Depth constancy and the absolute vergence anomaly

Vision Research 226 (2025) 108501

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Depth constancy and the absolute vergence anomaly

Rebecca E. Ranson [a], Peter Scarfe [b], Loes C.J. van Dam [a,c], Paul B. Hibbard [a,d,*]

[a] Department of Psychology, University of Essex, Wivenhoe Park, Colchester CO4 3SQ, UK
[b] School of Psychology and Clinical Language Sciences, University ofReading, Early Gate, Whiteknights Road, RG6 6AL, UK
[c] Institute of Psychology, Centre for Cognitive Science, TU-Darmstadt, 64283 Darmstadt, Germany
[d] Division of Psychology, University of Stirling, Stirling, FK9 4LA, UK

ARTICLE INFO

Keywords:
Binocular vision
Depth perception
Binocular convergence
Depth constancy

ABSTRACT

Binocular disparity provides information about the depth structure of objects and surfaces in our environment. Since disparity depends on the distance to objects as well as the depth separation of points, information about distance is required to estimate depth from disparity. Our perception of size and shape is biased, such that far objects appear too small and flattened in depth, and near objects too big and stretched in depth. The current study assessed the extent to which the failure of depth constancy can be accounted for by the uncertainty of distance information provided by vergence. We measured individual differences in vergence noise using a nonius line task, and the degree of depth constancy using a task in which observers judged the magnitude of a depth interval relative to the vertical distance between two targets in the image plane. We found no correlation between the two measures, and show that depth constancy was much poorer than would be expected from vergence noise measured in this way. This limited ability to take account of vergence in the perception of depth is, however, consistent with our poor sensitivity to absolute disparity differences. This absolute disparity anomaly thus also applies to our poor ability to make use of vergence information for absolute distance judgements.

1. Introduction

Our two eyes sample the ambient optic array from two locations (Frisby, 2009). This means that the visual direction from each of these points to any object in three-dimensional space will differ, with this difference depending on the direction and distance to the object. This optic array disparity, which is defined by the locations of the two eyes and the target object, can be used to determine the distance to the object (Fig. 1).

As can be seen in Fig. 1, in the simplest case of a target directly in front of the observer, the triangle created between the viewed object and the two eyes can be halved, to create two right-angled triangles. The optic disparity angle (a) is then given by:

$$\tan(a/2) = \frac{I}{2D} \quad (1)$$

Fig. 2 plots the optic array disparity as a function of viewing distance, using the average adult interocular distance (IOD) of 6.3 cm (Dodgson, 2004). Optic array disparities can therefore be used to judge the distance to objects if the IOD is known.

In the barn owl, the orientations of the two eyes are almost fixed (du Lac & Knudsen, 1990; van der Willigen, Frost, & Wagner, 1998). This means that the two visual directions, and thus the optic array disparity, can be determined primarily from the locations of the point in the two retinal images. This contrasts with humans and other primates, whose eyes rotate within their sockets, meaning we can fixate objects of interest so that they appear in the fovea for both eyes. This complicates the use of binocular parallax information, and the observer's information about the optic array disparity can be divided into an *extra-retinal* component, provided by the difference in gaze directions of the two eyes (vergence), and a *retinal* component, provided by the differences in the locations of the point in the two retinal images (binocular disparity). When the observer fixates a point, its retinal disparity is zero and information about the optic array disparity is provided purely by vergence. This means that, in principle, vergence can be used to determine the distance to objects when they are fixated, as has long been appreciated (Baird, 1903). As distance increases, the vergence angle decreases, to the point where the eyes are effectively parallel. We assume a just noticeable change in vergence (v) of 10 arc min Nagata (1991), and an IOD (I) of 6.3 cm (Dodgson, 2004). The distance (D) beyond which vergence is no longer useful can then be calculated as:

* Corresponding author at: Division of Psychology, University of Stirling, Stirling, FK9 4LA, UK.
E-mail address: paul.hibbard@stir.ac.uk (P.B. Hibbard).

https://doi.org/10.1016/j.visres.2024.108501
Received 18 January 2024; Received in revised form 4 October 2024; Accepted 7 October 2024
Available online 2 November 2024

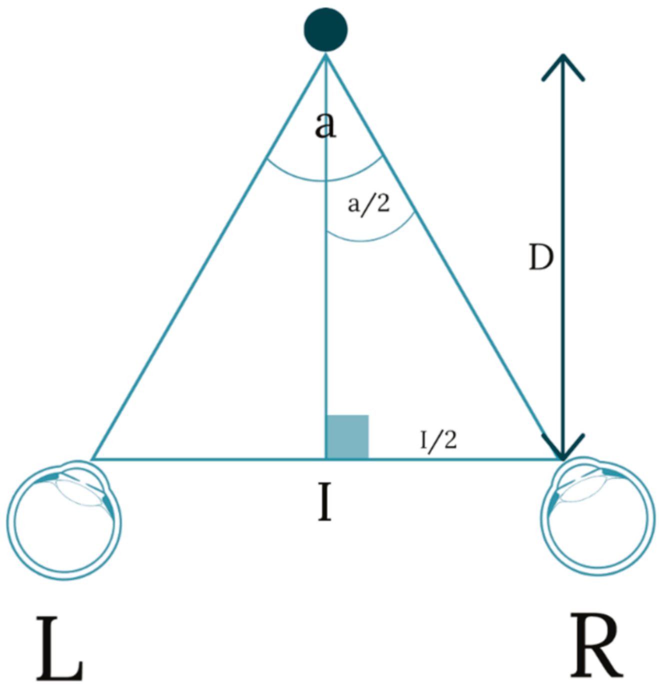

Fig. 1. Triangulation of distance from binocular parallax. An object at a distance *D*, with an interocular distance *I*, creates an optic array disparity *a*.

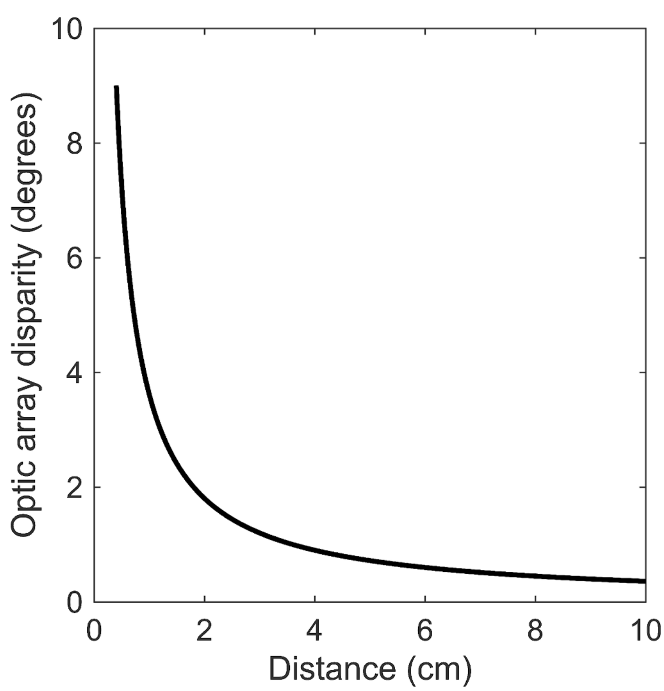

Fig. 2. Optic array disparity *a* as a function of distance, for a target directly in front of the observer, with an interocular distance of 63 mm.

$$D = \frac{I}{tan(\upsilon)} \tag{2}$$

From this, the maximum distance for which vergence is likely to be beneficial is 22 m. This is considerably further than the distance of around 6 m that is often assumed (Gregory, 1973). This, in theory, would make vergence a useful cue to distance across a reasonably extensive range, although the uncertainty of estimates is expected to grow rapidly with distance. A number of methods have been used to assess whether distance can be judged from vergence in this way. These include verbal judgements, pointing tasks, and reaching and grasping. Indirect tasks, in which the effect of distance from vergence on apparent size or depth, have also been used.

