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The unassisted visual system on earth and in space

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Abstract. Chuck Oman has been a guide and mentor for research in human perception and performance during space exploration for over 25 years. His research has provided a solid foundation for our understanding of how humans cope with the challenges and ambiguities of sensation and perception in space. In many of the environments associated with work in space the human visual system must operate with unusual combinations of visual and other perceptual cues. On Earth physical acceleration cues are normally available to assist the visual system in interpreting static and dynamic visual features. Here we consider two cases where the visual system is not assisted by such cues. Our first experiment examines perceptual stability when the normally available physical cues to linear acceleration are absent. Our second experiment examines perceived orientation when there is no assistance from the physically sensed direction of gravity. In both cases the effectiveness of vision is paradoxically reduced in the absence of physical acceleration cues. The reluctance to rely heavily on vision represents an important human factors challenge to efficient performance in the space environment.

1. Introduction

Perception is a complex process involving integrating sensations from many sources with expectations based on intent, motor acts and prior experience. Usually sensory signals are in agreement with expectations and assist each other in resolving ambiguities. For example, physical acceleration cues can assist the visual system interpret optic flow [4] and orientation [9, 11,16,17]. Perceptual errors may arise when information from one source becomes unavailable. When an object moves behind an occluder, for example, localization errors rapidly accumulate as predictions cannot be checked against sensory information [1,33]. In an aerospace environment some sensory information is often absent or misleading. Such an unusual sensory environment can lead to a number of well-documented issues related to spatial orientation, navigation and sickness that have been comprehensively investigated and reviewed by Chuck Oman [22–24,26].

Here we discuss two examples of responses to missing linear acceleration cues. The first example concerns perception in the absence of physical cues to linear self motion. In many aerospace environments visual motion and physical motion are presented in unusual combinations. For example, although some flight simulators are mounted on large moving platforms that can simulate some of the physical motion cues associated with flying, many simulators do not attempt to provide physical motion cues and rely instead on a purely visual simulation. Systems used to control remote vehicles, such as unmanned aerial drones, also generally provide only visual cues about the orientation and movement of the craft. If the operator were piloting a real aircraft there would be other physical cues available, especially physical accelerations. Teleoperators using remote cameras that provide them with visual information but no physical cues as to camera movement, such as the robotic-arm-mounted cameras on the International Space Station Mobile Servicing System, face a similar challenge. Furthermore, although movements

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in a microgravity environment generate normal linear accelerations, vestibular thresholds may be increased in space [3] effectively reducing perceived non-visual cues to motion. What are the consequences of the lack of physical motion cues to supplement or assist the visual system during translation? The second example involves the lack of vestibular orientation cues. In an orbiting space station or in interplanetary spacecraft gravity is effectively absent. How does the absence of the normally omnipresent gravitational reference signal affect the perception of orientation?

The problems experienced in these two examples are complementary. When simulating self motion using vision alone, the vestibular end organ indicates the direction of gravity as normal but is not stimulated by self motion: vision provides the only motion cue. On orbit an astronaut's movement around a spacecraft stimulates their vestibular system as usual but the accelerations due to gravity are absent: vision provides the major allocentric orientation cue. We will show that in both cases when vision provides what might be expected to be the most salient information, reliance on vision is paradoxically reduced.

2. The unassisted visual system on Earth

Moving about the world changes our viewpoint. Stable perception relies on our ability to predict how the direction of objects with respect to our head changes as we move about – a process known as spatial updating. Successful updating requires accurate knowledge of the relative motion between objects and the observer as well as knowledge about the layout of objects in the environment. Normally this process involves interpreting information about eye position [18], physical motion cues [14,21] and proprioception [2] to assist the visual system. The question as to whether visual information alone is enough to provide this information is controversial. For rotation, visual cues seem to be sufficient for automatic, obligatory updating [27]. For translation, however, the transformation required to predict the updated visual position of objects is considerably more involved. This is because each object in the scene moves differently relative to the observer depending on its distance and direction [15,32]. Here we test the effectiveness of spatial updating during ± 1 m, visually simulated, sinusoidal, linear translation presented using the Immersive Visual Environment at York (IVY) [28]. IVY is an 8' × 8' × 8' display environment in which high resolution stereo imagery is presented on each wall. Subjects sat within IVY and were presented with a textured virtual room within which a simulated playing card (of standard size) floated at various distances in front of them. For each trial the virtual room was oscillated in a cardinal direction (up/down, forwards/backwards or left/right). The simulated card was moved in phase with the room's movement but the amplitude of its motion was varied from trial to trial. The card was only present during one direction of room motion (right, up or towards the observer). The accuracy of spatial updating was assessed by asking subjects to identify whether the card moved more or less than the room. We used a staircase technique to find the amplitude of motion at which the card was perceived to be a stable feature of the simulated environment.

