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Perception of perspective in augmented reality head-up displays

Alexandra W.D. Bremers [*,a], Ali Özgür Yöntem [b], Kun Li [b], Daping Chu [b], Valerian Meijering [a], Christian P. Janssen [c]

[a] Jaguar Land Rover, Research Department, NAIC, University of Warwick, Lord Bhattacharyya Way, Coventry CV4 7AL, United Kingdom
[b] University of Cambridge, Centre for Photonic Devices and Sensors Group, University of Cambridge, 9 JJ Thomson Avenue, Cambridge CB3 0FA, United Kingdom
[c] Utrecht University, Experimental Psychology & Helmholtz Institute, Heidelberglaan 1,3584 CS Utrecht, The Netherlands

A R T I C L E I N F O

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Perspective cue

A B S T R A C T

Augmented Reality (AR) is emerging fast with a wide range of applications, including automotive AR Head-Up Displays (AR HUD). As a result, there is a growing need to understand human perception of depth in AR. Here, we discuss two user studies on depth perception, in particular on the perspective cue. The first experiment compares the perception of the perspective depth cue (1) in the physical world, (2) on a flat-screen, and (3) on an AR HUD. Our AR HUD setup provided a two-dimensional vertically oriented virtual image projected at a fixed distance. In each setting, participants were asked to estimate the size of a perspective angle. We found that the perception of angle sizes on AR HUD differs from perception in the physical world, but not from a flat-screen. The underestimation of the physical world's angle size compared to the AR HUD and screen setup might explain the egocentric depth underestimation phenomenon in virtual environments. In the second experiment, we compared perception for different graphical representations of angles that are relevant for practical applications. Graphical alterations of angles displayed on a screen resulted in more variation between individuals' angle size estimations. Furthermore, the majority of the participants tended to underestimate the observed angle size in most conditions. Our results suggest that perspective angles on a vertically oriented fixed-depth AR HUD display mimic more accurately the perception of a screen, rather than the perception of the physical 3D environment. On-screen graphical alteration does not help to improve the underestimation in the majority of cases.

1. Introduction

1.1. Increasing use of augmented reality applications calls for more studies of perception

Virtual Reality (VR) and Augmented Reality (AR) technologies are increasingly used in human-computer interaction settings (Raisamo et al., 2019). Specifically, a wider range of VR and AR technology is becoming commercially available (e.g., HoloLens, HTC Vive) and is studied and applied in a variety of domains, such as education and learning (Moro et al., 2017; Radu, 2014; Wu et al., 2013; Yuen et al., 2011), cultural heritage (Abbas et al., 2019; Fenu and Pittarello, 2018; Xiao and Deling, 2019), driving (Kun et al., 2019; Riener et al., 2019) and automotive research tools (Goedicke et al., 2018).

One example of a promising domain for AR is the automotive domain. In this domain, AR can be applied as a head-up display (AR HUD) which presents see-through visual information to the driver. Such automotive AR HUDs can be used for example to improve driving safety and enjoyment (e.g. Bark et al., 2014; Gabbard et al., 2014; Van Krevelen and Poelman, 2007; Riener, Gabbard, Trivedi), as well as to display information related to automated driving (e.g. Janssen et al., 2019; Paredes et al., 2018; Riener et al., 2019; Wintersberger et al., 2019; Yöntem et al., 2020). AR HUDs are particularly promising, as their use might increase attention to the road (instead of to an in-car display) while also potentially reducing cognitive workload (Crawford and Neal, 2006; Kim and Dey, 2009), reducing stress (Liu and Wen, 2004), increasing task performance (Liu and Wen, 2004; Wittmann et al., 2006), increasing safety (Poitschke et al., 2008), as well as improving driving performance specifically related to age-related deterioration (Pampel et al., 2019).

Although research and practice have gained insight into the *technology*, less is known about the *human perception* of stimuli in AR applications. An accurate understanding of human perception is essential for complex, safety-critical domains, such as driving, where technology

* Corresponding author at Cornell: Tata Innovation Center, Lab 351, 11 E Loop Rd, New York, NY 10044, USA.
E-mail address: awb227@cornell.edu (A.W.D. Bremers).

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is used in a dynamic environment (Ng-Thow-Hing et al., 2013; Riener et al., 2019). As AR graphics are shown directly in the driver's view, it is necessary to have a thorough understanding of their effects on depth perception (Ng-Thow-Hing et al., 2013). Although there is a body of research related to perceptual challenges involved with or applying to AR (e.g. Cutting and Vishton, 1995; Hagen et al., 2005; Poitschke et al., 2008; Sielhorst et al., 2006) including studies about depth perception in AR and AR HUD (e.g. Halit et al., 2015; Smith et al., 2015; Swan et al., 2007), there is no complete solution to prevent the various perceptual issues that can arise with AR or AR HUD (e.g. Drascic and Milgram, 1996; Kruijff et al., 2010).

One perceptual issue that arises in AR is that egocentric depth is known to be underestimated in applications of virtual and augmented reality (Swan et al., 2007). Several studies using head-mounted AR displays have suggested different theories to explain the depth underestimation that occurs (Creem-Regehr et al., 2005; Knapp and Loomis, 2004; Messing and Durgin, 2005; Richardson and Waller, 2005; Thompson et al., 2004). Swan et al. (2007) discuss previous work which has investigated the relationship between depth underestimation and technological aspects of a head-worn augmented reality device (such as its weight (Willemsen et al., 2004), field of view (Creem-Regehr et al., 2005; Knapp and Loomis, 2004; Wu et al., 2004), monocular versus stereo viewing (Creem-Regehr et al., 2005), or quality and method of rendered graphics (Thompson et al., 2004), size of the display screen (Plumert et al., 2004), usage of live video (Messing and Durgin, 2005)). Whereas this body of research confirms the underestimation of depth, the cause has not yet been fully understood.

We investigate depth perception differences between an AR setup, a flat-screen, and the physical environment in this work. We focus on the specific depth cue of perspective. Previous work on the perception of perspective cues in AR is limited, especially comparing AR, a flat-screen, and the physical world. This question is relevant, as a straightforward application of AR HUD could be to render 2D imagery on a transparent virtual display, treating the virtual display like a regular flat-screen. Furthermore, earlier research has shown that perception of perspective angles on a flat-screen differs from perception of angles on the physical floor (Erkelens, 2015b). We, therefore, compare perception in these three conditions (AR, flat-screen, physical world) in this paper. Specifically, experiment 1 compares whether perspective perception in AR is more similar to perspective perception in the physical world or a flat-screen. After this initial experiment, experiment 2 explores if graphical alterations affect perception of perspective.

1.2. Perspective as a depth cue in augmented reality head-up displays

Depth cues have been studied in the fields of vision science and human factors. Two essential types of depth cues are physiological cues and pictorial cues (Drascic and Milgram, 1996; Wickens et al., 1998; Wu et al., 2007). *Physiological cues* work based on the physical structure of the human visual system and eye adaptation. Accommodation, for instance, is a process in which the eye muscle tension changes to keep focusing on an object at a certain distance (Teittinen, 1993). *Pictorial cues* are cues in an image or at a further distance that create a sensation of depth. For example, graphical elements such as shadows or occlusion can create a sense of distance, but do not require adaptation by the eye.

AR HUDs can use a combination of physiological depth cues and pictorial depth cues. As a driver mostly looks at objects which are further away than a few metres (Gabbard et al., 2014), the most relevant depth cues in the driving context are likely pictorial (Cutting and Vishton, 1995; Gabbard et al., 2014).

In the present work, we focus on the pictorial depth cue of perspective. Perspective contributes to the perception of distance and slant (Erkelens, 2015b; O'leary and Wallach, 1980). The perspective cue applies to graphics that are slanted according to a set of lines with one or more vanishing points. Perception of perspective happens when a three-dimensional image is shown on a two-dimensional plane and is not an inherent quality of the three-dimensional world. Although linear perspective is a popular model of perspective used in, for instance, art (Edgerton, 2009), linear perspective might not result in the most realistic perception of depth (Costall, 1993; Hagen and Elliot, 1976).

Recent studies by Erkelens (2015a, 2015b, 2015c) have used a combination of empirical studies and theoretical models to demonstrate that linear perspective might not be an accurate model of perspective perception. In these studies, participants estimated the perspective angle between two bars, which were either physically placed on a floor or displayed on a flat computer screen. To manipulate observed angle sizes in the physical condition, the researchers manipulated the viewing height from which participants looked at physical bars on the floor. Photographs of the scene at different heights were displayed on the screen, to compare between angles on a flat display on the one hand and angles in a physical, three-dimensional space on the other hand. The observed angle size was based on the *proximal angle* size, calculated using the geometry of space, which describes the size of the vertically oriented angle projection when the horizontal angle on the floor is viewed from a specific height (we used this calculation for the creation of our stimuli, see section 2.3). Results showed that human perception estimates tend to be smaller for angles between physical bars on a floor than for (proximal) angles displayed on a flat-screen (Erkelens, 2015b).

