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The initial effects of hyperstereopsis on visual perception in helicopter pilots flying with see-through helmet-mounted displays☆

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A B S T R A C T

In see-through helmet-mounted displays (HMDs), image-intensifier tubes are located on the sides of the helmet. This HMD design increases the effective interpupillary distance and exposes the observer to hyperstereopsis. The modification of three-dimensional space perception by hyperstereopsis in laboratory studies is well known. Little is known, however, about its effects in real, operational conditions. The present study investigated the effects of hyperstereopsis on visual perception in helicopter pilots during the first flight of a night-flight training program using a see-through HMD. Fifteen pilots' percepts of distance and height under hyperstereoscopic viewing were assessed using a double-distance estimation task in standard flight circuits. In addition, two questionnaires were used to characterize the perceptual effects induced by hyperstereoscopic viewing during the first night flight, and to determine whether any aftereffects were still present during the 24-h period following the flight. Height and distance estimation errors were observed. On average, pilots tended to underestimate the near plane relative to the farther plane in the double-distance estimation task; this is the inverse of what is commonly observed under natural viewing. We ascribed this effect to a non-linear decrease in the hyperstereopsis effect with viewing distance. Six pilots experienced sensory illusions resembling a distortion of apparent visual space: the impression of "sinking into a hole" when landing, of objects appearing closer than they actually were, and reduced in size. Four pilots cited landing as the most difficult situation encountered during the flight. Only minor complaints were reported for the 24-h period following the flight. The results of this field study represent a step towards characterizing the perceptual and operational impact of this display technology in helicopter pilots during initial exposure.

1. Introduction

Modern tactical helicopter operations are increasingly being conducted at night and in all-weather conditions. See-through helmet-mounted displays (HMDs) provide visual information concerning the flight and aircraft status, and sensor images to pilots, who maintain visual contact with the outside world. Night vision sensor images and advanced flight symbology are superimposed on the pilot's view of the external world using a semitransparent combiner. As all relevant information is constantly available to the pilot regardless of his/her head position, the need to monitor cockpit displays—which diverts visual attention away from external events—is reduced, and situational awareness is enhanced [1]. This is especially important during critical "head-up, eyes-out" maneuvers that are performed close to the ground, such as landing. See-through HMDs may reduce the occurrence of spatial disorientation events, such as rotary-wing brownout [2].

The inclusion of night-vision capabilities in HMDs—especially stereoscopic HMDs—raises the issue of sensor placement [1,3]. In standard night-vision goggles (NVGs), the image-intensification tubes are located in front of the eyes. This results in a frontward shift of the helmet's center-of-gravity and an asymmetric loading of the head/neck system which contributes to musculoskeletal injuries in the neck [4]. A solution to this problem involves placing the image-intensification tubes laterally in see-through HMDs [5].

Although see-through HMDs with laterally displaced image-intensification tubes offer considerable physiological and operational advantages, they also introduce human factors challenges [1]. In particular, this type of stereoscopic displays increases—usually, by a factor of 4 or more—the effective interpupillary distance (IPD). This results in a particular form of distorted binocular visual stimulation known as hyperstereopsis, which affects binocular cues for the perception of three-dimensional (3D) space.

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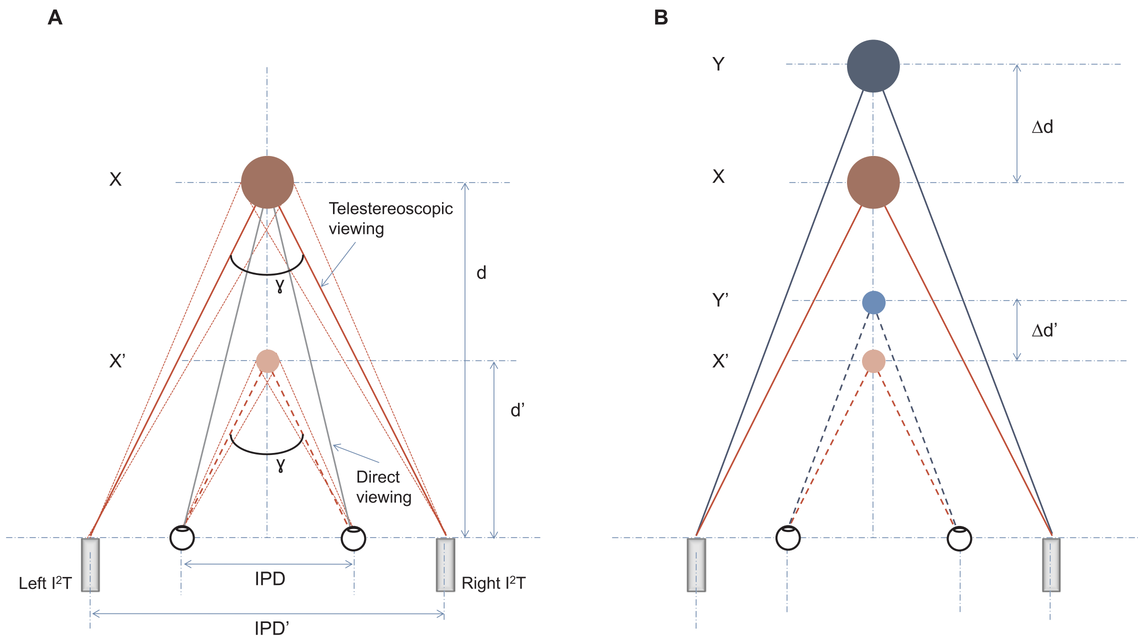