Baird (1903) asked participants to verbally estimate the apparent distance to a target light that was visible through a 10x15 mm aperture, presented at a range of distances between 30 and 90 cm, and viewed monocularly and binocularly. When viewed monocularly, accommodation provided a potential cue to distance; this was accompanied by vergence under binocular viewing. In both cases, judgements increased with actual distance, with a slope of 70 % for monocular viewing and 83 % for binocular viewing. These results demonstrate a role of both accommodation and vergence in the perception of distance. Viguier, Clement and Trotter (2001) also showed that observers were able to make accurate verbal distance judgements for targets up to a distance of 40 cm, but underestimated the distance of targets beyond this. In contrast, Morrison and Whiteside (1984) reported accurate estimates for distances up to 9.2 m. This is still within the geometrical range of 22 m for which vergence is predicted to be useful. However, judgements in this case are more likely to have been based on binocular disparity or diplopia, rather than vergence, since performance was only partially degraded when a brief stimulus presentation was used that did not allow time for convergence on the target.

Swenson (1932) asked observers to point to the apparent location of a target with an unseen hand. They showed that observers could make accurate distance judgements from a combination of accommodation and vergence up to a distance of at least 40 cm. Foley and Held (1972) found that the distance pointed to by observers increased with vergence-specified distance in the range 10–30 cm, but was consistently overestimated. Mon-Williams and Tresilian (1999) used prisms to alter the vergence-specified distance to targets presented between 20 and 60 cm. The distance pointed increased with vergence with a gain of 86 %, very similar to that found by Baird (1903) using verbal judgements.

Apparent distance from vergence has also been inferred from its effect on apparent size and depth. Here, we define distance as the egocentric distance between an observer and a location in 3D space, and depth as the difference in distance between two points (Tresilian & Mon-Williams, 2000), as shown in Fig. 3.

As the size of a retinal image of an object decreases with distance, for a given projected retinal angle, vergence consistent with a greater distance should increase the apparent size of a visual target. Similarly, the amount of depth perceived from a given magnitude of binocular disparity should increase with apparent distance. Since retinal image size scales with distance, and disparity approximately with the square of distance, the effect of distance on apparent depth should be more pronounced than its effect on apparent size (Johnston, 1991).

The effect of vergence on apparent size has been demonstrated in studies in which observers have been asked to set a stimulus to match the size of a hand-held standard (van Damme and Brenner, 1997; Bradshaw, Parton & Eagle, 1998; Brenner and van Damme, 1999). These studies have all shown that vergence-specified distance influences observers'

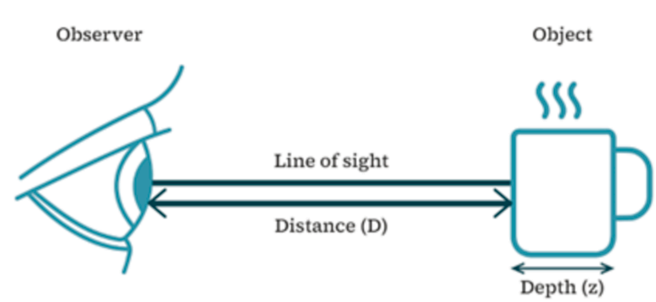

Fig. 3. Distance versus depth. Illustrating the difference between distance and depth in this work, showing the distance (D) from the observer to the object, and the depth (z) across the object.

size settings, with either complete (Bradshaw et al., 1998) or incomplete (van Damme and Brenner, 1997) scaling. Scaling for depth tends to be incomplete, such that depth relative to width or height is overestimated at near distances, and underestimated at far distances (Johnston, 1991; Tittle, Todd, Perretti & Norman, 1995; Glennerster, Rogers, & Bradshaw, 1998, Glennerster, Rogers, & Bradshaw, 1998; Scarfe and Hibbard, 2006). Where observers have estimated both size and depth, there is a strong correlation between the two, suggesting that they are scaled to take account of the same information about distance (van Damme & Brenner, 1997; Bradshaw et al., 1998; Brenner and van Damme, 1999).

Estimates of size and distance are necessary when reaching to and grasping objects, and it has been shown that vergence plays a particularly important role in the reaching component of prehension (Mon-Williams and Dijkerman, 1999; Bradshaw et al., 2004; Melmoth, Storoni, Todd, Finlay and Grant, 2007).

While the evidence summarised above has been taken to demonstrate a role for vergence in the estimation of distance, shape and size, there are some complications and reservations in this interpretation. Firstly, it has been suggested that, rather than having access to an absolute estimate of vergence, we are in fact sensitive only to differences in vergence relative to its resting state (von Hofsten, 1976), or to changes in vergence as a cue to changes in distance (Brenner & van Damme, 1999).

Linton (2020) has questioned whether we use vergence to extract absolute distance at all, based on the confounding effects of other cues. He argues that, when vergence is changed between trials of an experiment, this is typically accompanied by (1) initial diplopia when the to-be-fixated target is presented at a distance that differs from the observers resting fixation (2) a changing retinal image, as the binocular disparity of the target reduces to zero as the eyes move to fixate it and (3) conscious awareness of these eye-movements, as distinct from any estimate of vergence itself. He found that, when vergence is altered slowly, to remove these other cues, observers' estimates of distance do not change. That is, perceived distance does not change with slow, rather than abrupt, changes in vergence. These conclusions are consistent with reports that observers do not see depth from absolute disparity or vergence for large field stimuli moving in depth, and that depth from disparity is not affected by large errors of vergence (Erkelens and Collewijn, 1985ab).

Despite these reservations, the evidence nevertheless shows that distance is estimated through binocular parallax, albeit through some combination of static and dynamic information about vergence and disparity. However, while apparent distance does tend to increase with target distance, the scaling of these estimates is incomplete, such that far distances tend to be underestimated. It has been proposed that these biases in perceived distance result from the imprecision of our ability to estimate vergence.