In the present experiment, we evaluate perception of perspective on AR HUD. We study whether the perception of perspective in AR is more like perception of a flat-screen, or of 3D scenes in the physical world (bars on the floor). There are two primary motivations for this. Firstly, users tend to underestimate angles in the physical world, but not proximal angles on flat screens (Erkelens, 2015b). Therefore, to design for AR technology and accurate human perception, we need to know whether such underestimation also occurs in AR, where physical and virtual stimuli meet. Secondly, one approach to implementing graphics on an AR HUD would be to display a 2D image on a flat, vertically oriented plane, where the AR HUD is essentially treated as a flat-screen. Erkelens (2015b) showed that angle sizes are estimated differently on a flat-screen versus in the physical environment. Our experiment investigates whether perception in AR is more similar to perception of a flat-screen or perception in the physical environment.

To tackle these research questions, we adapt the methodology from Erkelens (2015b), and report on two studies. In the first experiment, we test perception of perspective angles on AR HUD and compare it to a replication of two conditions that Erkelens (2015b) also used: perception of physical bars and perception of a flat-screen. Like Erkelens, we manipulate stimulus angle sizes to study how perceived angle size varies with physical viewing height manipulation. In the second experiment, we test human perception for various layouts of relevance to practical automotive AR HUD applications: dashed lines, partially occluded lines, and low contrast lines.

2. Experiment 1: Angle size perception on AR HUD, compared to screen and physical

2.1. Overview and aims

Experiment 1 has two aims. Firstly, we test whether there is a difference between perception of angle sizes on AR HUD compared to angles on a screen or three-dimensional world **(RQ1)** (with angle size being manipulated by varying viewing height in the physical condition, and by changing displayed images in the AR HUD and screen conditions). Secondly, we investigate whether and how perception of angles on the physical floor varies with proximal angle size **(RQ2)**. Our hypothesis is that perception of angle sizes on AR HUD will differ from perception of angles in the three-dimensional world since the AR HUD shares properties with a screen, and previous work has shown that there is a difference between perception of angle sizes on a screen, and in the three-dimensional world (Erkelens, 2015b). During the user trials, we asked participants to estimate angle sizes on an AR HUD setup, on a

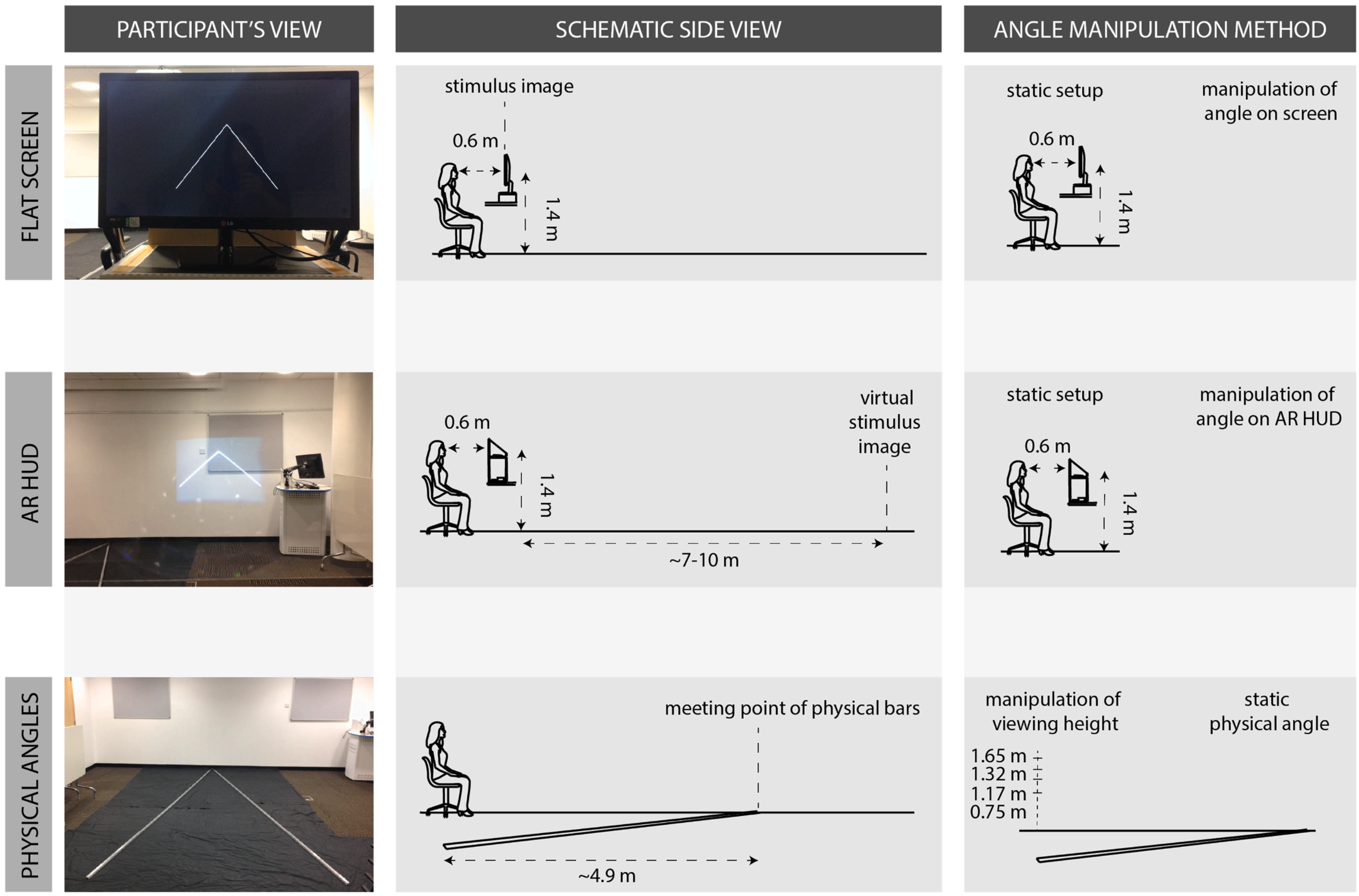

Fig. 1. Overview of the experimental setups: image of the angle (left), schematic side view (middle) and angle manipulation method (right). Slight deformations in the photographs were caused by camera characteristics.

flat-screen, and between physical bars on the floor, by matching them visually with the angle between legs of an angle ruler held to their side (cf. Erkelens (2015b), but with angle ruler in stead of compass). Pictures of the three display conditions are given in Fig. 1.

2.2. Participants

Ten participants[1] (4F; 6M) with an average age of 38.1 years (SD = 10.4, range 27–54 years of age), average height of 174.4 cm (SD = 8.1 cm, range 165–192 cm), took part on a voluntary basis. Nine participants self-reported normal or corrected to normal vision in both eyes. Participant P05 had a minor visual impairment (-0.5D in both eyes). Participants were recruited via the University of Cambridge, resulting in a sample of mostly researchers and supporting staff. We asked participants whether they were familiar with estimating angle sizes (4 answered "Yes"; 6 answered "No"). All participants provided informed consent and received a £10 gift card (= approximately US$14). The Department of Engineering Research Ethics Committee at the University of Cambridge approved the experiment.

2.3. Experimental design

We used a 3 x 4 within-subjects design. We manipulated Display Type with three levels (Physical, AR HUD, or Screen) and Proximal Angle sizes of 65°, 76°, 82°, and 107°. In the Physical condition, we placed two solid bars in a 23° angle on the floor. To manipulate proximal angle (i.e. the angle as it reaches the eye) we adjusted the viewing heights to four levels (165, 132, 117 and 75 cm, corresponding to proximal angles of respectively 65°, 76°, 82°, and 107°). The calculation from viewing height to proximal angle in the physical condition is shown in Fig. 2. For the AR HUD and Screen manipulations, proximal angles were manipulated by changing the angles of two lines on a screen, see Fig. 1 (the manipulation method was inspired by Erkelens (2015b)). Participants did not view AR HUD and Screen angles from different heights.

For each combination of display type and proximal angle size, there were ten task repetitions. The order was the same for each participant, and we presented repetitions in a blocked manner per condition, similar to Erkelens (2015b), in which a block refers to 10 trial repetitions with a specific angle and display type. The order of conditions started with the Physical display type, followed by AR HUD, and finally, the Screen. Within every display type, the order of proximal angle sizes was: 65°, 76°, 82°, and 107°. A fixed order of angle sizes was used to reduce time in the Physical condition, as the perceived angle was manipulated by viewing the physical bars from a different height. The Screen condition took place after Physical and AR HUD, to eliminate any potential influence of observing the Screen condition[2], from which the angle size could likely be most easily observed, on perception of other display conditions.

