Geometric illusions in astronauts during long-duration spaceflight

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In our previous studies, we have shown that the occurrence of geometric illusions was reduced in vestibular patients who presented signs of otolith disorders and when healthy observers were tilted relative to gravity. We hypothesized that the alteration in the gravitational (otolith) input was responsible for this change, presumably because of a connection between vestibular and visual–spatial cognitive functions. In this study, we repeated similar experiments in astronauts during long-duration spaceflight. In agreement with the data of otolithic patients, the inverted-T geometric illusion was less present in the astronauts in 0*g* than in 1*g*. In addition, the vertical length of drawings made by astronauts in orbit was shorter than that on the ground. This result is also comparable with the otolithic patients who perceived the vertical length of line drawings to be smaller than healthy individuals. We conclude that the impairment in the processing of gravitational input in long-duration astronauts affects their mental representation of the vertical dimension similar to the otolithic patients. The astronauts, however, recover to baseline levels within 1 week after returning to Earth. *NeuroReport* 23:894–899 © 2012 Wolters Kluwer Health | Lippincott Williams & Wilkins.

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Introduction

Recent studies have emphasized the interactions between vestibular and cognitive visual–spatial processes [1]. The dynamic vestibular input from the semicircular canals is associated with vestibular and visual interaction, whereas the static input from the otolith organs can alter performance in visual psychophysical and higher cognitive tasks [2]. In a previous study, we have shown that the occurrence of geometric illusions generated by the arrangement of vertical and horizontal lines such as the well-known inverted-T illusion [3] was reduced in vestibular patients who presented central signs of otolith disorders [4]. The inverted-T illusion, as well as the Ponzo and Müller-Lyer illusions (Fig. 1a–c), which induce horizontal or vertical length misestimation [5], were also reduced in healthy observers tilted relative to gravity [6]. It is well known that the sensitivity of otolith inputs is reduced when an observer is tilted relative to gravity [7,8]. We had therefore proposed that the alteration of the gravitational, otolith input was responsible for the decreased occurrence of geometric illusions in both otolithic patients and healthy tilted observers.

In this study, we tested this hypothesis by investigating the occurrence of geometric illusions in astronauts on board the International Space Station (ISS). The rationale was that continuous exposure to free-fall (0*g*) in orbit for several months is more comparable with the sustained change in the vestibular and cognitive interactions observed in otolithic patients than a transient tilt relative to gravity. In addition, testing astronauts during the immediate postflight period allows studying the recovery of cognitive visual–spatial functions following adaptation to spaceflight in the same way as otolithic patients after an intervention. We predicted that the geometric illusions that were affected in otolithic patients, such as the inverted-T figure, would show the largest alterations in astronauts when in orbit. If these alterations were indeed because of an adaptation of the cognitive–vestibular interactions during spaceflight, then they should also temporarily carry over to the postflight period after return to Earth.

Previous studies have shown that geometric illusions are dependent on the features of the figures such as their length, their thickness, the angle of the oblique lines, etc. [5]. Therefore, we first measured the magnitude of the geometric illusions used in this study in a large population of healthy individuals on Earth to determine the normative 1*g* responses, with which we could compare the responses of our astronaut-participants both in 1*g* before and after their flight, as well as in 0*g* while in orbit.

Also, in our earlier report, we showed that when presented with a line drawing of a square, the otolithic patients tended to perceive a perfect square when the height of the drawing was 5–10% shorter than its width (see fig. 3 in [4]). This result was in agreement with the decrease in the inverted-T illusion in the otolithic patients. Our second objective was to test whether such an alteration in the mental representation of basic geometric shapes was also observed in astronauts during

