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Estimation of Altitude in Stereoscopic-3D Versus 2D Real-world Scenes

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Abstract

Research on the role of human stereopsis has largely focused on laboratory studies that control or eliminate other cues to depth. However, in everyday environments we rarely rely on a single source of depth information. Despite this, few studies have assessed the impact of binocular vision on depth judgements in real-world scenarios presented in simulation. Here we conducted a series of experiments to determine if, and to what extent, stereoscopic depth provides a benefit for tasks commonly performed by helicopter aircrew. We assessed the impact of binocular vision and stereopsis on perception of (1) relative and (2) absolute distance above the ground (altitude) using natural and simulated stereoscopic-3D (S3D) imagery. The results showed that, consistent with the literature, binocular vision provides very weak input to absolute altitude estimates at high altitudes (10-100ft). In contrast, estimates of relative altitude at low altitudes (0-5ft) were critically dependent on stereopsis, irrespective of terrain type. These findings are consistent with the view that stereopsis provides important information for altitude judgments when close to the ground; while at high altitudes these judgments are based primarily on the perception of 2D cues.

Introduction

Binocular vision provides significant advantages in interacting with and moving through our environment. In particular, stereopsis provides extremely precise depth information based on registration of the positional disparity between points in the two eye's images [for review see 1]. While stereoscopic judgements of relative depth are precise, often we need information about the absolute distance of objects for tasks such as throwing projectiles, reaching and grasping, maneuvering vehicles, and avoiding obstacles. Binocular vision contributes to these tasks as it also provides cues to the absolute distance of an object based on the convergence of the eyes and patterns of vertical disparity. Visual cues to both distance and depth also exist in the monocular view. Considering this apparent redundancy, the necessity and utility of binocular vision for various tasks has been a topic of interest in many contexts.

The potential advantages afforded by binocular vision to aircrew have long been a focus of research. Surveys of accident reports, case studies of individual pilots, and controlled landing studies have come to sharply differing conclusions regarding the importance of stereopsis to flight crew [see 2,3]. For instance, it has been suggested that stereopsis may be important for performing operations such as formation flying, aerial refueling, helicopter operations and ground operations [4,5]. As might be expected given the fact that the stereoscopic system can provide high resolution relative distance information, these tasks all involve estimation of the relative location of objects in space. In recent studies investigators have capitalized on advances in flight simulation to assess the contribution of stereopsis to aviation tasks in more controlled environments. For example, Lloyd and Nigus [6] showed that remote vision refueling tasks are performed better (by a factor of 2.9) when stereopsis is used (compared to 2D performance alone), furthermore, improvements in such tasks are correlated with stereoscopic acuity [7].

Several researchers have focused on aircraft landing. However, these studies often compared binocular performance of pilot landing maneuvers to monocular performance, by patching one eye [8-11]. These studies generally report that monocular landings were successful. However, researchers reported several high-risk characteristics of monocular landings, including steeper approaches and sink rates at touchdown, more head movements and pilot apprehension [see 8-11]. It is difficult to determine the extent to which these effects are due to the loss of stereoscopic vision, or to the reduction in the field of view resulting from covering one eye.

One of the major obstacles to consolidating these studies is the range of tasks and test scenarios used. In this study, we focused on a task that is commonly performed by aircrew in a realistic scenario but only involves a single perceptual judgement (altitude estimation). We devised tasks that would assess the role of stereopsis when the task involved relative (low hover) and absolute (call-to-landing) altitude judgements that could be aided by stereoscopic depth and distance perception.

Altitude estimation is common to many flight situations both close to the ground (e.g. low hover, disembarkation) and while flying at moderate altitudes (e.g. call-to-landing, obstacle avoidance, terrain scouting). Such judgements are indirectly related to visual distance perception, as often the ground directly below is not visible or gaze is directed elsewhere. In Experiment 1, we assessed the impact of binocular vision and stereopsis on altitude estimates using a paradigm that simulated a low-hover, rotary-wing operation. In this scenario, we expect stereopsis to contribute since the helicopter skid was in view and could provide relative distance cues to aid in the estimation of altitude. In Experiment 2, we assessed the impact of binocular vision on absolute altitude estimates by simulating a distance-to-the-ground estimation task during a call-to-landing, rotary-wing operation.