The resulting order of blocks was as follows: 1: Physical, 65°, 2: Physical, 76°, 3: Physical, 82°, 4: Physical, 107°, 5: AR HUD, 65°, 6: AR

[1] By comparison, Erkelens (2015a,b) used 3–4 participants per experiment.

[2] Please refer to Appendix section A3 for an exploratory analysis of order effects. No order effects were observed.

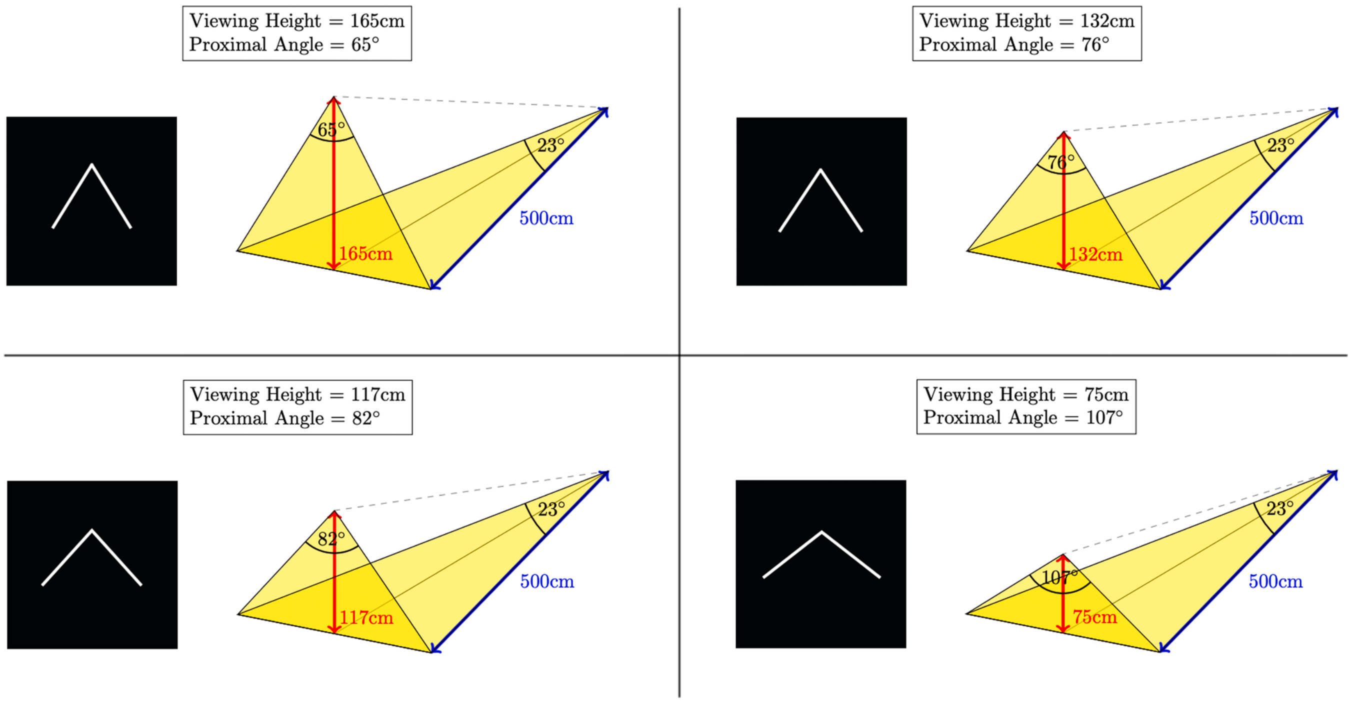

Fig. 2. Schematic depictions of how we calculated stimulus angle sizes for screen and AR HUD based on the viewing height in the physical condition. The sine function was used first to calculate the distance between the blue pole ends, taking the length and ground plane angle into account; afterwards, the vertical angle size was calculated using inverse tangent from half pole end distance and viewing height. Due to rounding effects and the graphics creation method, the angle sizes of the stimuli deviate $0-2^{\circ}$ from the outcome of the calculations. The actual stimuli angle sizes were taken as the Proximal Angle values in our analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

HUD, 76°, 7: AR HUD, 82°, 8: AR HUD, 107°, 9: Screen, 65°, 10: Screen, 76°, 11: Screen, 82°, 12: Screen 107°. For every condition, the measuring task was repeated ten times before moving on to the next stimulus. Therefore, each participant performed a total of 120 angle estimations (3 display types x 4 proximal angles x 10).

2.3.1. *Set ups*

The physical bar setup consisted of two 5-meter-long (cross-section of 25 * 25 mm) aluminium extrusions placed with a 23-degree angle between the far ends. The extrusions were placed on black optical fabric in order to cover the tiled pattern of the floor. We used a levelling rod for measuring viewing height, with a ±2 cm deviance allowed. The central point between the ends of the two bars was used as the viewing location.

The flat screen and AR HUD setup displayed schematic images representing angles. The flat-screen setup was a 23// high definition desktop monitor with the centre placed on a table at approximately 140 cm height. The AR HUD setup consisted of an AR HUD structure with the centre of the image at approximately 140 cm height. The AR HUD setup presented images at a virtual image distance of approximately 7 to 10 metres, for three reasons. Firstly, when an AR image is presented at 7–10 metres, it can be considered to be in the action space as described by Cutting and Vishton (1995). In the action space, which is between personal space (<3m) and vista space (>10m), some depth perception cues, such as accommodation and binocular disparity, start to play a smaller role in depth perception. As we focus on the pictorial cue of perspective, this is desirable. We reduced the effects of accommodation-vergence related cues significantly by increasing the observation distance. Secondly, a virtual image distance of 7–10 metres is also where displaying information has most applications in our context of displaying road markings, as a close distance would mean that the information is not mapped to the road, but on the bonnet of the car. Thirdly, there are industry applications that already use augmented reality head-up displays with a virtual image distance of 10 metres, such as the 2021 Mercedes S-Class (Giblin, 2020) - this highlights the practical relevance of studying perception at this virtual image distance. We placed a height-adjustable chair at 60 cm distance from the AR HUD and screen and used it to align the users' eye height with the middle of the screen. The lab room was lit evenly, with the lights directly above the AR HUD and screen turned off to avoid reflections on the screen and AR HUD display surfaces.

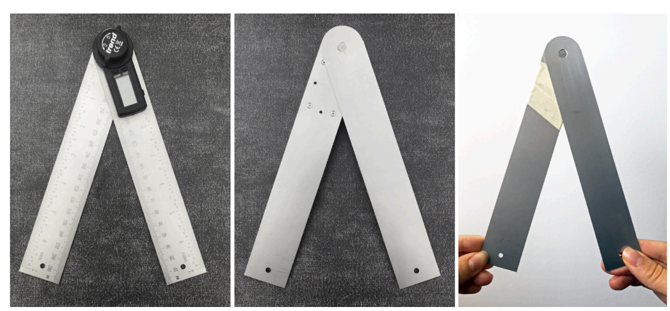

Fig. 3. A Trend DAR 200 angle ruler was used in the task. Left: front of the ruler, facing the experimenter. Middle: original back of the ruler. Right: back of the ruler, covered by tape to minimise appearance of screws, as held by participants.

2.4. *Angle size manipulation method*

In the physical condition, the proximal angle size was manipulated by changing the viewing height. For the screen and AR HUD setups, we displayed schematic images of angles. The angle sizes used in these images correspond to the proximal angle sizes when the physical angle between bars on the floor is viewed from a certain height. The calculation of viewing height for the proximal angle size conditions is illustrated in Fig. 2. We based the calculation on trigonometric ratios.

2.4.1. Angle matching task

In all three conditions (physical bars, flat-screen, and AR HUD), we asked participants to observe the angle and recreate the perceived size between the legs of an angle ruler[3] (see Fig. 3). Participants were instructed explicitly not to calculate what they think the actual angle size is, but to match the angle that they perceived from the stimuli with the perceived size of the angle that they created between the legs of the angle ruler. Participants were not allowed to overlay the ruler with the viewed angle and held the angle ruler to their side. The angle ruler was turned backwards so that the experimenter could read the value, whilst the participant could only see the backside and not the values. An angle ruler was used (instead of a compass by Erkelens (2015b)) to reduce the error margin and trial time when angles between compass legs have to be manually measured by the experimenter.

2.4.2. Dominant eye assessment

Whereas Erkelens (2015b) used binocular vision, we decided to perform the experiment with dominant eye monocular vision, to exclude binocular depth cues from influencing the perception. When necessary, an alignment test was done to assess a participants' dominant eye. In such a test, participants create a triangle between their thumbs and index fingers and centre a distant object in the triangle. When closing an eye, the eye with which the object remained most centred was deemed to be their dominant eye. The non-dominant eye was covered with an eye patch.