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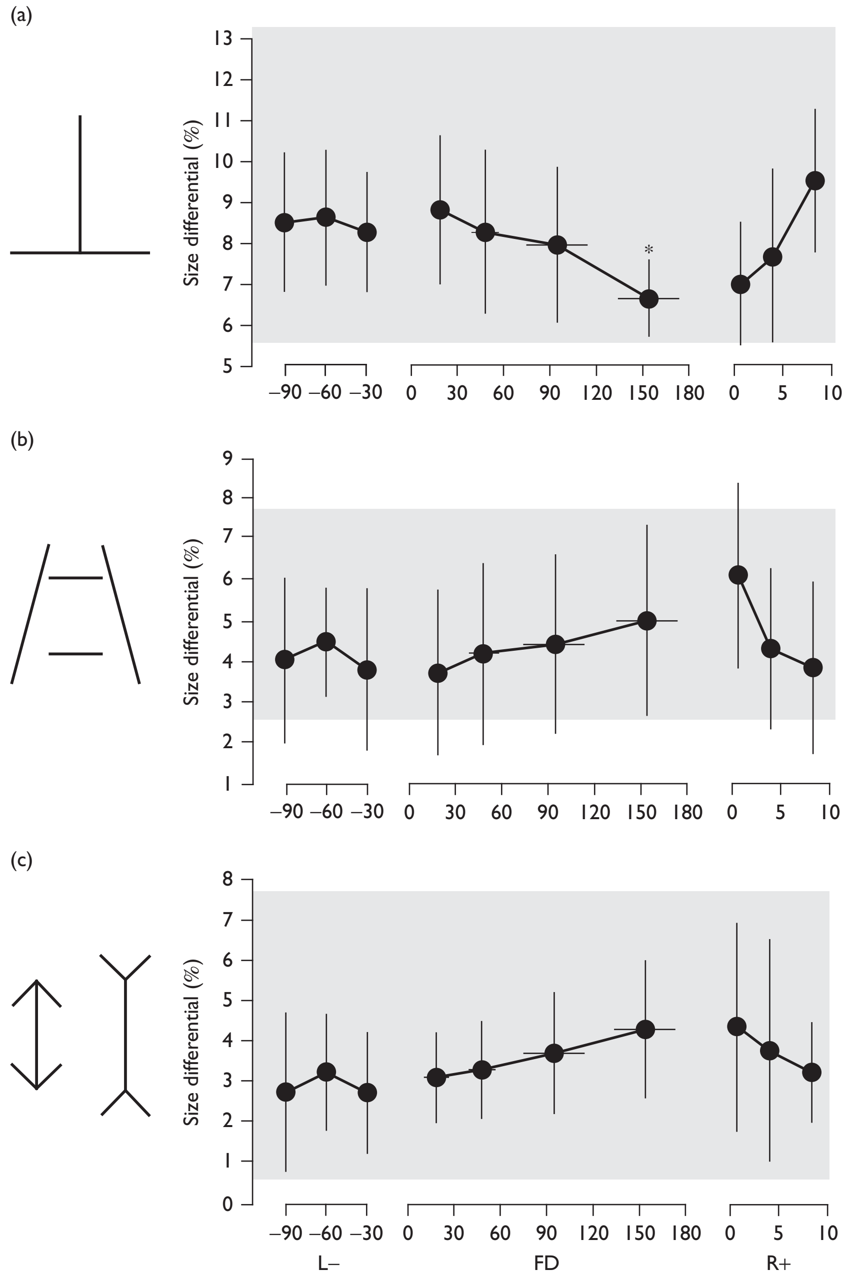
Fig. 1



Differences between the length of the horizontal and the vertical lines in the inverted-T illusion (a), the horizontal lines in the Ponzo illusion (b), and the vertical lines in the Müller-Lyer illusion (c). Mean±SD of six trials for the eight astronauts before (L −), during (FD), and after (R +) a space mission. The shaded area represents the mean±SD responses for the 91 ground-based controls. *$P<0.05$ relative to L − 30 days.

long-duration 0*g* exposure. Because of time constraints, rather than presenting geometrical shapes with various sizes, we simply asked the astronauts to draw a perfect square and a cross with equal horizontal and vertical dimensions on a digitizing tablet. Experiments on board the ISS were conducted with the astronauts free-floating and in darkness, which eliminated static otolith, somatosensory, and visual orientation cues.

Materials and methods

Study participants

Eight astronauts (one woman and seven men, aged 45–56 years) were tested before, during, and after a long-duration mission on board the ISS. Mission durations ranged from 57 to 195 days (mean 154.4). All the participants were tested at least three times before the flight (at ∼L − 90, L − 60, and L − 30 days), four times in-flight [flight day (FD)], and three times after the flight (at R + 0 or R + 1, R + 4, and R + 8 days). In addition, a control population of 91 participants (34 women and 57 men, aged 34–57 years) was tested in normal gravity (1*g*) on the ground. Informed consent was obtained from all participants. Study approvals were obtained from the investigators' institutional review boards, as well as from ESA, NASA, and JAXA medical boards. All participants had normal or corrected-to-normal vision with no known visual or vestibular deficits.

