitive functions in weightlessness is very important for the safety of manned space missions [7]. To this end, basic cognitive functions such as memory retrieval, logical reasoning, decision-making, working memory, and Stroop-tasks have been extensively explored and declared to be not noticeably impaired in microgravity [3,15]. However, such findings were not consistently found for mental rotation, where subjects are typically asked to judge stimuli that are presented in different orientations. Reaction times consistently increase with the angle between the actual and a canonical orientation, and this has been taken as evidence that the stimuli must be mentally rotated into canonical orientation before the judgment is made [9,10,19]. Previous studies that explored participants' ability to mental rotate

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objects in microgravity found egocentric body parts and human shapes to be impaired [6], but not allocentric object-based mental rotation tasks such as 3D-cubes [6,13,17]. These studies argued that allocentric tasks are not influenced by the effects induced by the missing gravitational force that can disturb vestibular and somatosensory processes, and they suggest that allocentric tasks can be solved by means of visual–spatial processes [7].

This outcome seems to suggest that egocentric and allocentric stimuli may be differently affected by microgravity. Those studies explicitly obscured visual reference frames within the environment in order to reduce the possible use of a visual compensation mechanism. This also increases the participants' dependence on egocentric (i.e., vestibular, somatosensory) information, which is known to be disturbed in microgravity [3]. It is important to note, however, that during everyday work (e.g., inside a space station) astronauts are routinely provided with visual cues from their surroundings and thus are able to use visual information, which is known to compensate for vestibular disturbances, to perform these tasks [2,3,7,12,21]. Therefore, providing subjects with visual information about their environment may limit the gravitation-induced effects on mental rotation tasks because of the compensatory effect of visual references that can be employed during distorted vestibular and proprioceptive sensations. In order to discover whether or not this is the case and to gain a better understanding of microgravity influences on mental rotation performance under more realistic working conditions, it may be useful to use data that provide subjects with both visual and tactile information concerning vertical reference. This could, for example, be realized by preventing the visual field not to the experiment tasks presented on a screen but to ensure the visibility of the plane's interior. In addition, tactile information could be provided by attaching subjects to a rack that provides tactile cues to the back of the legs, gluteus, and dorsum.

In addition, mental rotation studies in microgravity demonstrate an indisputable lack of experimental evidence because their conclusions are based on a very limited set of studies that also display distinctions between and within experimental designs and methodology. These studies involve a variety of experimental conditions, were performed in different body positions, did not employ both allocentric and egocentric tasks within any single experiment, used different medications both within individual studies and between multiple studies, and used different subjects, and involved different control conditions (e.g., [6,17]). These issues may have arisen because experiments in weightlessness are often confronted with very limited flight times and subject capacities. Nevertheless, truly convincing data must be obtained from standardized conditions, including tasks, flight protocol, control measurements, medication, and parabolic flight experience.

In order to yield results that are of practical consequence for astronauts and to overcome this lack of experimental evidence, the present study aims to explore whether typical allocentric and egocentric mental rotation tasks are affected by microgravity when visual and tactile cues about the surroundings are provided. In order to investigate specifically gravity-induced effects, we employed the mental rotation of external objects, body shapes, and complex scenes within a single experiment, with the same subjects, the same environmental conditions, the same medication, and the same parabolic flight experience and procedure. To our knowledge, this is the first study that compares all three stimulus categories in microgravity. We hypothesize that, by providing subjects with visual and tactile vertical reference to their environment, not only allocentric but also egocentric mental rotation will be unimpaired in microgravity.

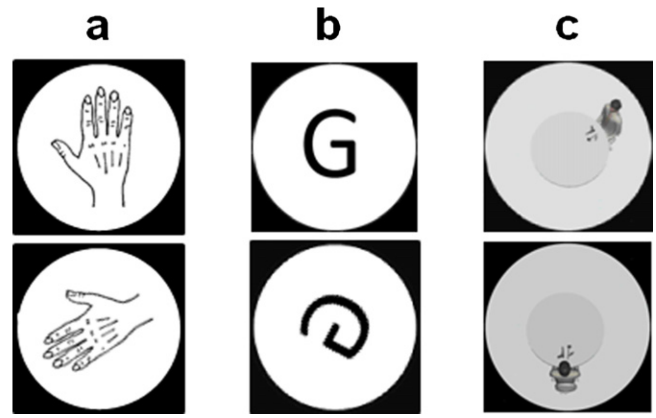

Fig. 1. Examples of stimuli in task HAND (a), LETTER (b), and SCENE (c). Stimuli requiring a right-button response are shown in the top row, and those requiring a left-button response are shown in the bottom row.

2. Materials and methods

2.1. Subjects

Six right-handed male volunteers participated in this study (aged 24.8 ± 2.8 years) during a parabolic flight campaign. They had no prior experience in sensorimotor research and no history of vestibular or sensorimotor deficits, and signed a written informed consent statement before participating. All participants underwent a clinical check prior to the campaign and received scopolamine approximately 1 h before takeoff to prevent motion sickness. The study was pre-approved by the Ethics Committee of the German Sport University.

2.2. Parabolic flight maneuver

Data were collected on board an Airbus A300 "Zero G". From a horizontal flight, the Pilot pulls the aircraft up until an angle of 47° in relation to horizontal flight is reached. During this so-called "pull up" phase, which lasts for about 20 s, the human organism and internal space of the aircraft are accelerated by approximately 1.8 G. This phase follows a thrust reduction that results in a 22-s phase of microgravity with about 0 ± 0.05 G. After reaching an angle of 42° toward the surface, the thrust is reactivated, leading to the so-called "pull out" phase. This hypergravity phase again lasts for about 20 s and accelerates the organism about 1.8 G. These maneuvers are made repeatedly for 30 times, with differing durations of horizontal flight periods (between 2 and 8 min) under normal gravity conditions.

2.3. Procedures

Subjects were seated 50 cm in front of a laptop monitor (17 in., 1280×1024 pixels) on which single grayscale images were presented sequentially. The monitor was mounted to a rack, and subjects were secured by means of two-point seat belts to prevent floating during phases of microgravity. The subjects were not prevented from seeing their surroundings, and they were also provided with tactile cues of the vertical via the rack, which was in contact with the back of their legs, gluteus, and dorsum.

In accordance with the flight profile, the experiment was subdivided into 22-s trials, and mental rotation tasks were presented within those trials. In task HAND, images of the back of a hand (see Fig. 1a) were presented, and subjects were instructed to judge whether they saw a right or a left hand. In task LETTER, images of the letter G (see Fig. 1b) were presented, and subjects judged whether each letter was presented non-reversed or mirror-reversed. In task