2.5. Procedure

Upon arrival, participants received a brief overview of the experiment, filled out a demographic questionnaire and signed a consent form. Where participants did not know their dominant eye, an alignment test was used to assess eye dominance.

Participants then performed the experimental trials with the physical bars. Before the first trial, we demonstrated the physical bar estimation task, after which participants could try out the task. Participants stood between the far ends of the physical bars. They were placed at a specific height (for a specific condition) by standing, sitting on a height-adjustable chair, or sitting on the floor. The following condition was the AR HUD setup. Participants were asked to take place behind the AR HUD setup on a height-adjustable chair. As the image looked distorted in terms of shape and colour when participants would move their head up and down and further and nearer from the AR HUD, participants adjusted their seat height such that when they sat comfortably and looked at the AR HUD, they saw an image that did not have separating colours or bending lines. The chair was then kept at this height for all conditions. Finally, the participants completed the task with the flat screen. In total, the experiment took approximately 45 minutes.

2.6. Measurements

The collected measurement was the matched angle. By matched angle, we refer to the angle that could be read from the angle ruler when the participant indicated that they perceived the angle between the angle ruler legs the same as the stimulus angle that they were shown. Our AR HUD setup had a technical limitation, which meant that slight variations in viewing height and viewing distance influenced the size of the displayed angle (i.e. the proximal angle). Participants P0A and P0B viewed the stimulus from a slightly different position than P01-P08. After the data was collected, two authors measured the proximal angle

Table 1
Tables showing the measured angles in the AR HUD (top), and the corresponding viewing heights calculated from those angles (bottom).

Angle Conditions				
Intended Angle	65°	76°	82°	107°
Near Measured (15 cm)	59.3°	69.2°	76.2°	102°
Far Measured (60 cm)	47.8°	57.4°	65°	92.6°
Corresponding Viewing Height Conditions				
Intended Viewing Height	1.65 m	1.32 m	1.17 m	0.75 m
Near Calculated (15 cm)	1.87 m	1.51 m	1.32 m	0.82 m
Far Calculated (60 cm)	2.53 m	1.96 m	1.65 m	1.02 m

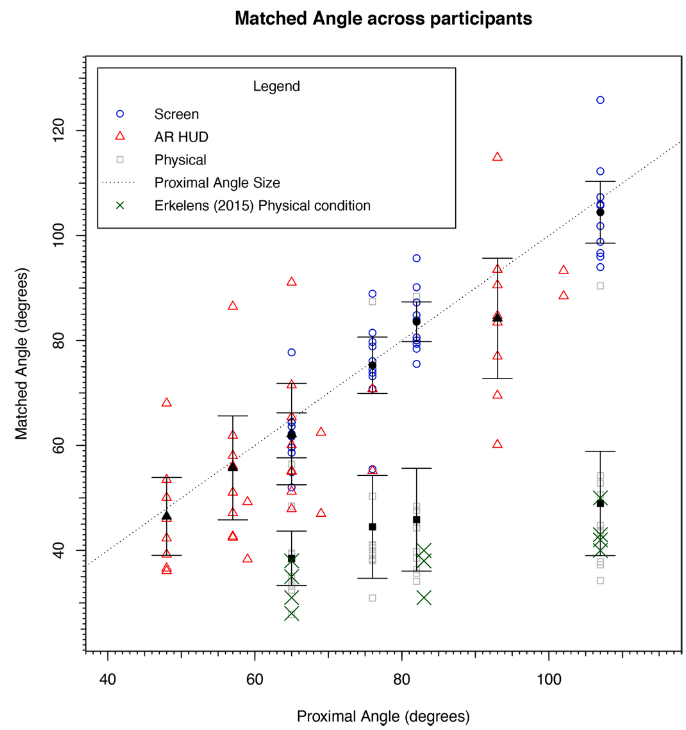

Fig. 4. Experiment 1: Plot of matched angle versus the proximal angle per condition: Screen (blue circles), AR HUD (red triangles), and physical (grey squares) and comparison with physical data from Erkelens (2015b), approximated from Figure 4 (green crosses). Coloured data points show mean data for an individual; black data points show the averages together with their 95% confidence intervals. If a measurement falls on the grey dotted line, it means that the matched angle size was equal to the proximal angle size (i.e. stimulus angle size). Averages and error bars are not shown for AR HUD proximal angle conditions with only two data points. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

size when the stimulus was viewed from the two different positions by overlaying the angle ruler before their eyes. These measurements are given in Appendix section A2, and were used in our visual analysis figures. In Fig. 4, we used the proximal angle (i.e. stimulus angle) as the independent variable for the measurements in the AR HUD condition. Slight variations in viewing position caused the measurements to shift to the right on the *x*-axis. For statistical tests, we apply an alpha level of $p < .01$.

2.7. Results

We plotted the measurements of all participants in Fig. 4, together with data from the physical condition in Erkelens (2015b). As seen in Fig. 4, the data in our physical condition largely overlap with Erkelens' observation (see the converging bars condition in Figure 4, Erkelens,

[3] The angle ruler used was the 'DAR/200' from the manufacturer 'Trend': a stainless steel angle ruler measuring7// or 20cm when folded, with a digital display showing angles from 000.0° to 360.0° with an accuracy of 0.3°, and a locking function. Manufacturer website:https://www.trend-usa.com/u-dar-200-digital-angle-rule-200mm-7-inch.

2015b) and replicate his findings that angles in the physical conditions were perceived to be smaller than angles on a screen, and that all matched angles were larger than the 23° angle between the bars on the floor. Contrary to Erkelens (2015b), we do not find that matched angles are consistently smaller than the proximal angle (line y=x), but this could be because we did not show a picture of the angle, but a schematic image in the AR HUD and screen conditions. From the data, we can see that the proximal angle values (i.e. the position on the x-axis) for the AR HUD measurements do not align with Screen and Physical conditions, which was due to slight angle deformation (as explained in section 8.2). Thus, we perform our initial statistical analysis only between displaying on a flat screen and in the physical environment. A visualisation of individual measurements can be found in the Appendix, section A1.

A 2 (Display Type: Physical or Screen) x 4 (Proximal Angle) ANOVA found a main effect of Display Type, $F(1, 9) = 88.03$, $p < 0.0001$. The matched angle size was larger for angles displayed on a screen (M = 81.3°, SD = 17.8) compared to angles in the physical world (M = 44°, SD = 4.4). There was also a main effect of proximal angle size, $F(3,27) = 143$, $p < 0.0001$. In Fig. 4 it can be seen that matched angles for both display conditions have an upward slope: the matched angle increases with an increase of proximal angle.

These main effects were also affected by an interaction effect between display type and proximal angle, $F(3, 27) = 25.32$, $p < 0.0001$. As Fig. 4 illustrates, the interaction pattern is that in the Screen condition (blue circles) the matched angle increases with an increase in proximal angle size. By contrast, in the Physical condition (grey squares), there seems to be less or no effect of proximal angle size (and thus, viewing height) on the matched angle, as indicated by the strong overlap between the 95% confidence intervals of the data points within this condition. Interestingly, participants did perceive the physical angle to be larger than the physical angle was on the floor (i.e. the 23° angle between the physical bars).

When we plot the measurements for Display Type condition AR HUD in the same graph (red triangles), the confidence intervals of the AR HUD condition overlap more with the screen condition than with the physical angle condition. This suggests that the AR HUD condition produces results similar to the screen condition, and not similar to the physical condition. The average matched angle size for AR HUD was 62.6° (SD = 16.9).

Furthermore, when we compare the matched angles in the three display conditions in Fig. 4 to the situation where proximal angle size would be exactly matched (plotted as a grey dotted line, $y = x$), the confidence intervals of the screen and AR HUD conditions overlap with the proximal angle values. In contrast, the physical angle confidence intervals do not overlap with the proximal angle values. Similar to the observation by Erkelens (2015b), the matched angles in the physical angle condition are consistently smaller than the proximal angle size (i.e. are to the bottom right of the line y=x in Fig. 4).

2.8. Discussion of results

Firstly, we replicate that Screen and Physical angle measurements are significantly different, cf. Erkelens (2015b). Looking at a visualisation of the distribution of measurements, it seems that perceived angle sizes in the AR HUD condition overlap more with the Screen condition than the Physical condition **(RQ1)**. This suggests that there might be a difference between perception of angle sizes in AR HUD compared to angles in the physical (three-dimensional) world. Secondly, visual inspection of the overlapping error bars indicates that perceived angle sizes in the Physical condition do not vary with proximal angle size **(RQ2)** (similar to Erkelens (2015b)). We did find significant effects for proximal angle size in the screen and AR HUD display types. Lastly, participants consistently underestimate the physical angle sizes in the Physical condition for all four proximal angle size conditions (cf. Erkelens (2015b)).