Mon-Williams and Tresilian (1999) noted that, due to the non-linear relationship between distance and vergence, a just noticeable difference in vergence will correspond to a smaller distance in front of versus behind fixation. This means that the central distance of the uncertainty range for vergence will be at a distance beyond the true value. They argued that the underestimation of far distance may be a strategy to compensate for this expected bias.

Based on a similar logic, Scarfe and Hibbard (2017) showed that an unbiased, symmetrical likelihood function for vergence, once transformed to a likelihood function for distance, will have its peak at a distance closer than that corresponding to the vergence angle. They thus argued that a maximum likelihood estimate of distance from vergence would tend to result in an underestimation of far distance, but accurate perception of near distance. In both interpretations, biases in perceived distance are a direct consequence of uncertainty in vergence. This means that the distance constancy (the extent to which perceived distance increases with vergence-specified distance) will be less than 100 %, with the degree of constancy reducing as the uncertainty of vergence increases. As a further consequence, depth constancy is also expected to be incomplete, with the degree of depth perceived, relative to that predicted geometrically from binocular vergence and disparity, also decreasing with increasing distance.

The purpose of the current study was to assess whether the precision of vergence predicts the degree of shape constancy in a simple binocular three-dimensional shape task. This allows us to determine whether biases in perceived distance are the result of uncertainty in vergence. We used two tasks, one that tested participants' certainty and bias of vergence, and one that measured their shape constancy across distance.

Participants' certainty of vergence was assessed using a nonius line task that involved presenting participants with a pair of vertical lines dichoptically - one to each eye (Jaschinski, Broede and Griefahn, 1999), and asking them to judge their horizontal alignment. Presenting one image to each eye in this way requires the two images to be compared and a way to assess the vergence signal of the perceived fixation point, since uncertainty or bias in vergence leads to uncertainty or bias in the alignment judgement.

Chopin, Levi, Knill and Bavelier (2016) used this nonius line task to measure noise of the vergence signal to explore the suggestion that vergence noise accounts for the observed difference between the accuracy of absolute and relative depth estimates. They estimated a value for vergence noise of 225 arc seconds at a viewing distance of 2.1 m. They found that absolute disparity thresholds were 10 times higher than relative disparity thresholds, but concluded that this could not be explained by vergence noise alone.

The second task was designed to measure depth constancy across distance. Participants were presented with a stimulus consisting of three points in a triangular formation, at four distances ranging from 40 to 100 cm, and asked to make a judgement about the depth of the stimulus presented relative to its height (Bradshaw, Parton and Glennerster, 2000). In line with previous work, an underestimation of depth relative to height was expected to increase with physical distance, indicating a lack of shape constancy (Johnston, 1991, Bradshaw, Parton and Glennerster, 2000).

The stimulus was a triangle in 3D space, defined by three dots in a vertical line. The top and bottom dot were presented at the same distance, and the middle dot at a closer distance to create a triangle in depth. Participants judged whether the depth of this triangle was larger or smaller than half its height, i.e. whether it was taller or shorter than an equilateral triangle. This allowed us to calculate a Point of Subjective Equality (PSE) indicating the point at which the presented stimulus appears to have a depth equal to its height. A Just Noticeable Difference (JND) was calculated to quantify the precision of these judgements. A regression slope was then calculated from the PSE scores from the four distances, which provided a measure of the change in bias with increasing distance, showing the degree of shape constancy. With perfect constancy, the slope of this line would be zero. If participants underestimated depth at far distances relative to close distances, the slope of the line would be positive, since this would show that observers required an increasing amount of depth in the stimulus to maintain a constant perceived depth. Therefore, the greater the magnitude of slope, the worse the shape constancy.

Given the expected differences in bias and precision between observers, the current work was interested in individual differences of certainty of vergence and associated shape constancy, and thus correlated measures from the two tasks to determine the relationship between the two. Similar methods have previously been employed to make use of individual differences as a way of understanding the mechanisms of depth perception (Hibbard, Bradshaw, Langley and Rogers, 2002; Wilmer, 2008; Nefs, O'Hare and Harris, 2010; Harris et al., 2012; Peterzell, Serrano-Pedraza, Widdall, & Read, 2017). We predicted that all participants would exhibit increasing underestimation of depth relative to height with increasing stimulus distance, requiring a deeper triangle, and therefore larger PSE scores, for further distances. As the JND is expected to scale with the size of the stimuli, we also predicted that the JND would naturally increase as the PSE increased in the depth task.

We predict a systematic bias in the vergence task, on the assumption that observers would accurately fixate the target. However, the JND was expected to decrease with increasing stimulus distance following Weber's law, since vergence angle reduces with distance.

Finally, we predicted that, if vergence uncertainty contributes to distance underestimation, there would be a positive relationship between the slope of the PSE in the depth task, and the JND in the vergence task. This would show that if an observer is less certain of vergence, as shown by a larger JND, they would also show less shape constancy through a steeper slope of PSE scores in the depth task.

In summary, observers' certainty of vergence was tested with a nonius lines vergence task to establish a JND, their shape constancy was measured using the PSE from a depth task, and the correlation between the two measures was calculated to assess whether or not there is a relationship between certainty of vergence and shape constancy. We predicted that, if uncertainty of vergence contributes to failures of depth constancy, then observers with less certainty of vergence shown in the nonius lines task should exhibit reduced shape constancy and greater variability in the triangle task.

2. Method

2.1. Participants

35 participants between the ages of 18 and 28 were recruited. 26 identified as female and 9 identified as male. All were screened prior to the start of the experiment for normal or corrected-to-normal vision, as well as stereoscopic acuity. Participants included one of the researchers, as well as 34 people naïve to the purpose of the experiment

2.2. Recruitment

Participants were recruited through the University of Essex's online SONA system, as well as through word of mouth. Some participants who were enrolled as Psychology students received course credit for their participation, while others were compensated financially.

2.3. Screening

Two vision tests for normal stereo acuity and visual acuity were administered to screen participants for the experiment. The Stereo Optical Butterfly random dot depth test was administered to screen for sufficient binocular depth perception, with the cut-off point for participation being if participants could view the entire 3D butterfly, which equated to 700 s of arc. This was viewed through polarised glasses at a distance of 41 cm (16 in.), as per the test instructions. Participants were also screened for normal or corrected-to-normal vision using the Lighthouse Distance Visual Acuity Test. The cut-off point for participation was receiving a Snellen score of 32 or better, equivalent to a logMAR acuity of 0.2. Participants who did not meet the screening criteria were thanked for their time and did not participate. Participants' IOD was measured as the distance between the two eyes using a standard ruler, while viewing through one eye at a time to minimise the parallax error. This was measured three times and an average of the three estimates was used.