Experiment 1 Relative Altitude Judgement

In Experiment 1, we focus on a rotary-wing, low-hover scenario that is relevant for debarkation-related tasks. In a typical scenario, a Flight Engineer estimates the altitude (distance to the ground) by eye and may use helicopter landing gear (i.e. skid) as a reference for relative distance judgments. Here we present simulated imagery of realistic scenes to assess the impact of stereopsis on such altitude judgements.

Methods

Stimuli The stimuli were still images simulating level hover over one of four flat terrains (Figure 1). The display simulated the view of a seated Flight Engineer looking out a helicopter door, past the helicopter's skid. The simulated viewing direction was oriented 45° in yaw and 45° pitched down. The modeled skid was dark grey and 2" diameter. Thirty-one test altitudes were assessed, ranging from 0' to 5' from the skid to the ground with a 2" step size. Images were pre-rendered using Autodesk MAYA 2016 at a resolution of 3840x2160. Lighting conditions approximated a bright overcast day. The field of view of the virtual camera was set to 31° to match the visual angle of the display at the viewing distance. The stereoscopic camera in MAYA was set to a parallel configuration with 60mm interaxial distance. Post-rendering horizontal image translation (opposite translation of the left and right images) ensured all images converged on the point where the skid met the screen plane. Thus, the skid appeared at the same location in the scene and at the same distance from the observer in every condition. The four terrains modeled were: (1) Grass, (2) Stones, (3) Runway and (4) Cross. The Grass and Stones terrains were flat plane textures mapped with standard MAYA materials. Texture size, scale and density in the image varied with simulated altitude as expected from projective geometry. The Runway consisted of a uniformly-textured black tarmac texture painted with a yellow line marking. The width of the line was randomly jittered between renderings to make it an unreliable cue to distance. The Cross condition consisted of a quadripartite plane of alternating uniformly-textured dark and light regions. The four parts joined in the centre to form a cross. This pattern is invariant at different scales, that is, the image of the Cross is identical at all altitudes (for a camera located midway between the eyes) and thus provides no monocular cues to distance. Since the left and right cameras are offset there is binocular parallax which results in a symmetric shift (binocular disparity) between the left and right images that varies with altitude. The Cross stimulus served as an important control condition, effectively isolating the impact of binocular disparity. For all terrains except for the Cross condition the position of the simulated helicopter was jittered across the conditions so that the absolute position of texture markings, the runway line or other features were not informative to altitude. For the Cross condition, the centre of the cross was always in the centre of the image to eliminate monocular altitude cues.

Observers Fourteen observers (7 female; mean age 19.6, SD:0.9) were recruited. All observers had normal or corrected-to-normal vision and wore their corrective lenses during testing. Observers could all reliably perform a random-dot stereoacuity task at 40arcsecs of disparity.

Apparatus Images were presented on a LG 55" 4K UltraHD 3D LED SmartTV (55LA9650) display, which was mounted on a customized stand at a slant of 45° relative to the ground and located 45° in yaw off straight-ahead. The display was rotated so that the plane of the display was normal to the line of sight when the observer looked in the simulated view direction. The observer's head was positioned 6.5ft diagonally from the midpoint of the screen, looking down on the screen in the direction of the simulated view. At this distance, the screen subtended 31.5° of visual angle and one pixel subtended 0.01°. Images were presented using Stereoscopic Player [12] which presented left and right images on alternate rows of pixels aligned with the display's film patterned retarder polarizer. Observers wore passive 3D glasses to perceive the S3D images. A 4ft round black plastic pipe (2" diameter) was positioned to extend from the on-screen skid and create a real-world reference to the skid. Figure 2 shows a schematic of this layout.