3. Experiment 2: Effects of graphical alterations on perceived angle sizes

3.1. Overview and aims

The second experiment investigates how various graphical characteristics of lines impact the perception of perspective on a screen **(RQ3)**. This exploratory study aims to bring the findings from experiment 1 closer to their relevance for practical applications. The exclusion of the AR HUD condition from this study is based on the assumption that graphical alterations might affect perceptions of a screen in a similar way as on an AR HUD. We motivate this, as Fig. 4 shows an overlapping pattern for the screen and AR HUD conditions.

We focus on characteristics that are relevant to the automotive field. Although the stimuli in experiment 1 were depictions of full lines that meet at the top, in high contrast, using solid lines, these assumptions might not always hold for in-vehicle AR HUD displays.

First, for in-vehicle AR HUD displays, it is not always feasible to use full lines. When driving in or near an urban area, it may not be possible to see the "end" of the road in the sense of the angle between lane markings reaching the horizon. Similarly, bends and obstructions can prevent the driver from being able to see the road far ahead. This motivates us to test various setups with lines that are not fully shown, but rather cut off at the top to leave an open end between converging lines.

Second, we also know that in AR HUD setups, factors like glare or varying backgrounds behind the AR HUD projection can cause the AR HUD image to have lower contrast. For this reason, we compare lines with relatively high or relatively low contrast in this experiment.

Third, lines in automotive contexts (such as lane markings) are sometimes not continuous but dashed or partially absent instead. To account for these conditions, we also compare participants' perception of angle sizes between continuous and dashed line conditions.

Fourth, we know from experiment 1 that matched angles in the screen condition closely follow the size of the proximal angle. We thus add (proximal) angle size as a parameter to investigate in this experiment.

This leads to the consideration of 8 stimuli that we use to investigate the effect of specific graphical manipulations on the perception of angle sizes. We compared the angle estimations with two baseline stimuli: a high contrast, continuous line that intersects (for both 65° and 107°). Full lines that meet at the top (from the baseline conditions) are compared against their cut-off counterparts **(RQ3a)**. The stimuli are a combination of relatively small (65°) or large (107°) angles, continuous lines or lines that have been manipulated to be dashed **(RQ3b)**, and high contrast lines or lines in lowered contrast **(RQ3c)**. The choice for the two angle sizes was motivated as they were also used in Experiment 1 and approximate the extremes of the range of viewing heights that people experience in a vehicle (sports car to SUV).

3.2. Participants

Five participants (2F; 3M) with an average age of 31.2 years (SD = 9.7, range 23–50 years of age) and height of 175.8 cm (SD = 6.8 cm, range 165–183 cm, 1 participant did not answer) participated. All participants self-reported normal or corrected to normal vision in both eyes and were researchers or engineers working in the automotive sector. Before participating, we asked participants whether they were familiar with estimating angle sizes ("Yes" = 2, "No" = 2, one participant provided no answer). All participants provided informed consent. Participants were not offered monetary compensation but were offered a snack after participating.

3.3. Experimental design

We used a 2 x 2 x 2 repeated measures within-subjects design (all partial lines), with two control stimuli (full lines that meet at the top) at

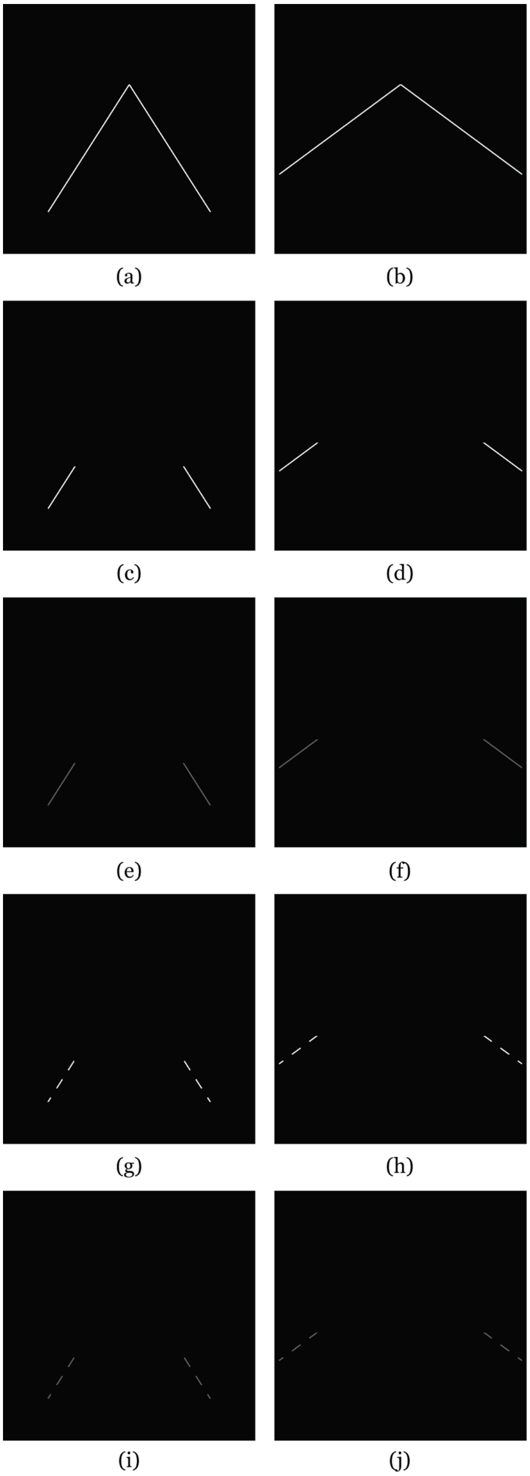

Fig. 5. Stimuli shown on the screen in experiment 2. The stimuli show angles of 65 (left) or 107° (right). Stimuli (a) and (b) are baseline conditions with full lines, in high contrast. Stimuli (c) and (d) show the partial line condition. Stimuli (e) and (f) show partial and low contrast lines, (g) and (h) show partial and dashed lines, and (i) and (j) show partial, low contrast and dashed lines.

the beginning. Fig. 5 shows the stimuli. We manipulated angle size with two levels (65° and 107°), partial lines with two levels (partial and full), line type with two levels (continuous and dashed, where the line was interrupted with equal intervals where the line was present and where it was not present), and contrast with two levels (100% line opacity and 50% line opacity). All manipulated conditions showed angles between converging, but not touching lines. In addition, there were two control conditions showing full lines that met at the top (high contrast, continuous) identical to those used in experiment 1, at 65° and 107° (see Fig. 5(a) and Fig. 5(b)).

We decided to present stimuli in the same order for every participant to enable direct comparison between subjects. In experiment 1, the order of stimuli was grouped by display type, and within each display type from small to large proximal angle. In experiment 2, there was only one display condition (screen) and multiple test variables. The experiment was blocked, in which a block refers to 10 trial repetitions with a specific angle and specific type of graphical form. The order of blocks was randomised, but with the constraint that no two subsequent blocks could have the same angle size. If the same size of angle would be shown for too many subsequent task repetitions, the participants might get used to making a specific movement with the angle ruler, which we aimed to avoid[4]. The two control images were added to the front of the resulting stimulus order. The order of the blocks was as follows: 1: Full angle 65°, 2: Full angle 107°, 3: High contrast, continuous 65°, 4: Low contrast, dashed 107°, 5: High contrast, dashed 65°, 6: High contrast, continuous 107°, 7: Low contrast, dashed 65°, 8: Low contrast, continuous 107°, 9: Low contrast, continuous 65°, 10: High contrast, dashed 107°.

For every condition, the measuring task was repeated ten times before moving on to the next stimulus. Therefore, each participant performed a total of one hundred angle estimations.

3.4. Materials

We placed a flat-screen on a table with the centre of the screen at approximately 120 cm height from the floor, and at approximately 60–80 cm distance from the participant's eyes. We showed schematic images representing angles on the screen. Each task took place on an adjustable height chair behind the screen. The chair was adjusted so that the participant's eye height aligned with the centre of the screen and remained this way throughout the experiment. The experiment took place in a room with indirect daylight. The angle measurement task was the same as before: participants had to estimate the angle between two lines using an angle ruler.

3.5. Procedure

The procedure of the experiment was similar to the procedure for experiment 1. During instructions, the experiment leader again emphasised participants to visually match the perceived angle to the flat angle between the angle ruler legs.

3.6. Measurements

The collected measurement was, similar to Experiment 1, the Matched Angle.