2.4. Apparatus

The stimuli for both tasks were generated and presented using MATLAB with the Psychophysics Toolbox extension (Brainard, 1997; Pelli, 1997; Kleiner, Brainard and Pelli, 2007) and were viewed on a 52 by 29 cm VIEWPixx3D monitor with a resolution of 1920 by 1080 pixels. NVidia shutter goggles were synchronised to the 120 Hz refresh rate of the screen, using the 3DPixx IR emitter, This allowed us to present a different image to each eye giving a refresh rate of 60 Hz to each eye. Stimuli were presented in red to minimise crosstalk between the eyes, which was measured to be 0.12 % using a Minolta LS-110 photometer. Participants sat with their head on a chin rest, adjusted so that the middle of the screen was at eye level for each participant, to minimise head movements during trials to eliminate additional depth cue information. Responses were recorded using either the 'Up' or 'Down' arrow keys on a standard computer keyboard.

2.5. Stimuli

The stimuli presented to participants in both the vergence and depth tasks were generated using a 'psi-marginal' psychophysical method (Prins, 2013) using the Palamedes Toolbox extension (Kingdom and Prins, 2010) within MATLAB. This calibrates the stimulus level based on participants' responses in the previous trials to get a good fit for the psychometric function by positioning points along the curve to get a good measure of both the midpoint and the slope. A maximum of 20 stimulus steps was set.

The stimulus presented for the vergence task was a pair of red vertical nonius lines, 10 mm tall and 1.4 mm wide, set against a black background. One line was presented above the location of the 10 mm fixation cross, the other below, with the two lines presented to different eyes, using the VIEWPixx stereo goggles. The fixation cross was not presented when the nonius lines were visible. On each trial, the lines were shifted horizontally in equal and opposite directions.

The stimulus used in the depth task consisted of three red dots presented against a black background in a vertical line, representing a triangle in 3D space (Fig. 4). Dot size scaled with distance, rendered to be consistent with an object that had a diameter of 5 mm. The base height of the triangle, as represented by the top and bottom dots, was 4 cm.

100 trials were displayed per block. Although the range of stimuli seen by each participant was unique to them, there were limitations on the range of stimuli that was programmed. For the vergence task, the range for the distance between the nonius lines ± 2000 arc seconds. For the depth task, two ranges were used. At closer distances from the monitor (40 and 60 cm), the depth of the triangle presented could be between 0 and 8 cm, and for further distances (80 and 100 cm), the range of triangle depths was between 0 and 15 cm. These ranges were determined during piloting of the study and were found to offer a wide enough range of stimuli to capture sufficient data.

2.6. Procedure

Written informed consent was obtained from participants, and the screening tests were administered, with only those whose performance was better than the set criteria being invited to take part in the study.

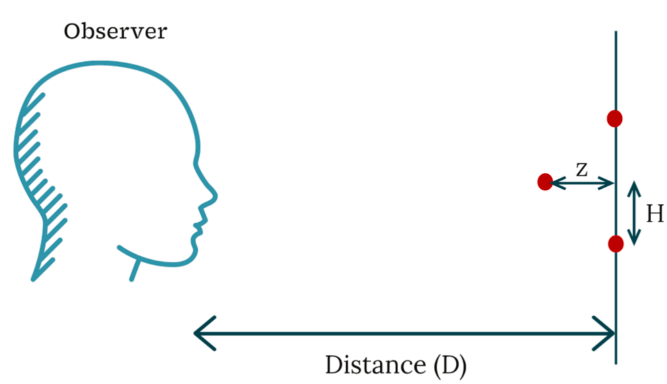

Fig. 4. A side view of the participant in the depth task, where D is the distance of the monitor, either 40 cm, 60 cm, 80 cm or 100 cm. Participants were tasked to decide if a presented triangle was too shallow or too deep, relative to one in which the distance between the closest dot and the line created by the other two dots (z) was equal to half of the height of the vertical line (H).

Both tasks took place in a darkened room, and stimuli were presented at a distance of 40, 60, 80 or 100 cm by moving the monitor to these distances from participants' eye level. Each of the two tasks was presented at each of the four distances, giving a total of eight blocks. Blocks of trials at the four distances were randomised between participants to cancel out practice effects. During a block of trials participants were seated in the darkened room stabilizing their head using a chin rest. Between each of the eight blocks, the dark room was once again illuminated to reduce participants' dark adaptation.

For the vergence task, a 10 mm fixation cross appeared at the centre of the screen for 1 s. This was then replaced by a set of nonius lines, which were presented for 100 ms. This presentation time is too brief to allow a vergence response to be made (Schor & Ciuffreda, 1983). These were then replaced by a black screen and participants were given as long as they required to respond. Participants were required to report which line appeared to them to be on the right. For instance, if participants thought the line on the right was the top of the pair of lines they were instructed to press the 'Up' arrow key on the keyboard, and to press the 'Down' key when the line on the right appeared to be the bottom of the pair of lines. If participants were unsure of which line was right-most, or if the lines appeared to line up perfectly participants were instructed to guess. Once participants had pressed the key corresponding to their answer, the next trial began automatically, as indicated by the fixation cross. The procedure for both tasks is outlined in Fig. 5.

For the depth task, again a 10 mm fixation cross appeared at the centre of the screen for 1 s. This was then replaced with the three dots. These were presented for 100 ms, before being replaced by a black screen, and allowing participants as long as required to input an answer. Again, this was done by pressing either the 'Up' or 'Down' arrow key. If the triangle presented on the screen looked too shallow to be a 'standard' triangle, participants were instructed to press the 'Up' arrow key, and to press the 'Down' arrow key if the presented triangle looked too deep. Once participants had pressed the key corresponding to their answer, the fixation cross appeared once more to indicate the start of the next trial. Once the block of trials was finished, the room was illuminated and the screen moved to the appropriate distance for the next block of trials, as per the randomised order for each participant. At the end of the eighth block, participants were debriefed on the purpose of the experiment. All procedures were performed in compliance with relevant laws and institutional guidelines and were approved by the University of Essex Research Ethics Committee (reference RR1801, 18th January 2018). The privacy rights of human participants have been observed.

3. Results

3.1. Data treatment

The psi-marginal method estimated the alpha (threshold) and beta (slope) parameters from each 100 trial run, while marginalizing gamma (the chance rate) and lambda (the lapse rate). From these, the threshold, or alpha parameter, indicates the Point of Subjective Equality with values for unbiased performance expected to match the veridical point, which is 2 cm for the depth task, and 0 min of arc for the vergence task. The slope value, or beta, denotes the function's rate of change, with a smaller result indicating a shallower slope and therefore less certainty of response. For the JND measure of uncertainty we used the criterion of 84 % correct performance relative to the PSE. The 84 % correct performance directly corresponds to the standard deviation of the underlying Gaussian distribution. An example dataset, with the fitted psychometric function, is plotted in Fig. 6.

We assessed how each of these measures varied with distance. As the experiment uses a repeated measures design, we used a linear mixed effects model, using the MATLAB fitlme() function. By including the grouping variable of observer in the model, this allows individual observers' intercepts and slopes to vary from the average (Morrell, Pearson and Brant, 1995). The formula used for the linear mixed effects model is:

$$p \sim 1 + D + (1 + D \mid o) \quad (3)$$

This tested a linear model of whether the fitted psychometric function parameter (p) of PSE or JND changed significantly over distance (D) as a fixed factor, with random slopes and intercepts and a grouping factor of observer (o). Four models were used to account for the depth task PSE and JND and the vergence task PSE and JND.