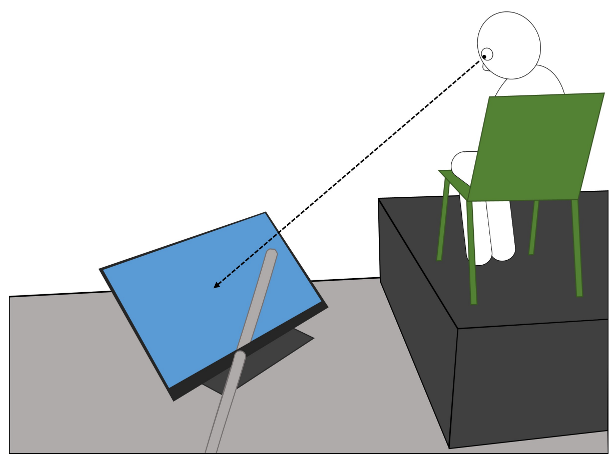

Figure 2. *Schematic of apparatus set-up from Experiment 1. Images were displayed on a 3D TV that was angled on a custom-built mount. Observers were seated 6.5ft from the midpoint of the screen (indicted by the dotted line). A plastic tube extended from the screen to act as a real-world reference to the skid.*

Procedure The experiment took place in a dark room. Observers were instructed to estimate the distance between the skid and the ground (altitude of the helicopter). They were first shown a 'reference image' of the skid with a blank white background. Observers were asked to assign a value (a modulus) to represent the distance between their head position and the skid shown in a

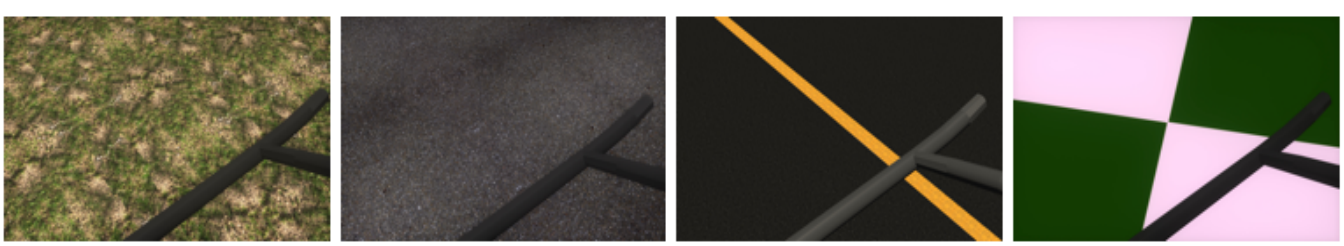

Figure 1. *Sample images from Experiment 1 modelled in Autodesk MAYA 2016. Four terrains were created: grass, stones, runway and cross. In each image, the same helicopter skid was visible and used as a relative reference point. The images shown here depict an altitude of 5ft from skid to ground.*

reference image. In subsequent trials, they judged the altitude of the skid off the ground relative to the modulus. For each trial, the image was presented for 5s, followed by a blank response screen. Observers reported their response verbally to the experimenter. Trials were blocked by viewing conditions and counterbalanced (S3D and monocular). In the monocular block, the non-dominant eye (assessed using a pointing task) was patched such that only one eye's view would be visible on the stereo-display. There were 124 conditions per block (31 altitudes x 4 terrains) with one presentation of each image.

Results

Figure 3 depicts the normalized (trial estimate/modulus) altitude estimates as a function of altitude in inches for each terrain under S3D and monocular viewing conditions. Inspection of the plot shows that altitude estimates were markedly larger in the S3D compared to the monocular condition. The data was analyzed in R using the nlme package [13] to fit a linear mixed-effects model with full maximum-likelihood estimation. The model accounted for repeated-measures variables in the data by using nested random effects arranged in a hierarchy. This modelled the correlation of the variance of intercepts for each subject within each type of viewing condition (S3D vs monocular), within each terrain. An approximation of Pearson's correlation coefficient (r) was used as a measure of effect size for each test [14]. The analysis showed a significant 3-way interaction between the type of terrain and viewing condition as a function of altitude, $X^2(20)=8.46$, $p=0.037$. This significant interaction suggests that the relationship between estimated and predicted altitude depended on the type of terrain and viewing condition. To understand this interaction, the data was subdivided by the type of viewing condition and the analysis was repeated for each viewing condition.