3.7. Results

Results are plotted in Fig. 6. In the baseline case, with full, continuous lines in high contrast, measurements across participants are relatively consistent. This is visible in the figures by the narrow 95% confidence intervals. By comparison, in all the other conditions, the average matched angle across the ten repetitions per condition varies more between participants. In general, participants tend to underestimate the true angle in both angle size conditions, with about 11.69° for smaller angles (range -24.31° to +5.45° difference) and 4.76° for larger

[4] This consideration was more pressing in experiment 2, as there were only two proximal angle sizes (compared to four in experiment 1) and these were each shown ten times in four conditions (compared to only 10 times per interface type in experiment 1).

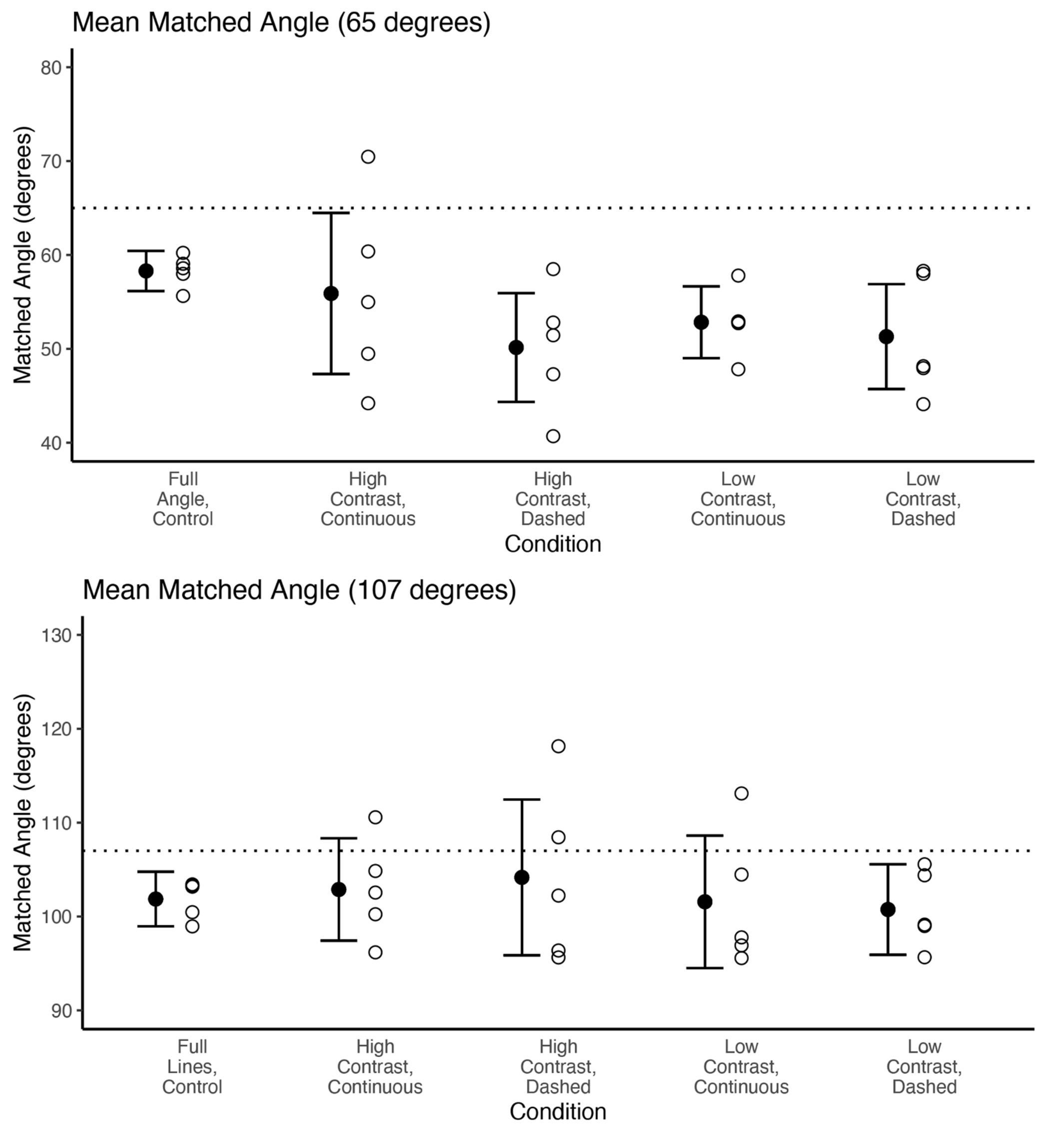

Fig. 6. Experiment 2: Matched angle per condition. Each plot shows the actual proximal angle as a dashed line. Per condition, open points show data of individual participants and closed points with error bars show the mean and 95% CI. The top plot shows performance in the 65° setup, the bottom in the 107° setup.

angles (range -11.43° to +11.14° difference). No consistent pattern emerges in which one factor has a more substantial influence than another on the matched angle sizes.

In general, most participants' matched angle sizes were smaller than the actual proximal angle (i.e., the data points lie below the dashed lines). However, on some trials (particularly for the larger actual angle of 107°), there were over-estimations of the angle. Over-estimation of the 65° angles is seen in P2, and of the 107° angles is seen in P2 and P4.

3.8. Discussion of results

Experiment 2 investigated how participants' perception of depth (using angle size estimation) changes for various graphical parameters that might be more realistic for applied (automotive) AR HUD graphics. The most important finding is that participants tend to vary more in their estimates for the conditions in which there were no full lines shown (i.e., all conditions but the baseline control). Moreover, the majority of the participants tends to underestimate the observed angle in most conditions. Interestingly, this effect was not seen for the Screen and AR conditions in Experiment 1. That is, in Experiment 1, the means of the matched angles in the Screen conditions were close to the proximal angle, i.e., were close to the line $y = x$ in Fig. 4, suggesting that there was no systematic underestimation.

4. Discussion

4.1. Main findings

In our two experiments, we found that perspective angle sizes on AR HUD are not perceived differently than on a flat-screen, but are perceived differently than angle sizes between bars on a physical floor **(RQ1)**; that proximal angle size has no significant correlation with perceived angle sizes in the physical condition, but does have an effect in the AR HUD and Screen conditions **(RQ2)** cf. Erkelens (2015b); and that no consistent effect emerges in which one visual factor (i.e. full/partial lines, high/low contrast, dashed/continuous lines) has a more substantial influence than another on perceived angle sizes **(RQ3a, RQ3b)**. Angle size estimations of cut-off lines varied more than estimations of a baseline condition showing full lines that meet at the top **(RQ3a)**. Our findings from experiment 1 confirm the hypothesis that angle size perception on an AR HUD differs from angle perception on the floor of a three-dimensional space. In the following section, we will outline the implications of our findings for theory and design.

4.2. Implications for theory

4.2.1. Underestimation of depth in AR could be linked to properties of human visual system

We discussed several studies that investigated possible causes of depth underestimation in (head-mounted) AR displays, as summarised by Swan et al. (2007). We found that the perceptual difference in flat-screens compared to physical angles (Erkelens, 2015b) is also seen for AR. Pilots making night landings also rely largely on monocular perception of an angle (the image shape created by runway lines). Our findings are in line with Mertens (1981), who found that the ratio between the height and width of the runway image is often overestimated (i.e.: the angle size between lines is underestimated). This suggests that the underestimation of depth depending on angle sizes is a property of the *human visual system* when observing a virtual interface (be it a flat-screen or an AR display) and not just a property of an AR *technology*. Our findings that estimated angle sizes in physical ground plane angles are smaller than estimations of their proximal angles on a screen or AR display, aligns with the theory that people underestimate distances in AR and virtual (screen) environments. If angle sizes on the physical plane are significantly underestimated compared to their proximal angle sizes, this means that people are interpreting the lines as if they were longer and intersecting at a farther vanishing point. Since this underestimation of angle size is smaller on a screen or AR HUD, it means that the lines displayed on a screen or AR HUD are *not* being interpreted as longer or intersecting at a farther point. When observed lines in AR HUD and Screen observations are perceived to be shorter compared to physical angle observations, underestimation of distances could thus be the result.

4.2.2. The role of experience of the world in depth perception

Our first experiment confirms the finding from Erkelens (2015b) that perception of angle sizes in the physical condition, compared to the screen condition, correlates less with proximal angle size **(RQ2)**. This might be due to the fact that next to observation, experience of object sizes and distances in the natural world might also influence human depth perception (Erkelens, 2015a; Gilinsky, 1951). Experiments by Bülthoff et al. (1998) found that people recognise familiar three-dimensional objects even with a scrambled depth structure, which means that expectations about the object's structure override the stereoscopic perception of the object. Humans know from experience that angle sizes between parallel lines, such as on the road, vary with viewing height, whereas the actual road has not changed. When viewing height changes, prior familiarity might have a bigger influence than the observed proximal angle size. Schematic lines on a screen and AR HUD bear less resemblance to actual physical world objects, which might lead to the angle size perception depending mostly on proximal angle size, and less on experience.