Note that the model in Equation (3) takes into account both random slopes and intercepts for the grouping variable of observer. We selected the full model by fitting other models, without a random intercept and slope, and comparing the Akaike Information Criterion (AIC) values across models. AIC compares the accuracy of the fit of each model, while also taking account of the differing number of parameters in each. The full random slopes and intercepts model provided the best goodness of

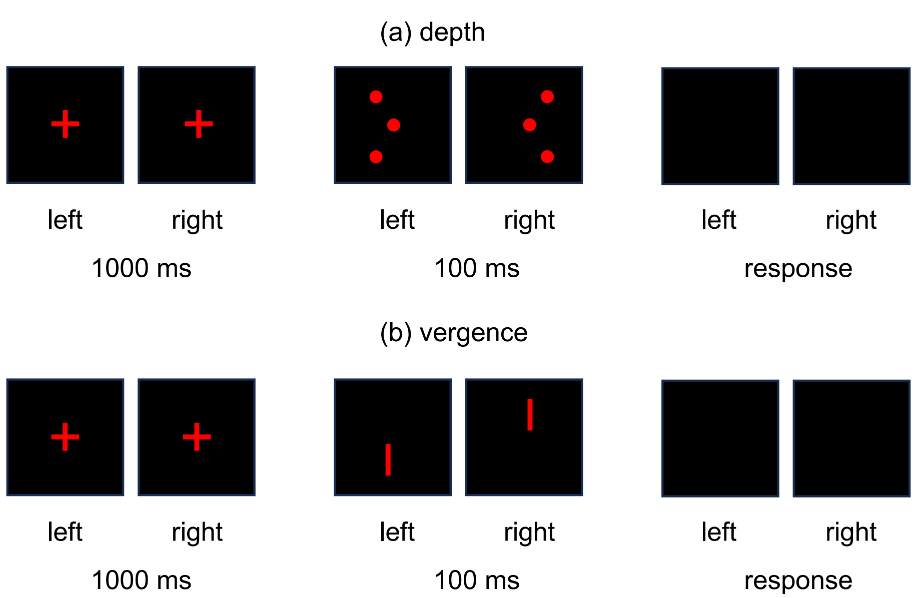

Fig. 5. Outline of the procedure for each task (stimuli not to scale). A fixation cross was presented for 1000 ms, which was then replaced by (a) the three dots forming a triangle in the depth task or (b) the nonius lines for the vergence task, each for 100 ms. This was then replaced by a black screen while the participant judged (a) the depth of the triangle or (b) the alignment of the nonius lines.

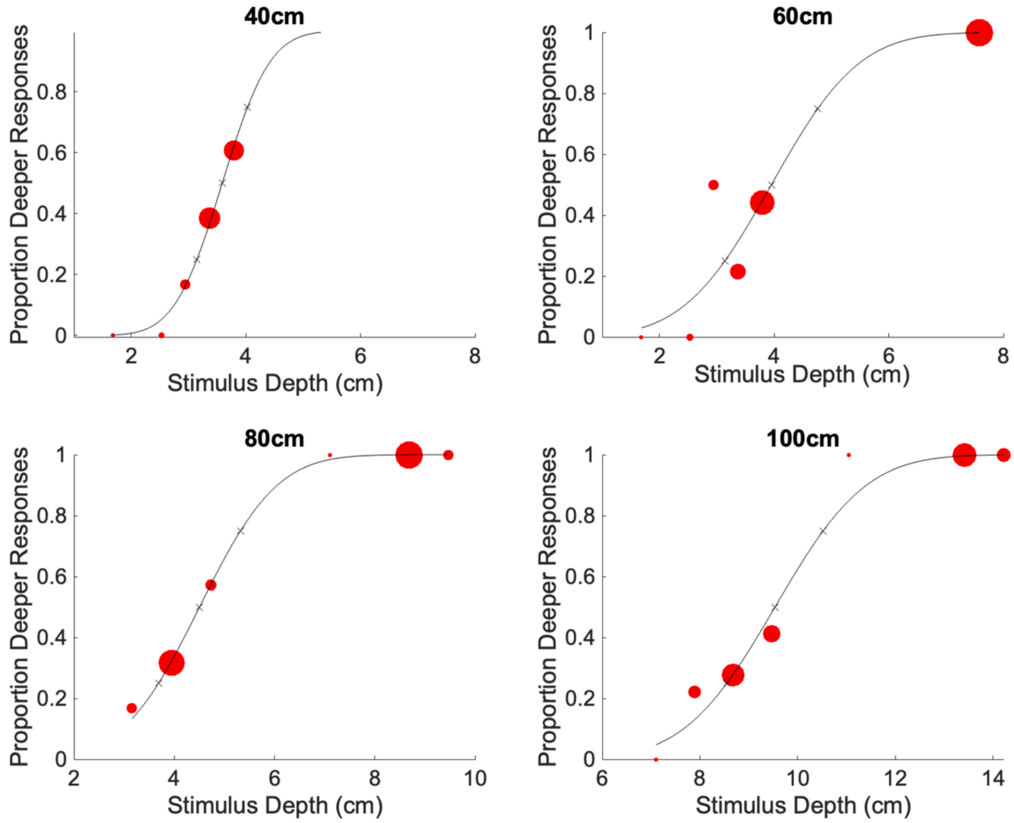

Fig. 6. Example psychophysical data, with psychometric functions fitted, for the depth task. Data are for a single observer, for the four viewing distances. The diameters of the symbols are proportional to the number of trials presented at that stimulus level.

fit with the lowest Akaike Information Criterion (AIC) values in all four cases (Field, 2017). Moreover, we verified that changing the model to other combinations of random factors did not significantly change the estimates.

3.2. Depth judgements

Means and standard errors (SE) for the PSE (Fig. 7a) and JND (Fig. 7c) in the depth task were calculated as a function of distance. The dashed line in Fig. 7a indicates where unbiased PSEs would fall. The PSE for the depth task increases with increasing stimulus distance, showing the predicted failure of shape constancy. Observers were instructed to set the depth of the triangle to half the height of the 4 cm base, and we found that they set the depth veridically at 40 cm, with increasing errors (depth underestimation relative to height) with increasing viewing distance. The JND in the depth task also increased with distance as predicted. The linear mixed effects regression model results are summarized in Table 1, showing that the effects of distance on the PSE and JND in the Depth Task were significant.

3.3. Depth constancy

The disparity produced by a depth of 2 cm will reduce with the square of distance. The degree of disparity scaling can thus be quantified from the approximate geometrical relationship between disparity (γ), depth (z) and distance (D) by IOD (I):

$$tan(\gamma) = \frac{Iz}{D^2} \quad (5)$$

Taking the log of each side gives:

$$\log(tan(\gamma)) = \log(Iz) - 2\log(D) \quad (6)$$

With full scaling, the slope of log(disparity) against log(distance) should have a value of −2. This can be used to assess the degree to which disparity settings actually scale with distance. Rewriting the equations above to include a scaling parameter k, and then taking logs gives:

$$\log(tan(\gamma)) = \log(Iz) - k\log(D) \quad (7)$$

This relationship is shown by the black line in Fig. 8.