Monocular Viewing Condition Figure 3A shows the normalized altitude estimates for the monocular viewing condition for each of the four terrains plotted as a function of altitude in inches. The Cross-terrain condition was designed to have no monocular altitude cues and, as predicted, the slope obtained in this condition was very small and not significantly different from zero, that is, altitude estimates did not significantly change as a function of altitude ($b=0.001$, $t(1676)=1.56$, $p=0.12$, $r=0.04$). We also compared the slope in the Cross condition to other monocular conditions that were expected to provide monocular altitude cues using planned contrast comparisons. These analyses confirmed that the slope in the Cross-terrain condition was significantly more shallow than the Stones ($b=0.004$, $t(1676)=8.02$, $p<0.0001$, $r=0.19$), Grass ($b=0.005$, $t(1676)=9.29$, $p<0.0001$, $r=0.22$) and Runway ($b=0.002$, $t(1676)=3.92$, $p=0.0001$, $r=0.10$) conditions. In addition, the slope in the Runway condition was significantly more shallow than the Stones ($b=0.002$, $t(1676)=4.11$, $p<0.0001$, $r=0.10$) and Grass ($b=0.003$, $t(1676)=5.38$, $p<0.0001$, $r=0.13$) conditions.

3D Viewing Condition Figure 3B depicts the normalized altitude estimates for the S3D viewing condition for each terrain as a function of altitude. For all conditions the S3D slopes were much steeper than in the equivalent monocular conditions. The slopes in the S3D case were all significantly different from zero and very close to geometric predictions. Contrasts between pairs of conditions revealed that the slope in the Cross-terrain condition was significantly shallower than in the Stones ($b=0.005$, $t(1676)=7.13$, $p<0.0001$, $r=0.17$), Grass ($b=0.004$, $t(1676)=6.16$, $p<0.0001$, $r=0.15$) and Runway-terrain conditions ($b=0.004$, $t(1676)=5.54$, $p=0.0001$, $r=0.13$). The shallower slope in the Cross-terrain condition presumably reflects the absence of monocular cues; but the binocular cues appear to be more important as the binocular altitude estimates for this stimulus were much larger ($b=0.01$, $t(1676)=25.22$, $p<0.0001$, $r=0.52$) than in the corresponding monocular condition. However, comparison of results obtained using stimuli with texture cues, showed no significant difference in the slopes obtained the Stones and Grass ($b=-0.0006$, $t(1676)=-0.97$, $p=0.33$, $r=0.02$), Stones and Runway ($b=-0.001$, $t(1676)=-1.58$, $p=0.11$, $r=0.04$), or Grass and Runway-terrains ($b=-0.0004$, $t(1676)=-0.61$, $p=0.54$, $r=0.01$). In sum, when viewed stereoscopically the results were the same for the three terrains which contained scalable monocular texture.