Fig. 1. Geometry of hyperstereoscopic viewing. (A) Egocentric distances and sizes. Hyperstereoscopic viewing increases the effective interpupillary distance from IPD to IPD′ with IPD′/IPD = N. IPD′ is determined by the separation between the two image-intensification tubes indicated by I^2T. In this illustration, N = 2. Vergence demand γ is proportional to the interocular distance IPD and inversely proportional to the fixation distance *d*, expressed as: $\tan(\gamma/2) = \mathrm{IPD}/2\mathrm{d}$ (1). Therefore, an increase in IPD by a factor of N results in a factor-of-N increase in vergence demand. Based on vergence as a cue for distance, an object placed at distance *d* will be perceived at a closer distance *d′*. This is because the observer interprets the vergence signal for distance according to his/her natural IPD. The perceived distance, *d′*, is related to the physical distance, *d*, by the factor 1/N. (B) Relative distances. The disparity δ produced by an object located at a given distance Δd from the fixation point at distance *d* is proportional to the interocular distance IPD, and inversely proportional to the square of the fixation distance *d*, approximately expressed as: $\delta = \mathrm{IPD}^*\Delta \mathrm{d}/\mathrm{d}^2$ (2). The apparent relative distance $\Delta d'$ (based either on disparity or on vergence difference) between the objects placed at X′ and Y′ is related to the physical relative distance Δd between the objects placed at X and Y by the factor 1/N. Although these objects appear to be smaller, their apparent proportions (depth, height and width) are preserved [67,68]. The apparent depth of the object is related to the physical depth by the same 1/N factor. Apparent height is not directly affected by increasing the IPD, as the vertical dimension is preserved, but is nevertheless likely to be reduced due to the size–distance invariance principle [15]. According to (1) and (2), the hyperstereopsis effect on apparent egocentric and relative distances decreases nonlinearly with increasing distance from the observer. Hyperstereoscopic viewing is usually studied using a telestereoscope, which is a simple device composed of two pairs of lateral, parallel mirrors placed in front of the eyes of the subject, artificially increasing the IPD [review in 6].

The geometric principles of hyperstereoscopic viewing are illustrated in Fig. 1. Binocular cues for 3D space perception include binocular disparity (horizontal and vertical) and oculomotor information from the vergence system. Artificially increasing the IPD by a factor of N increases the required vergence angle for all viewing distances by the same factor N. This potentially alters the perception of egocentric distances (Fig. 1A): Increasing the effective IPD by a factor N is equivalent to scaling down the egocentric distances by the same factor when using a natural IPD [6]. The pattern of vertical disparities (vertical size ratio), which provides information about absolute distances to objects [7], is also distorted during hyperstereoscopic viewing [8].

Another effect of increasing the IPD by a factor of N is to increase horizontal disparities by the same factor. Horizontal binocular disparities, a consequence of the slight horizontal retinal differences that result from the different viewpoints of the two eyes, provide an important cue for the perception of depth and relative distance; this mechanism is traditionally referred to as “stereopsis.” Horizontal disparities are scaled by apparent egocentric distance to interpret the relative depth between two objects, i.e. depth specified by disparity inversely varies with the square of the viewing distance. The perception of veridical depth on the basis of disparities from estimate of viewing distance is called depth constancy [9–14]. Geometrically, since increased horizontal disparities are scaled by decreased apparent egocentric distance, the ratio between depth and the other dimensions is preserved (provided depth constancy is perfect) (Fig. 1B). Furthermore, as perceived distance is decreased for the same angular size of objects on the retina, near objects appear smaller according to the size–distance invariance principle [review in [15]].

Following these geometrical considerations, Helmholtz [16] proposed that “subjects viewed an exact reduced scale model of the world” during hyperstereoscopic viewing, and that increasing the IPD by a factor of N would scale down the apparent (egocentric and relative) distances by the same factor. In sum, telestereoscopic viewing scales down the visual scene by a factor related to interocular separation, while leaving all ratios of sizes, depths and distances of objects unchanged [6].

Predicting the actual effects of hyperstereopsis on 3D visual space perception is more difficult. One key factor is viewing distance. The perceptual effects of hyperstereopsis are likely to decrease with distance away from the observer, as binocular cues lose their efficiency. This efficiency varies, however, with the nature of binocular cues. Binocular disparities can be detected up to several hundreds of meters [17–19] and thus hyperstereopsis may affect perceptual space over a wide range of distances. In contrast, the sensitivity of the human visual system to vergence for egocentric distance perception is limited to a few meters [20]. Helmholtz’s theory for the reduction of apparent relative distance and depth may apply, provided that the object is actually seen at the correspondingly reduced distance. Conversely, compensation for increased disparity by an apparent reduction of egocentric distance may not apply for larger viewing distances.

Another complicating factor in the interpretation of the effects of hyperstereoscopic viewing is that hyperstereopsis leaves monocular cues for distance and depth unchanged. When exploring a natural visual scene, multiple binocular and monocular cues (including familiar size) usually contribute to 3D space perception. The contribution of altered binocular cues may tend to decrease (i) as the number of other unaltered monocular cues increases [21], and (ii) as the fixation distance increases [22]. However, Rogers [6] observed results consistent with Helmholtz’s scaling theory under hyperstereoscopic viewing in an indoor environment where familiar-size cues were available, suggesting a stronger reliance on altered binocular, than familiar-size, cues. In the latter study, it is likely that the short viewing distance (within about