The red data points show the mean disparity settings made by observers. Disparity does not remain the same over all viewing conditions, showing that observers do indeed use distance to scale disparity information. However, participants' actual mean settings do not match the expected correct settings beyond the 40 cm viewing distance. This shows that observers are scaling depth settings with distance, but that this scaling is incomplete.

A linear regression was used to compare log(disparity) against log (distance) to provide a measure of the degree of scaling. Here, we found a slope value of −0.65, considerably less than the value of −2 that would indicate full scaling, and also different from a simple linear scaling of disparity with distance, which would give a value of k = −1.

3.4. Vergence task

Means and standard errors (SE) for the PSE (Fig. 7b) and JND (Fig. 7d) for the vergence task were calculated as a function of distance. The dashed line in Fig. 7b indicates where unbiased PSEs would fall. Observers were least biased in the nonius task at 80 cm. These results suggest that observers were fixating on a point closer than the stimulus at the far distance, causing a slight crossed disparity that is reflected in an uncrossed PSE, and beyond the screen at a closer distances, creating an uncrossed disparity. JND measures for the vergence task decrease with distance, consistent with the reduction in vergence angle.

We used LME-regression to assess the correspondence between fixation distance and viewing distance. The results from the nonius lines

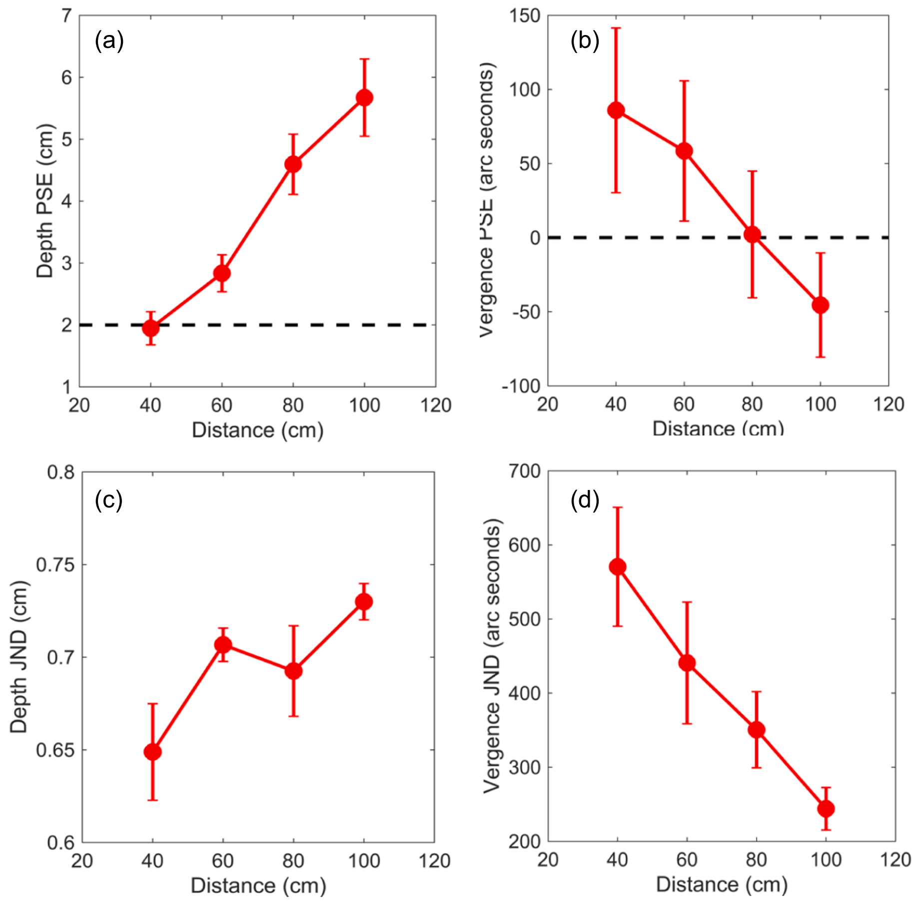

Fig. 7. JND and PSE measures for the depth and vergence tasks. Red symbols plot the mean across observers. (a) PSE measures for the depth task. The horizontal dashed line indicates the correct depth setting of 2 cm (half the height of the base). Observers were accurate at 40 cm, but required increasing amounts of depth with increasing distance. (b) PSE measures for the vergence task. The horizontal dashed line indicates the unbiased value of 0. Observers were accurate at 80 cm, but the results are consistent with an uncrossed fixation disparity at nearer distances and a crossed fixation disparity at 100 cm. (c) JND measures for the depth task increase with distance. (d) JND measures for the vergence task decrease with distance, consistent with the reduction in vergence angle with distance. Error bars indicate ± 1 standard error of the mean.

Table 1
Linear Mixed Effects model results for PSE and JND for both the depth and vergence tasks.

Variable	Model	Slope	Standard Error	*p* Value	Lower 95 % confidence interval	Upper 95 % confidence interval
Depth PSE (*pd*)	$pd \sim 1 + d + (1 + d\|o)$	0.0647	0.0082	**0<.001*****	0.0484	0.0809
Depth JND (*sd*)	$sd \sim 1 + d + (1 + d\|o)$	0.00115	0.0004	**0.013***	0.00024	0.00205
Vergence PSE (*pv*)	$pv \sim 1 + d + (1 + d\|o)$	−2.252	0.638	**0.001****	−3.514	−0.990
Vergence JND (*sv*)	$sv \sim 1 + d + (1 + d\|o)$	−5.35	1.40	**0<.001*****	−8.13	−2.57

were converted to the equivalent fixation distance before running the model (Fig. 9a). This means that unbiased fixation would yield a slope of 1. Here, stimulus distance was found to predict fixation distance very closely, with an estimated slope of 0.99 ($p < 0.001$, 95 % CI [0.98 1.00]). Thus, despite the small biases in fixation disparity (Fig. 9b), fixation distances were highly congruent with the stimulus distances. JNDs for the nonius lines tasks also decreased with distance. This reduction reflects the decrease in vergence angle with distance, and indicates a Weber fraction for vergence differences of approximately 2 %. The linear mixed effects regression model results are summarized in Table 1.

3.5. Depth constancy and the bias and precision of vergence

The correlations between PSEs in the vergence and depth tasks were calculated to see if biases in vergence predicted biases in the depth estimates (Table 2). No significant relationship was found between these, suggesting that the small observed biases in vergence are not linked to the failure of shape constancy.

Likewise, correlations in the JND for the depth and vergence tasks were calculated to see if uncertainty in vergence predicts uncertainty in depth estimates (Table 3). No correlation was found between the JND for the depth and vergence tasks at any distance, showing no relationship between the noise and therefore uncertainty for vergence and depth judgements.