4.2.3. Various on-screen graphical manipulations resulted in more overall variance between participants, and angles were consistently underestimated

The findings from our second experiment, where we explored the effects of showing partial versus full lines **(RQ3a)**, dashed versus continuous lines **(RQ3b)** and low versus high contrast lines **(RQ3c)** show that participants generally underestimated angle sizes across all conditions. No consistent pattern emerged in which one factor influenced matched angle sizes more than another in the eight partial angle conditions. The level of variation in the partial lines conditions contrasts with the control condition where full lines were shown and where participants' angle estimation was relatively constant (i.e., small error bars in Fig. 6). We hypothesise that since the manipulated images did not include factors aimed explicitly at distorting the perceived angle size (such as fading lines), it could be expected that the angle sizes were still perceived similarly. All of the manipulated conditions resulted in less information about the line trajectory (i.e., fewer white pixels on the black background), which might have influenced the greater variance between participants.

4.3. Implications for design

4.3.1. Over-reliance on perspective as a depth cue could cause perceptual differences between AR and physical environments

In line with related studies (e.g. Erkelens, 2015b; Mertens, 1981), our findings suggest that an over-reliance on angle perception could result in distorted depth perception when compared to a physical environment **(RQ1, RQ2)**. Therefore, it could be of interest for developers of AR HUD applications to investigate alternative methods of displaying graphics, to potentially minimise the perceptual difference that the reliance on angle perception might cause. Examples of mitigating factors could be the introduction of additional monocular and stereoscopic depth cues in the AR graphics or in the optical AR design (such as described in Li et al., 2020; Meijering et al., 2020; Yöntem et al., 2020). Furthermore, testing of the graphics in low light conditions could give researchers and practitioners insight into potentially adverse depth perception effects. Examples could be blackout or whiteout conditions where reliance on AR HUD graphics might increase.

4.3.2. Graphical alterations of lines might not affect perspective perception

We did not find a consistent pattern in which one factor of graphical manipulation had a stronger effect on angle size perception than another **(RQ3a, RQ3b, RQ3c)**. If it would be the case that our design alterations do not affect perception of perspective angles and the resulting perception of depth, this could imply that designers would not need to limit their choice of graphics to account for differences in angle size perception. The absence of a clear pattern implies that none of the explored design combinations could help overcome the underestimation of angle sizes compared to the proximal angle size. More research is needed to investigate how underestimation of depth angle size can be overcome with other perceptual features. This could potentially be achieved by combining multiple depth cues, such that depth perception does not rely on perspective angles alone.

4.4. Limitations

The AR HUD setup that we used had a technical limitation in that it slightly altered the perceived angle as a function of the distance to the AR HUD, which was different between participants P01-P08 and participants P0A-P0B. We re-calculated the corresponding viewing heights of the AR HUD measurements using spatial geometry (trigonometric calculations based on the measured correct angle). The Appendix and Table 1 give a detailed description of the recalculation. We used the outcomes of the correction to plot the data points for the AR HUD condition in Fig. 4 and Fig. 7. The scope of our studies has focused on investigating a fundamental aspect of perspective perception and did not include many variations or higher fidelity implementations of the AR HUD setup. The AR HUD setup was limited to a planar image and had a limited field of view. Although we do not believe that this has had a significant influence on the perception of the angle size, the horizon was visible in the scene. The horizon itself was not aligned to the angle, and thus, we do not believe it provided meaningful distance information for the angle matching task.

Another limitation is that conditions (physical, AR HUD, screen) and angle sizes were presented in a fixed order, similar to Erkelens (2015b). We did not expect a significant learning effect in the angle matching task, and a randomised ordering could significantly increase the trial duration and risk of other errors in the setup. However, through visual analysis of the individual data points for each repetition, as given in Appendix section A3, we did not see significant patterns that could indicate a learning effect. For follow-up studies, different ordering designs may be considered.

Comparing different age groups was out of scope for this research, and cf. Erkelens (2015b), we did not control for age. Age primarily

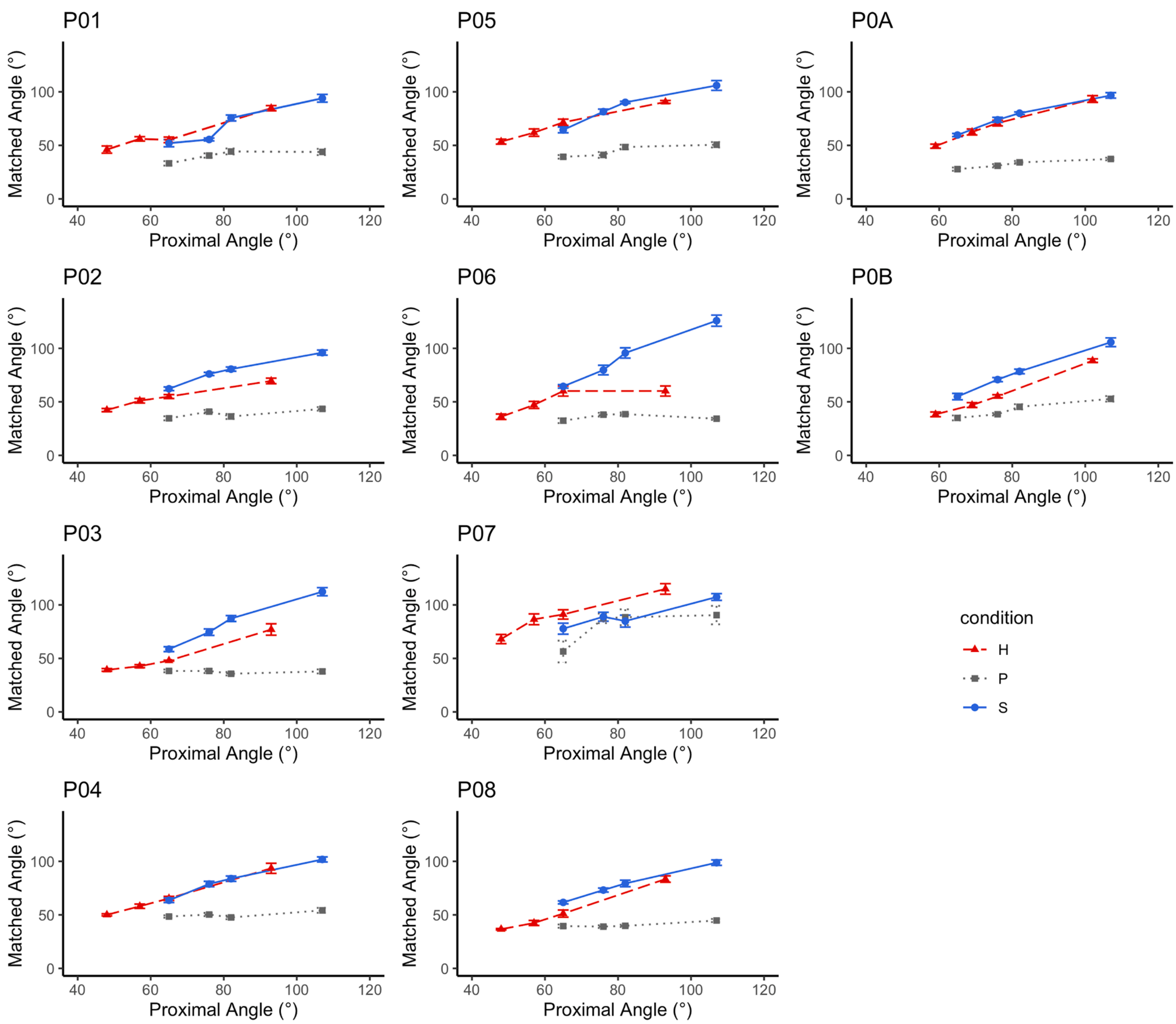

Fig. 7. Individual results of experiment 1. Results are shown for Screen Conditions AR HUD (H), Physical (P) and Screen (S). Matched angle in ° is plotted against proximal angle.

influences stereoscopic depth perception, such as shown in Bell et al., 1972, whereas our studies focused on pictorial depth cues.

Lastly, the AR HUD condition was not included in the second experiment. Although the first experiment shows the overlap between the perception of angle sizes on AR HUD and screen, further experiments should confirm if they apply consistently to AR HUDs. In the next section, we will provide recommendations for future work, which will involve a higher complexity of manipulations.

4.5. Future work

Future work can explore even further how humans perceive perspective and other depth cues in AR HUDs. We found that perspective perception on an AR HUD is different from the physical world, but similar to a screen - angle sizes on the ground plane in physical reality are consistently underestimated when compared to their proximal angle size, whereas this is not the case for angles on AR HUD and on a screen. Our findings might provide a theory behind the phenomenon of depth underestimation in virtual environments. Whereas some prior studies (e.g. Creem-Regehr et al., 2005; Knapp and Loomis, 2004; Messing and Durgin, 2005; Plumert et al., 2004; Swan et al., 2007; Willemsen et al., 2004; Wu et al., 2004) assign underestimation of depth to a technical problem with the augmented reality setup, the perceptual similarities that we found between augmented reality and a screen might indicate that depth underestimation based on perspective is an aspect of human perception that is *not* limited to augmented reality display technologies. Further research could be carried out to investigate why this is the case and how this affects driving performance and user experience.