If the playing card were a fixed size and in a fixed position in the room then its simulated linear motion would be the same as that of the room, independent of its distance from the observer. However, Fig. 1 shows that the closer the target was to the observer, the less far the card needed to move in order for it to appear stable within the room. Subjects required the card to remain visually aligned with a fixed point on the background, effectively eliminating parallax between the card and the background, for it to be judged as room stationary. Subjects had a compelling impression of sitting in a rigid, moving, three-dimensional room and did not report that they perceived the simulated size of the card to change: size-distance invariance [13] was not violated since subjects perceived the size of the card as unchanging. Subjects generally did not report perceiving self-motion (vection), nor did they report any distortion of the simulated room that might have arisen for example from changes in the effective disparity cues provided by the immersive projective display.

These results indicate that in the absence of physical motion cues, spatial updating in response to visually simulated translation is performed incorrectly, in this case completely discounting the parallax appropriate for the depth difference between an object and the background. This is despite the compelling perception of three-dimensional structure that our observers reported and that such moving simulations typically induce [5, 30]. Although this preliminary experiment is unable to probe fully the 'perceptual solution' chosen by the subjects (did subjects ignore disparity cues or perceive the room as moving in some other path – perhaps rotating instead of translating?), the net effect is that subjects did not solve the problem as though the world was a stable 3D environment. The visually signaled motion