Evidence for a relationship between shape constancy and certainty of vergence was also assessed. To evaluate changes in observers' bias in depth estimates with increasing stimulus distance, and therefore their failure of shape constancy, a regression slope value was obtained for the four PSEs in the depth task for all participants. The average vergence JND score was calculated across the four viewing distances for each participant as an overall measure of the uncertainty in vergence. The correlation between the regression slope value of the PSEs in the depth task and the average vergence JND scores was calculated (Fig. 10). Two outliers, having a Cook's distance of more than three times the average,

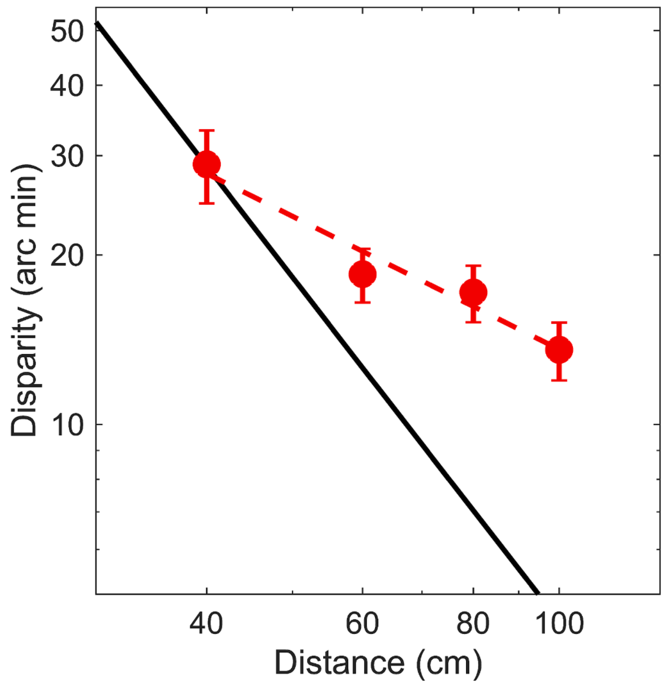

Fig. 8. Disparity settings in the triangle depth task. The black line shows the expected correct settings (with a slope of −2) against actual mean settings made by observers (red circles). The red dashed line shows a linear fit of log(distance) against log(mean settings) (with a slope of −0.78). Error bars indicate ± 1 standard error of the mean.

were removed; this did not affect our conclusions. This showed no evidence of a relationship between certainty of vergence and shape constancy, $r = 0.14$ ($p = 0.425$, 95 % CI [−0.210 0.464]). The biases in depth setting also cannot be explained by the very small biases in the vergence PSE, since the fixation distances calculated from these measures were very close to the actual distances, with a slope of 0.99.

4. Discussion

The aim of the current study was to assess whether departures from depth constancy across distance are related to uncertainty in vergence. This was achieved by measuring changes in depth perception across viewing distance and the certainty of vergence, and calculating the correlation between these two measures. As predicted, observers increasingly underestimated depth relative to height with increasing stimulus distance. This supports the work of many previous studies that show that depth is underestimated at far distances (Baird, 1903; Brenner & van Damme, 1999; Johnston, 1991; Scarfe and Hibbard, 2006; Viguier et al., 2001). We also found that observers were able to accurately scale depth relative to height at a viewing distance of 40 cm only, in line with previous research that has reported accurate absolute estimations from vergence below 50 cm (Foley and Held, 1972; Komoda and Ono, 1974; Mon-Williams and Tresilian, 1999). The JND for the depth task also increased with increasing stimulus presentation distance, consistent with the geometrical relationship between disparity and distance (Johnston, 1991).

Our stimuli were presented with a constant size of 4 cm at all distances. This means that visual angle increases with decreasing distance. A constant physical size was used for consistency with previous studies

Table 2
Correlations between PSEs for the depth and vergence tasks.

Distance	Pearson correlation coefficient r	p value	Lower 95 % confidence interval	Upper 95 % confidence interval
40 cm	0.08	0.630	−0.26	0.41
60 cm	0.06	0.722	−0.28	0.39
80 cm	0.06	0.732	−0.28	0.39
100 cm	−0.01	0.958	−0.34	0.33

Table 3
Correlation between JNDs for the depth and vergence tasks.

Distance	Pearson correlation coefficient r	p value	Lower 95 % confidence interval	Upper 95 % confidence interval
40 cm	0.22	0.197	−0.12	0.52
60 cm	0.06	0.733	−0.28	0.39
80 cm	0.06	0.726	−0.28	0.39
100 cm	−0.00	0.990	−0.34	0.33

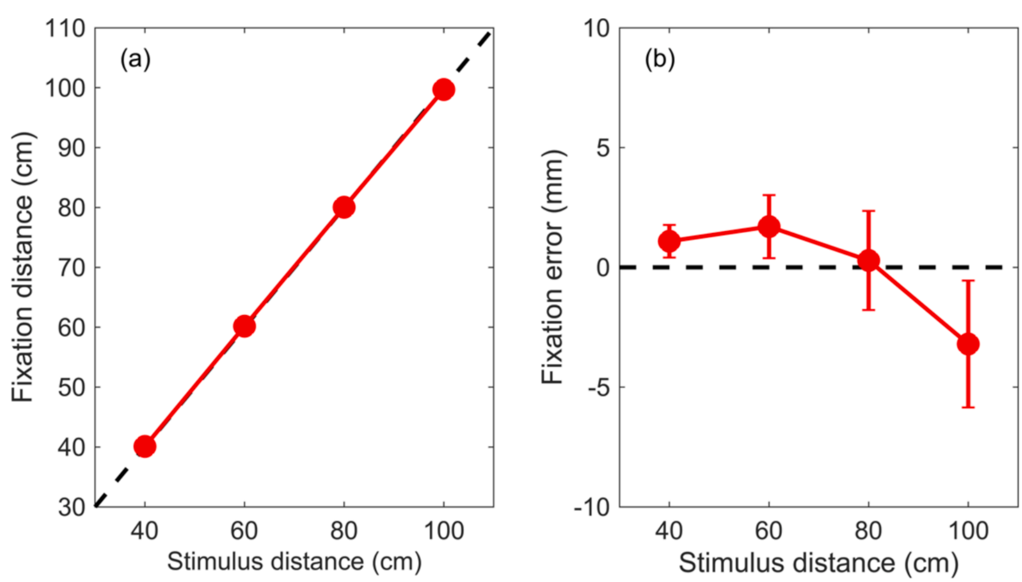

Fig. 9. (a) Fixation distance inferred from nonius line settings plotted against the stimulus distance. The distance is calculated from the actual vergence angle required to fixate the screen, plus the apparent fixation error inferred from the bias in the nonius alignment task. (b) The small biases evident in vergence PSEs plotted as errors in fixation distance. Error bars indicate ±1 standard error of the mean.