Geometric illusions

Participants were presented with the inverted-T, Ponzo, and Müller-Lyer figures (Fig. 1a–c) in a head-mounted visual display (Z800 3DVisor; eMagin Corporation, Bellevue, Washington, USA). All external visual references were blocked by a fabric cover placed over the head-mounted display. The figures were made of white lines on a black background. The figures subtended a viewing angle of 30° at a perceived distance of ~50 cm. The three figures are known to generate systematic distortions in the apparent size of some of the pattern elements [5]. The participants were asked to adjust one segment of the figures using a finger trackball mouse (3G GreenGlobe Co., Ltd, Taipei City, Taiwan) so that it had the same apparent size as a reference segment.

When presented with the inverted-T figure, the participants could decrease or increase the size of the vertical line segment to match that of the horizontal line segment, or vice versa. Six trials were performed, half of them with the horizontal segment, the other half with the vertical segment. In each trial, one segment started off with a very large size differential. The same method was used for the other two figures, with the participant adjusting the size of one of the vertical lines in the Müller-Lyer figure or the size of one of the horizontal segments in the Ponzo figure. During each session, the figures were presented in a random order.

Line drawings

In the second test, a 5-s video clip showing someone drawing a square or a cross was shown in the head-mounted display. The test participants then drew the specified shape using an electronic pen on a digital writing tablet (Intuos A4; Wacom Co., Ltd, Vancouver, Washington) without visual feedback. The participants were instructed to match their drawing to their internal representation of a perfect square or cross. The size of the tablet's active area was 305 × 231 mm and the spatial resolution was 5080 lpi. The tablet was attached to the participants' thighs by knee straps. Each shape was drawn six times. There was no time limit set for the duration of the drawings.

Data analysis

For the geometric illusions, we calculated the size differential between the adjusted and the reference segments. For each of the hand drawings, we calculated the ratio between the vertical and the horizontal length of the figure drawn. The responses for the six trials were averaged individually and the mean and SD were calculated for each flight period. Because the in-flight sessions were not performed at the exact same days for each participant (depending on the mission duration and other on-board operations), the responses were binned by flight periods, that is, FD6–30, FD38–60, FD65–120, and FD133–192. The number of data points per flight period was not the same. However, all the data were included in the analysis because of their rarity.

Statistical analysis consisted of one-way analysis of variance (ANOVA) with post-hoc Dunnet's adjustment across eight levels (the combined 1*g* data of the control group and the astronauts L – 30 days session; the four in-flight sessions, and the three postflight sessions).