Also, other experiments can look at other features of the visual world. Examples could be replacing the schematic angle depictions with schematic images of angles in a road setting, photographs, such as done in Erkelens (2015b), or even moving images. Research could focus on complex road situations, such as sharp bends, hills or descends, unpaved roads or heavy traffic conditions. When better suited to complex setups, researchers may consider alternative methods for assessing the perception of depth, like perceptual matching, as suggested as a method for AR depth judgement in Swan et al., 2006.

Lastly, our AR HUD setup showed a two-dimensional image projected on a plane at a fixed virtual image distance. We suggest further studies to look into other optical designs of AR HUDs, such as a multi-depth display system as developed by Meijering et al., 2020.

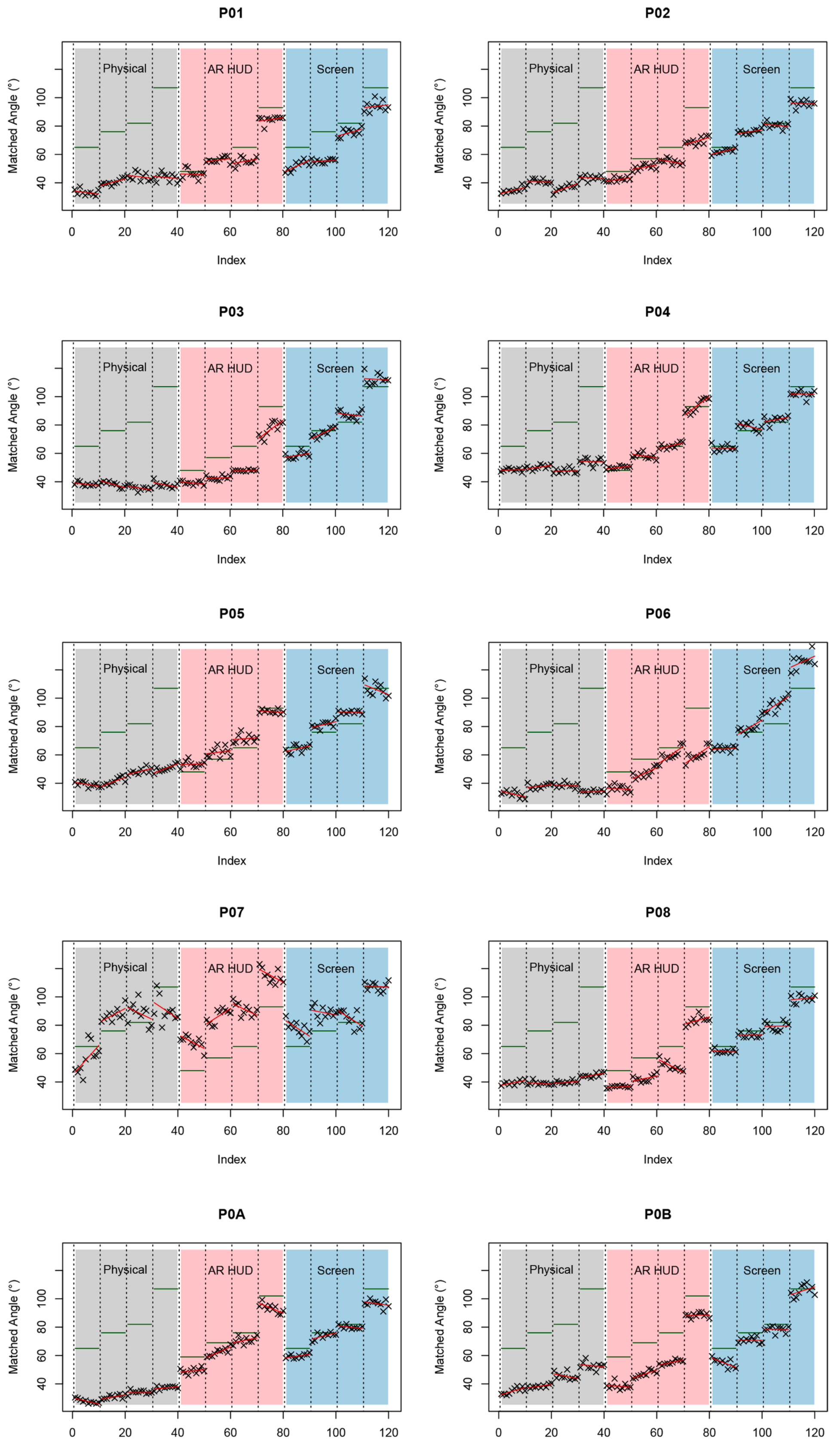

Fig. 8. Visualisation of all data points in experiment 1. The green horizontal line indicates the proximal angle size, and the crosses are ten repetitions within each condition. Each graph shows one participant. The *x*-axis gives the index of the measurement over time. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5. Conclusion

We conducted two experiments to investigate depth perception on augmented reality head up displays. We found that perception of angle sizes between an AR HUD and a flat-screen display does not differ significantly, while it does differ between physical angles and angles on AR HUD **(RQ1)**; perceived angle sizes in the physical world do not appear to vary with proximal angle size (viewing height) **(RQ2)**; full angle lines result in more consistent perception between individuals than partial angle lines **(RQ3a)**; and using dashed lines, or using a lower contrast, does not seem to lead to a clear pattern of change in perception **(RQ3b, RQ3c)**.

CRediT authorship contribution statement

Alexandra W.D. Bremers: Conceptualization, Methodology, Investigation, Visualization, Formal analysis, Writing – original draft, Writing – review & editing. **Ali Özgür Yöntem:** Investigation, Resources, Writing – review & editing. **Kun Li:** Investigation, Resources, Writing – review & editing. **Daping Chu:** Supervision, Writing – review & editing. **Valerian Meijering:** Supervision, Writing – review & editing. **Christian P. Janssen:** Supervision, Visualization, Formal analysis, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The work presented in this article was performed during an internship at Jaguar Land Rover and submitted as a master's thesis to the Artificial Intelligence program at Utrecht University. There are no known competing interests regarding this work.

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

A1. Experiment 1: Individual results

Fig. 7 shows individual results against proximal angle.

A2. Experiment 1: Corrected angle sizes for AR HUD

Participants P01-P08 viewed the AR HUD at a distance of 60 cm. Participants P0A and P0B viewed the AR HUD from a distance of 15 cm. The calculations of corresponding viewing height were achieved by measuring the displayed angle size by overlaying an angle ruler for distances of 60 cm and 15 cm to the AR HUD, and using the geometry of space to calculate the corresponding viewing height as given in Table 1. The corrected angle was measured by viewing the angle on the AR HUD from their viewing distance (15 cm). The corrected corresponding proximal angle for P0A and P0B in the AR HUD condition thus were (59°, 69°, 76°, and 102° respectively), as opposed to (65°, 76°, 82°, and 107° respectively) in the screen and physical conditions. The corrected corresponding proximal angles for P01- P08 were measured to be (48°, 57°, 65°, and 93°, respectively). From these proximal angles, the corresponding viewing heights were calculated using spatial geometry and trigonometric functions. For P0A and P0B, the viewing heights in the AR condition corresponded to (1.87, 1.51, 1.32, and 0.82 m, respectively) instead of (1.65, 1.32, 1.17, and 0.75 m, respectively) in the screen and physical conditions. For P01- P08, the calculated corresponding viewing heights were (2.53, 1.96, 1.65, and 1.02 m, respectively). Table 1 in the Appendix shows the outcomes of these calculations. These outcomes were used when plotting the data points for the AR HUD condition in Fig. 4.

A3. Exploratory analysis of order effects

Fig. 8 shows per individual (plot) how angle was estimated by participants over trials. The horizontal axis gives the trial index over time. Coloured blocks isolate the specific conditions: physical (grey), AR HUD (pink), and Screen (blue). Vertical dashed lines isolate 10 trials, and horizontal green lines give the target line. The crosses show observations and red lines show linear trend lines.

There is no consistent pattern visible between the repetitions within each condition. For example, if there had been consistent learning effects between AR HUD and Screen, then we would have expected consistent (Near) horizontal trend lines in the screen condition (i.e., that experience from the AR HUD quickly transferred to screen). If there were carry-over effects between trials of different angles, then we would expect angle estimation to be biased more towards the previously observed trials. We find none of these effects consistently. This suggests that there was no learning effect for this type of task.

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