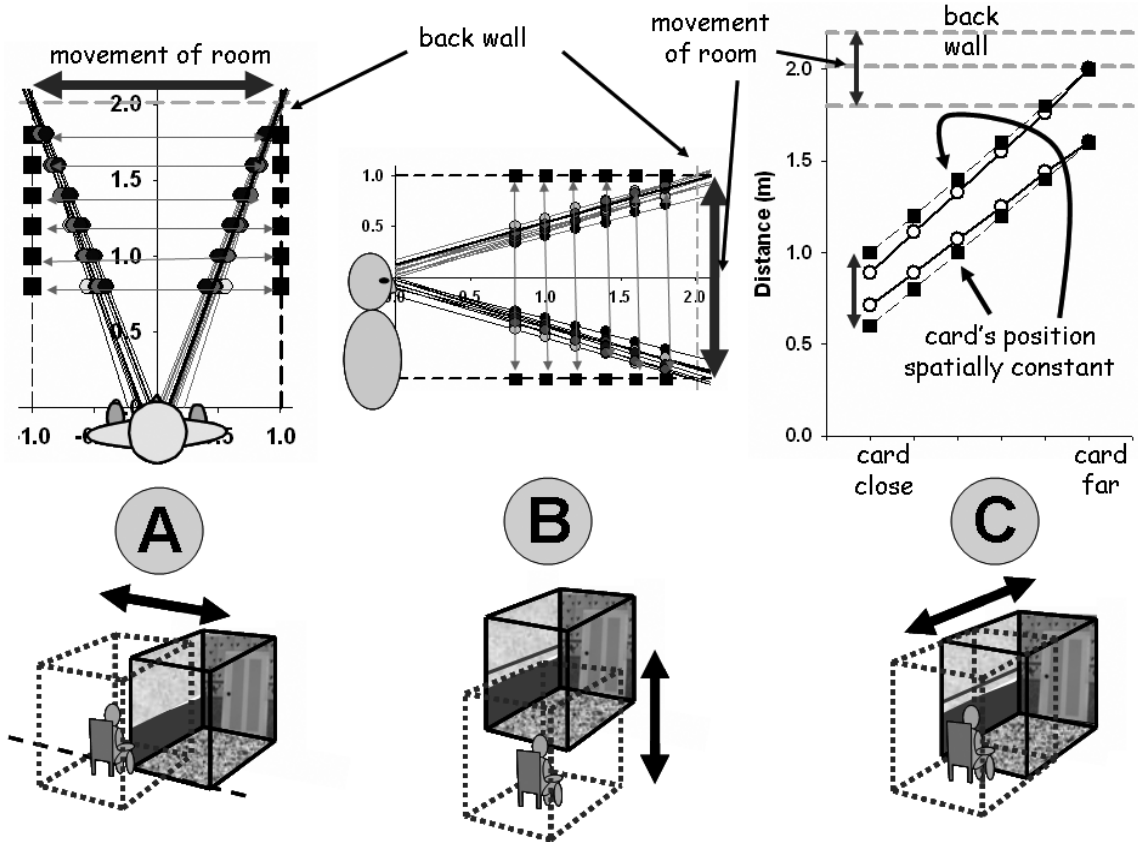

Fig. 1. Judging stability in the absence of non-visual cues to motion. Each graph plots the end points of the motion of a simulated floating playing card that was regarded as stationary relative to a moving room, plotted relative to room motion for several viewing distances. The filled squares and dashed lines indicate the end points of the geometrically correct distance that the card would have to move to be accurately simulated as fixed relative to the moving room. Circles show the end points of the motion of a simulated floating card that was judged as being room stationary. Judgements were made by 11 subjects during ± 1 m sinusoidal left/right (A) or up/down (B) oscillations of the room. For forwards/backwards motion (C) group average data points are shown. The thick solid lines are regression lines through the pooled data (slopes of 1.0 ± 0.02 for left/right motion, 0.8 ± 0.02 for up/down motion and 1.0 ± 0.13 for forwards/backwards motion) where a slope of 0 corresponds to room stationary and a slope of 1 corresponds to zero parallax (card lined up with a constant point on the background). Inserts below each graph illustrate the observer sitting in the centre of IVY with the physical location of the screens shown in dotted lines. The movement of the virtual room is indicated by a two-headed arrow for each condition.

of the room when unassisted by physical motion cues was not adequate to update the perceived position of objects within it correctly. This finding raises a concern about vision-only motion simulators in which critical judgements are made about the updated position of objects relative to the observer based purely on visual motion. We also predict spatial updating errors during microgravity associated with changes in non-visual linear motion thresholds [3] placing greater demands on the visual cue.

3. The unassisted visual system in space

In microgravity, the visual system operates unassisted by normal vestibular cues to the direction of gravity and this impacts a wide range of different perceptual processes including our understanding of which way is up. Determining which way is up is a critical question that underlies a vast range of perceptual and cognitive operations including character recognition [6], shape perception [29] and the recognition of faces [31]. Cues to the direction of up include visual, vestibular, kinesthetic and an internal representation of the orientation of the body, sometimes referred to as the idiotropic vector [19]. The consequence of microgravity on the perception of self-orientation is operationally critical. Following from issues raised in Chuck Oman's important review about perceived orientation in space [23], our group has identified two separable aspects of perceptual orientation – the subjective visual vertical (SVV)