Results

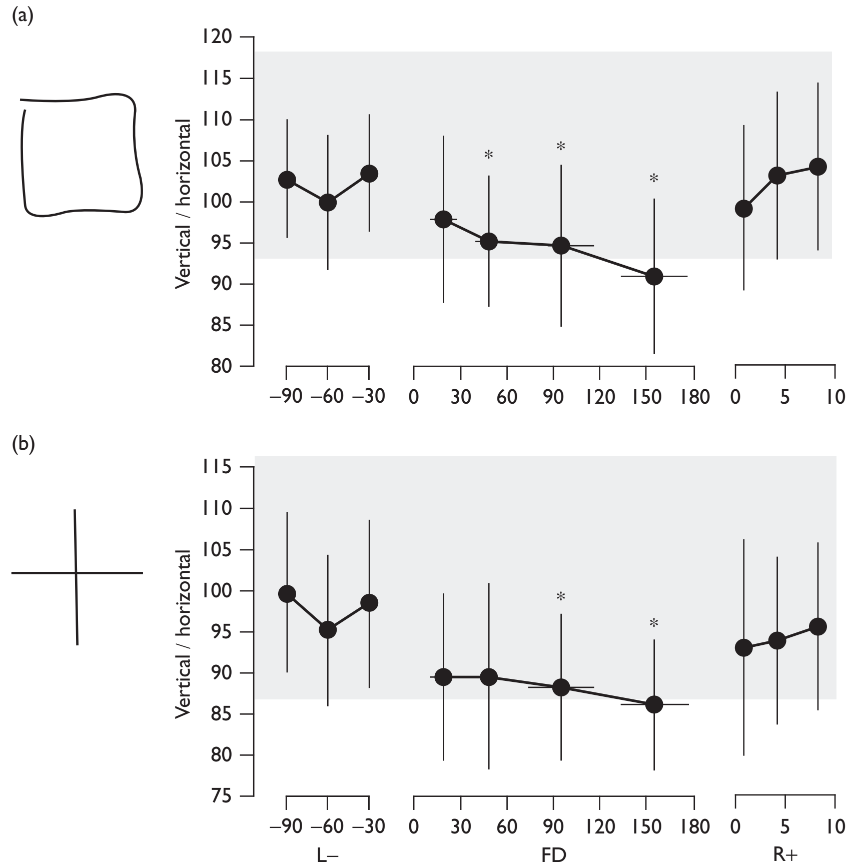
Geometric illusions

Figure 1 shows the results with the geometric illusions for the eight astronauts before the flight, in-flight, and after the flight. The shaded area on each graph also represents the range of responses seen in the ground-based, healthy participants ($n = 91$). Their mean size differential was 9.6 ± 3.7% (SD) for the inverted-T, 5.2 ± 2.5% for the Ponzo, and 4.3 ± 3.5% for the Müller-Lyer figures.

There was no significant difference between the three preflight responses across all astronauts and illusions (F < 1), which confirmed that the magnitude of the illusions did not change with the repetition of the tests [9]. The preflight responses of the astronauts were generally smaller than the ground-based controls, but this difference was not found to be significant. Therefore, the ground-based data and the last trial of the astronaut preflight data (L – 30 days) were combined ($n = 99$) for analysis. When taken all together, during ground-based testing, the overall size differential was significantly larger [$F(2,294) = 76.78$, $P < 0.001$] for the inverted-T figure (mean 9.4%) than for the Ponzo (mean 5.1%) and Müller-Lyer (mean 4.1%) figures.

A one-way ANOVA [$F(7,157) = 2.09$, $P = 0.048$] showed that the inverted-T figure is the only illusion that showed a significant change in-flight compared with before the flight (Fig. 1a). The size differential of the inverted-T illusion decreased to 6.6% after 3 months in orbit. This decrease carried over (7%) to the early postflight period (R + 0 to R + 1 day). Later postflight (R + 4 and R + 8 days) responses had returned to preflight values (8.3% on L – 30). The decrease in the inverted-T illusion seen in the astronauts is consistent with that previously reported by otolithic patients on Earth [4].

Fig. 2



Ratio of vertical and horizontal length × 100 for the line drawing of a square (a) and a cross (b). Mean±SD of six trials for the eight astronauts before (L −), during (FD), and after (R +) a space mission. The shaded area represents the mean±SD responses for the 91 ground-based controls. $^*P<0.05$ relative to L − 30 days.

Line drawings

One-way ANOVAs showed that the ratios of vertical versus horizontal length for the hand drawings of squares and crosses were significantly reduced during spaceflight [$F(7,157) = 4.49$, $P < 0.001$ and $F(7,156) = 3.813$, $P = 0.001$, respectively]. When comparing the results for the eight astronauts, there was no difference between the three preflight responses across participants, which also confirmed that repeating the tests at regular intervals did not alter the individual responses. In-flight, the astronauts drew squares with a shorter height (mean 5.4–12.1%) than width (Fig. 2a) and a cross with a vertical bar shorter (mean 9.2–12.6%) than the horizontal bar (Fig. 2b). This decrease was significant for FD38–60 ($P = 0.009$), FD65–120 ($P = 0.034$), and FD133–192 ($P = 0.004$) for the square, and for FD65–120 ($P = 0.029$) and FD133–192 ($P = 0.028$) for the cross. The responses for both drawings returned to normal within 1 day after the flight. This result indicates that simple geometrical shapes with a shorter vertical size presumably appeared normal to astronauts after long-term exposure to 0*g*. The same observation was made previously during a short-duration flight in one astronaut [10] and in otolithic patients on Earth [4]. The data reported in fig. 3 of reference [4] included the overall measurements with shapes such as square, a circle, and a cube. When the height of a square was equal to its width, 80.8% of healthy participants and 67.5% of otolithic patients perceived it as a perfect square. When the height was 5% less than its width, only 48.4% of healthy participants continued to perceive it as perfect, whereas this was still the case for 68.5% of otolithic patients. Thus, clearly, both the otolithic patients on Earth and the astronauts in orbit had the similar perception that a 5–10% vertically compressed square looked perfect.