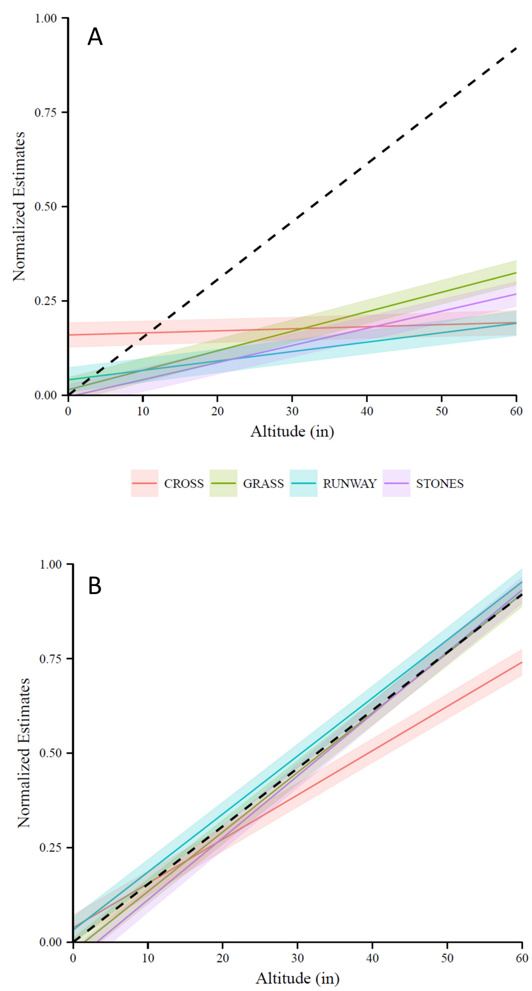

Figure 3. *Averaged results for the relative altitude estimation of four terrains; Cross (red), Grass (green), Runway (blue) and Stones (purple). (A) Monocular trials and (B) S3D trials. Solid lines represent the predicted fit of the linear mixed-effects model and the dotted line represents veridical estimates. Shaded regions represent one standard error of the predicted mean.*

Discussion

The results of Experiment 1 demonstrate that stereopsis improves relative altitude judgements for static images depicting small altitudes (up to 5ft), typical of low-hover, rotary-wing operations. When stereoscopic information was available, altitude estimates increased as a function of altitude. While relative altitude estimates increased with altitude in three of the 2D conditions, the relationship was weak as the slopes were much shallower than in the S3D conditions. Further, the advantage provided by stereoscopic viewing was consistent for all terrains tested, thus it was not due to the presence of a specific texture or image feature. This stereoscopic advantage was also evident in the results for the Cross condition, which contained no useful 2D distance information. In the monocular test condition, observers consistently assigned the same estimate to all test altitudes for the Cross images. However, in the binocular test condition, relative altitude estimates for the Cross did increase in a linear manner but were underestimated compared to theoretical predictions. For the other conditions, observers' altitude judgements were very similar to the theoretical predictions. The difference between the slope of the functions representing estimates for scalable textures (Grass, Runway, Stones) versus the Cross condition, which contained no 2D texture cues, highlights the fact that the presence of monocular distance cues helps to scale depth from stereopsis [see 15-17].

In the current study, we did not include 2D objects or features that could be used to track the changes in distance. In fact, in the Runway condition the width of the yellow centre line was deliberately changed from trial to trial to make it an unreliable size cue. In addition, in this study the randomization of textures within blocks might have made it more difficult for observers to compare the 2D textures from trial to trial. This paradigm allowed us to separately evaluate S3D and 2D altitude estimation. The question remains whether the advantages afforded by stereopsis for relative distance estimation would still be seen if stronger 2D size cues were available. This question will be the focus of future experiments; however, it should be noted that there are many operational scenarios in which aircrew are faced with ambiguous or misleading 2D texture information in low hover (e.g. landing in deserts, or in snowy regions or over unusual or unfamiliar vegetation. Psychophysical studies have shown that familiar and relative size information can be used to judge distance however size-based distance estimates are often unreliable because they are influenced by several variables including the distance to the object or plane, whether the object is fixated or seen in the periphery [18,19], and the familiarity of the object [among others see 20-22].

Experiment 2 Absolute Altitude Judgement

Altitude estimation can be also critical to rotary-wing call-to-landing: a scenario where an aircrew member calls out the altitude successively as the aircraft approaches touchdown. The call-outs are visually-based, and begin at over 100ft altitude and proceed down to touchdown. When viewed as monocular static images (as would effectively be available during slow descents), absolute altitude estimation could be based on 2D cues to distance such as object size and/or texture scale. When viewed binocularly, it is possible that observers could improve altitude estimation by monitoring their convergence angle [23]. There is psychophysical evidence that, in isolation, this extraretinal distance information can support accurate distance estimation in near space, less than 40cm [24]. However, at longer distances observers underestimate the distance based on vergence alone, which may be due in part to the specific distance tendency described by Gogel [25]. The aim of Experiment 2 is to determine if, and to what extent, stereopsis provides a benefit to the estimation of altitude using natural and simulated S3D imagery containing multiple 2D depth cues.