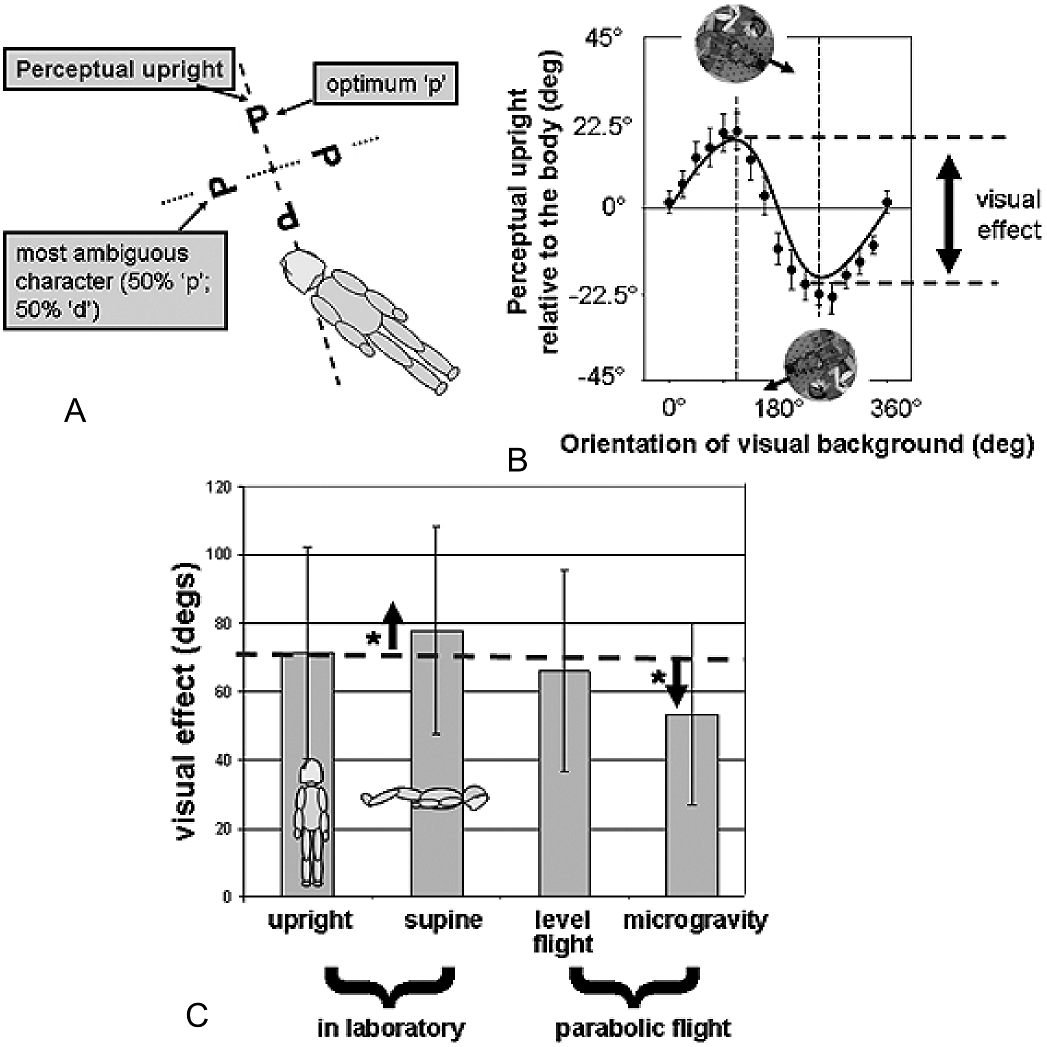

Fig. 2. The perceptual upright (PU) is defined as the orientation at which polarized objects (in this case a character) are most easily identified (A). The orientation of the visual background has a strong influence on this orientation when measured in the laboratory (B). Panel B also shows how we define the "visual effect" as the difference between the PU measured against the background in two pre-defined orientations shown as inserts in C. Minimizing the number of backgrounds tested is necessary because of the time constraint of parabolic flight (just 22s of microgravity per parabola). Although the visual effect increases when gravity is shifted from its normal orientation, aligned with the long axis of the body, by lying supine (C, compare first and second bars) the visual effect unexpectedly and significantly decreases during the microgravity phase of parabolic flight (C, compare third and fourth bars). See [7,8] for further details.

and the perceptual upright (PU) [7]. The SVV represents the visually probed direction of perceived gravity and the PU represents the preferred orientation for perceiving polarized objects such as faces and text.

The SVV is estimated by asking subjects to align a line in the direction which a ball would fall. The PU is estimated by presenting an ambiguous character at different roll orientations and identifying the orientations at which it is maximally ambiguous. In a normal gravity environment both the SVV [19] and PU [7] are affected by the direction of gravity, as well as body and visual background cues. Both the SVV [20] and the PU [10] are therefore affected by microgravity. Experiments using parabolic flights have shown that visual cues have less influence on perceived orientation during short-duration microgravity than expected from their weightings measured on Earth. Figure 2 summarizes results for the influence of different gravity states on the PU. As gravity is removed as a cue the perceptual up appears to be driven towards increased reliance on body (idiotropic) cues.

4. Conclusions

Integration of visual and non-visual cues is required for normal perception. When non-visual cues to self motion are unavailable to assist the visual system during translation systematic errors in spatial updating occur. When non-visual cues to self orientation are unavailable to assist the visual system, systematic errors can also occur. We therefore conclude that responding to the challenge of keeping astronauts comfortable and minimizing operational errors due to sensory changes in space may require providing alternative assistance to the visual system, perhaps by enhancing the visual cues themselves or by providing supplemental information through other sensory channels. Feedback using tactile cues correlated with visual motion to establish the stability of the world or artificial pressure cues correlated with a consistent visual upright might usefully become part of the training required to face the perceptual challenges of the space environment. Both our experiments suggest that, paradoxically, less emphasis is placed on visual cues in situations when the observer must depend on them most. The multisensory brain does not take kindly to the loss of a functional vestibular system, one of its most ancient senses. Understanding vestibular deprivation effects and developing appropriate countermeasures to them are key challenges to human perception in an aerospace environment, a field which owes considerable thanks to the contributions of Chuck Oman [12,25,26].

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