Discussion

The magnitude of the inverted-T illusion and the perceived vertical height of geometrical figures decreased in astronauts during long-term exposure to 0*g*, just as they did for otolithic patients [4]. The inverted-T illusion became less pronounced (the vertical bar that appeared equal to the horizontal was shorter than usual – more compression) and perfect squares were drawn with the vertical dimensions compressed (suggesting that the vertical lines needed to match the horizontals were shorter than usual – more compression). The changes in the Ponzo and Müller-Lyer illusions were not significant, which also confirms the observations in the otolithic patients. The magnitude of the inverted-T illusion is considerably larger than the other two illusions on the ground; consequently, the magnitude of the Ponzo and Müller-Lyer illusions might be too small to observe a decrease in magnitude. Also, unlike for the inverted-T figure, the illusion for the Ponzo and Müller-Lyer is not that of a length misestimation between two orthogonal lines. Therefore, the difference found across the two types of illusions in-flight suggests that it is the judgment between horizontal and vertical segments that becomes less ambiguous after adaptation to 0*g*.

The similarities between the results found in the otolithic patients and the astronauts in terms of both the magnitude of the inverted-T illusion and the representation of geometrical shapes are a further confirmation of the role of the central otolith system in the mental representation of external space. Both the otolithic patients and the astronauts in 0*g* showed a decrease in the strength of the representation of objects in the vertical dimension. The vertical dimension is particularly affected presumably because the frames of reference normally used for spatial orientation and motion are either based on the gravitational vertical or the long-body vertical axis. Previous experiments conducted on astronauts in orbit have suggested that the magnitude of the idiotropic vector was reduced during adaptation to 0*g* [8,11,12], but returned to baseline after a few days back on Earth. With a gravitational vertical almost absent and an idiotropic vector whose amplitude is reduced, there would be less of reliance for spatial orientation toward the vertical dimension. Consequently, the geometrical illusions on the basis of the difference between horizontal and vertical sizes would be reduced. Other experiments on spatial orientation during long-duration spaceflight have indicated that the idiotropic vector was initially dominant in the judgment of 'above'. However, after 1 month in orbit, the previously strong correlation between the actual body position and perceived above weakens, suggesting that the idiotropic vector amplitude has then reduced as a form of adaptive process [13]. Similarly, when observers on Earth are tilted relative to gravity, their perceived spatial orientation coincides with neither the subjectively perceived axis of gravity nor the idiotropic vector, but with an intermediate orientation [14].

The recovery of the astronaut responses to baseline within a few days after spaceflight suggests that the observed changes in the mental representation of the vertical are taking place at a central rather than at a peripheral level. Indeed, changes in the peripheral end organs in animals, such as number of hair cell synapses or the sensitivity of utricular nerve afferents, last for much longer periods after spaceflight [15,16]. In our study, as the otolithic patients show the same responses as the astronauts, this tends to confirm that their symptoms have a central origin [4]. Recent imagery studies have confirmed that the interaction between otolith and cognitive function might take place in the multisensory parieto-insular cortex [17,18]. Following post-traumatic vertigo, perilymph fistula, labyrinthitis, and phobic postural ataxia, these patients typically experienced typical otolithic syndromes, including a vertical falling, rising, or floating sensation; erroneous sensation of linear motion during transportation; and perceived tilt or distortion of the body or the environment [19].

Today, tests in vestibular patient tests are mostly investigating the functioning of the peripheral end organs (by injecting water or using a rotating chair). There is virtually no test of the central otolith function [19,20]. Simple tests such as those used in the present study might be helpful for the diagnosis of otolithic disorders and the follow-up of their recovery. Already, optical illusions are being used for exploring the syndrome of unilateral neglect and its recovery in patients with cerebral lesions [21] and the square drawing test has been used to test vestibular patients [22]. For vestibular patients, the responses to these simple tests could be compared between the upright and the supine position for investigating the integration of sensory inputs for spatial orientation.

Conclusion

Exposure to changes in gravity level or direction was known to elicit orientation illusions, errors in sensory localization, postural imbalance, changes in vestibulo-spinal and vestibulo-ocular reflexes, and even motion sickness [23]. The results of the present study indicate that an alteration in cognitive visual–spatial processing, such as the mental representation of the vertical shape of objects, is also taking place in reduced gravity. As a similar deficit was also observed in patients with vertigo of otolithic origin on Earth, simple visual cognitive tasks such as those used in this study might be useful in clinical settings.

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Conflicts of interest

There are no conflicts of interest.

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