Methods

Stimuli **Natural Images** Stereoscopic images were captured during flight exercises at CFB Borden (Ontario, Canada) using a Fujifilm FinePix REAL 3D W3 stereoscopic camera with interaxial separation of 63mm (resolution 3584×2016). Images were taken at six altitudes (10, 20, 40, 60, 80, and 100ft) at a viewing angle of 10°. See Figure 4A.

Simulated Images Images were captured as in-game screenshots using ARMAII gaming software in two terrains: 'Desert' and 'Road' (see Figure 4B and C, respectively). The same altitudes and viewing angle were simulated as in the natural image set. The camera parameters were orthostereoscopic for the middle seat in the front row of observers (viewing distance of 325cm, 50° viewing angle). All images were presented with a black oval aperture at zero disparity, which acted as a reference frame.

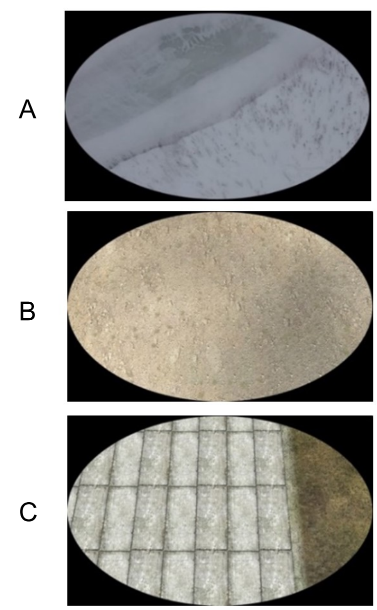

Figure 4. Sample images from Experiment 2, of natural and simulated scenes taken from a helicopter. (A) Natural scene taken at CFB Borden (B) Simulated ARMAII images for Desert (left) and Road (right) terrains. Images here were taken at the maximum altitude (100ft) and 10° viewing angle.

Apparatus The experiment was conducted in a dark screening room with multiple viewers tested simultaneously. Images were rear projected onto a cinema screen (300x168cm) using a Christie Digital 3D Mirage projector (resolution 1920x1080) via Stereoscopic Player [12]. Viewers wore LC shutter glasses that alternately blocked the left and right eye view at 120Hz in synchrony with the display of the right and left images, respectively. This provided a time-multiplexed stereoscopic display and the percept of the content in stereoscopic 3D. Viewers were positioned in two rows, at viewing distances of 325cm and 420cm from the screen. At the closest distance, the screen subtended 50° of visual angle and one pixel subtended 0.03°.

Observers Twenty observers (11 female; mean age=20.1, SD=1.5) were recruited and tested in separate sessions. Eleven of the observers viewed naturalistic images, while the remaining nine viewed simulated imagery. All observers met the stereoscopic vision criteria described in Experiment 1.

Procedure Natural and simulated images were assessed in separate sessions with separate groups. In both sessions, viewers performed a magnitude production task [26] to estimate altitude. For each image set, a reference image depicting an altitude of 40ft was presented as the standard. Viewers were told they were viewing a downward oriented view of the ground and instructed to write down a value to represent the altitude or "distance to the ground." All other altitudes were judged relative to this modulus. Each image was presented for 10s, followed by a blank response screen for 5 s. Responses were made in paper booklets. Conditions were blocked by the image set (i.e. terrain). S3D images and 2D images (the left image in both eyes) were interleaved in each block. Each image was displayed twice within a block

Results

Figure 5 shows the mean normalized estimates as a function of altitude for each image set. Normalized estimates for each image set were calculated as the average of the ratio of each observer's estimates to the value of their modulus. For all image sets, altitude estimates demonstrated a linear increase as a function of altitude. A repeated-measures analysis of variance with a Greenhouse-Geisser correction was used to assess the impact of stereopsis on perceived altitude. Variables included view type (2 levels) and altitude (6 levels) with separate analyses for the Natural, Desert and Road image sets.

For all image sets, perceived altitude increased significantly as a function of altitude (Natural: $F_{(2.3,23.0)}$=17.23, p<0.0001, η^2=0.40; Desert: $F_{(1.3,10.4)}$=23.87, p<0.0001, η^2=0.60; Road: $F_{(1.3,10.1)}$=33.20, p<0.0001, η^2=0.64). While there was no significant effect of Image Type (2D vs 3D) in the Natural and Road scenes (Natural: $F_{(1,10)}$ = 3.75, p=0.081, η^2=0.01; Road: $F_{(1,8)}$=2.00, p=0.195, η^2=0.005) there was a significant difference between the 2D and 3D conditions in the Desert terrain condition ($F_{(1,8)}$=32.36, p<0.0001, η^2=0.01). Finally, the interaction between Altitude x Image Type was not significant in any image set (Natural: $F_{(2.6,25.2)}$ = 1.58, p=0.222, η^2=0.01; Desert: $F_{(2.3,18.3)}$ = 1.44, p=0.263, η^2=0.01; Road: $F_{(2.2,17.3)}$=1.33, p=0.291, η^2=0.004).

Discussion

The results suggest that stereoscopically displayed images do not provide a consistent benefit to judgements of absolute altitude for this set of altitudes. However, there was one terrain type for which S3D viewing increased altitude estimates. It is possible that there was some feature present in this simulated terrain that helped observers monitor their vergence state, but we are reluctant to place too much emphasis on this result given that while statistically significant, the effect size was very small. Furthermore, the range of altitudes used was well beyond the reported effective range of vergence [23]. We also note that there is more variability in the Natural image set, which may be caused by the inconsistencies in the capture conditions between images. In contrast to Experiment 1 where 2D relative altitude estimation was poor, here we find that for absolute altitude estimation 2D texture information does support scaling of altitude estimates.

To extract absolute distance from binocular disparity the visual system requires information concerning where the observer is fixating. This can be obtained by monitoring the vergence state of the two eyes; by monitoring this angle it is theoretically possible to estimate the absolute distance to the fixated location by triangulation [for review see 1]. This process relies on monitoring relatively noisy eye position signals and has limited precision. Vergence eye movements have been shown to influence absolute distance judgements but only at near distances (<2 m). Distance judgements at longer distances usually rely on cues such as linear perspective, height in the field, gradients of texture or relative disparity, and other perspective based cues. This makes the altitude estimation problem is particularly challenging, as there are little or no features between

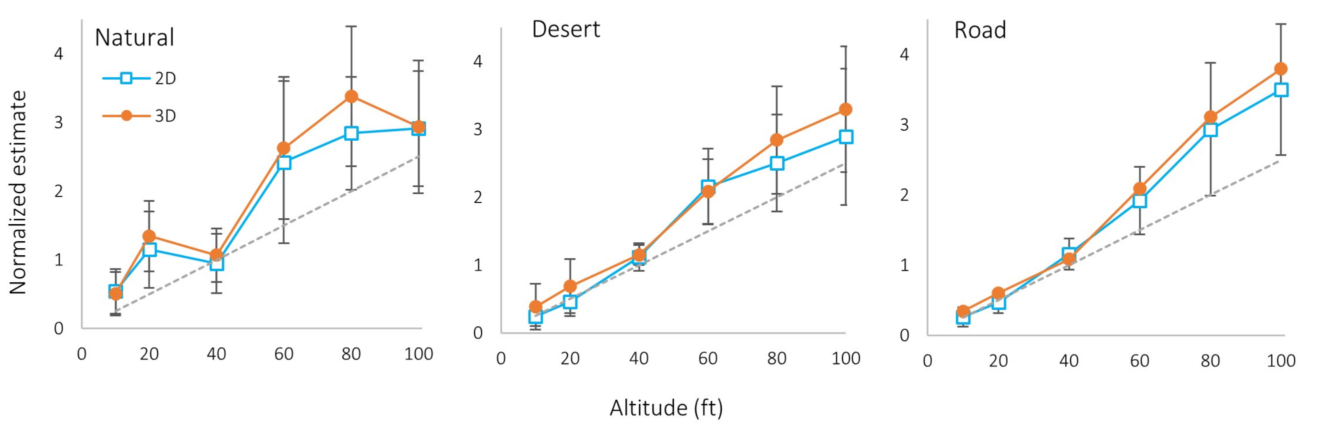

Figure 5. *Normalized altitude estimates are plotted as a function of altitude (feet). From left-to-right, results are shown from the Natural, Desert and Road scenes. 3D estimates are shown in orange circles, and 2D results shown in blue open squares. The error bars represent 95% CI.*

the ground and the viewer that could provide these cues. Thus, the observer is required to rely on visual features on the ground itself including 2D cues such as relative size and texture.

General Discussion

As outlined in the Introduction, there is a long history of research in depth perception that applies to aviation [for review see 2, 3]. In the present experiments, we explored the advantages provided by binocular viewing in both relative and absolute altitude estimation tasks specific to low hover and call-to-landing scenarios commonly experienced by flight engineers. As a starting point, still images were used, which provided more precise control of depth cues (e.g. eliminating motion parallax and changes in viewing distance). In Experiment 1 we found that binocular viewing provided clear benefits for altitude estimation in the presence of a reference stimulus for low hover scenarios (0-5ft), and this benefit was seen even in the absence of 2D texture cues (the Cross condition); however, we note that the presence of 2D information does increase apparent altitude, with estimates closer to predicted values when both 2D and S3D cues are present. As expected, at higher altitudes and in the absence of a reference stimulus (Experiment 2) observers relied on 2D texture information to estimate altitude; S3D viewing afforded little benefit.

Previous research has established that, when making binocular distance estimates, observers rely on several cues, but the reliability of these cues varies depending on the scene [27-30]. Because we were trying to simulate (or in Experiment 2 use) natural imagery, many potential sources of depth information were present in our stimuli: from natural features (rocks and snowy ground plane) to man-made constructs (runway and road paving). Our results show that relative altitude judgments at low hover were impacted by the presence of monocular cues. First, the type of terrain was important; in the monocular trials, the Grass and Stones that had the most prominent textures, tended to generate higher altitude estimates than the Runway and Cross terrains. Second, in the binocular trials the presence of textured terrains enhanced the altitude estimates above the levels for disparity alone (Cross). Our data are consistent with previous studies conducted in real environments that have shown that the interaction between stereopsis and other depth cues, such as familiar size and perspective, can be effective in scaling depth from disparity [15-17]. In contrast, it is not necessarily surprising that there was no effect of stereopsis in the absolute judgments of higher altitudes; research in real world and virtual reality has shown that many monocular cues are effective at indicating distance at high altitudes including: familiar size [31,32], angular elevation [33,34], vertical extent in relation to the horizon [35-37] and motion parallax [16,38,39]. In the set-up presented here, it appears that the 2D pictorial features were sufficient to permit appropriate distance scaling.

From an operational perspective, the results presented here highlight the need for situation-specific training. We found that stereopsis was an important determinant of accurate judgments in low hover. Moreover, the results suggest that stereopsis may play a substantial role in situations where monocular cues are absent or unreliable (e.g.: dust cloud or blowing snow). On the other hand, the reliance on monocular cues at higher altitudes underlines the need for terrain-specific training for aircrew. For instance, aircrew might be trained to use the average tree height as a 2D cue during altitude estimation. However, average tree height can change dramatically with changing latitude, and therefore this cue might not be reliable across flight situations. If the flight crew make errors in the assumed tree height, their altitude estimates will also be in error; a potentially disastrous mistake.

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