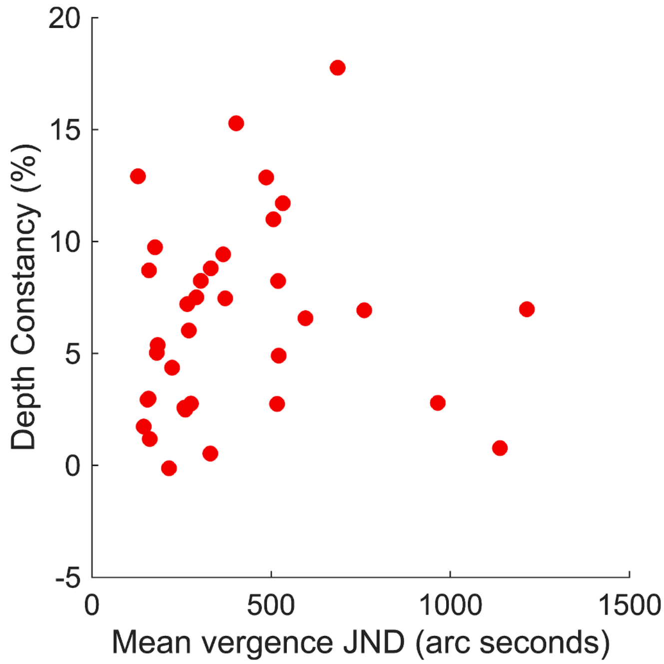

Fig. 10. Depth constancy plotted againt the mean vergence JND. Depth constancy is defined as the slope of the depth PSE scores plotted against distance, with a slope of 0 indicating perfect constancy, and a positive slope indicating a flattening of depth against height with increasing distance. No significant correlation between the two meaures was found. The uncertainty in vergence, as measured through the nonius lines task, does not therefore predict the degree of depth constancy.

(e.g. Johnston, 1991) and to avoid the possibility that a constant angular size might act as a cue to constant distance. In contrast, a change in angular size provides another potential cue to viewing distance. A consequence of keeping physical size constant is that the precision of size judgements will have decreased with viewing distance (Ono, 1967). This decrease in precision is expected to have been greater for depth judgments, due to the scaling of binocular disparity with the square of distance. These two factors will have contributed to the increase in JNDs with increasing distance (Fig. 7c).

No significant relationship was found between the JND and PSE for vergence, meaning variation in vergence bias across individuals was unrelated to vergence noise. The JND in the vergence task was found to decrease with distance, as expected. A systematic bias was observed in the PSE scores for the nonius task, meaning the point at which the lines appeared aligned shifted between viewing distance conditions. This indicated that participants were fixating a point closer than that at which the stimuli were being presented at the far distance, and at a point beyond the screen at a closer distance. This was only a small effect, however, insufficient to account for the failures of depth constancy. This fixation disparity bias mirrors that found by Jaschinski et al. (1999), where observers' fixation disparities were measured using nonius lines at 20, 30, 40, 60 and 100 cm. They found that fixation disparity changed from 1 arc minute eso (crossed) to 3.5 arc minute exo (uncrossed) with decreasing viewing distance, meaning that at far distances observers were converging on a point in front of the target creating crossed disparity, and at close distances converging on a point beyond, creating uncrossed disparity.

In the present study, a small negative trend in the set disparity across viewing distance was found, which suggests that observers were indeed scaling disparity information with perceived distance. However, this change in set disparity was much less than required for full constancy, suggesting that observers were underestimating distance in the far conditions, and therefore not correctly scaling the vergence information, resulting in underestimations of depth at the far distances. No correlation was found between PSE in the vergence and depth tasks, indicating that bias in vergence does not predict the biases in depth perception. Likewise, JNDs did not significantly correlate between the vergence and depth tasks, showing that certainty of depth estimates cannot be predicted by certainty of vergence.

Vergence noise reduced from 570 arc sec to 244 arc sec between 40 and 100 cm. This is in line with the value of 225 arc min at 2.1 m reported by Chopin et al. (2016), for a similar presentation time of 200 ms. These results reflect a high degree of precision in vergence, corresponding to an average Weber fraction of 1.9 % in the current study, and 3.5 % in the results reported by Chopin et al. (2016). They found no correlation between this measure and an absolute disparity task. In their task, a single point was presented and observers judged whether this was a close or far point, relative to the average distance of the distances they had seen in previous trials. Chopin et al. (2016) found both no correlation between vergence and absolute disparity thresholds, and that uncertainty in vergence was much smaller, by a factor of 10, than uncertainty in absolute disparity. Thresholds for absolute disparity were much larger than predicted by a combination of vergence and relative disparity thresholds.

Similarly, in our study we found no correlation between vergence thresholds and both depth thresholds and the degree of shape constancy. Moreover, our measured uncertainty in vergence, while in line with previous estimates, is too small to account for biases in distance estimation from vergence, or its potential role in scaling disparity for the perception of depth. The vergence uncertainties measured here range from an effective distance of around 0.6 cm at 40 cm up to 1.8 cm at 100 cm, with the asymmetry in this uncertainty range varying from 0.7 cm to 1.9 cm. This difference is much smaller than the biases in apparent distance (Baird, 1903; Swenson, 1932; Foley & Held, 1972; Mon-Williams and Tresilian, 1999; Viguier et al., 2001) or failures of depth constancy (Johnston, 1991; Tittle et al., 1995; Glennerster et al., 1996, Glennerster, Rogers, & Bradshaw, 1998; Scarfe and Hibbard, 2006) that have been reported. This mismatch between the degree of vergence uncertainty, and much larger failures of shape constancy, are consistent with the well-established inability to make use of vergence or absolute disparity information in the perception of motion in depth (Erkelens & Collewijn, 1985a; Erkelens & Collewijn, 1985b).

In contrast to our measures of vergence threshold, thresholds for making relative distance judgements against a remembered distance based purely on vergence or absolute disparity have been estimated to be around 50 arc min (Brenner and van Damme, 1999; Chopin et al., 2016). Chopin et al. (2016) refer to this difference as the 'absolute disparity anomaly' – that while absolute disparity is encoded in V1, and may be used to drive vergence and calculate relative disparity, it is inaccessible to the perception of depth, at least to the level of precision that it provides as input to relative disparity judgements. Our results show that this absolute vergence anomaly also applies to our poor ability to make use of vergence information for absolute distance judgements, compared with the measured sensitivity to vergence (Brenner and van Damme, 1999). Vergence uncertainty here relates to our inability to make precise use of this information for distance or depth judgements, rather than leading to perceptual fluctuations or loss of binocular fusion. This reflects a general phenomenon that such perceptual noise is not reflected in our visual experience (Morgan, Chubb & Solomon, 2008; Solomon, 2009; Todd, Christensen & Guckes, 2010).

In the case of both absolute disparity and vergence, binocular information is potentially available for which there is apparently no conscious readout (Chopin et al., 2016). This means that accuracy in depth, distance and shape tasks is poorer than would be permitted by the available information. This anomaly is likely to reflect the inherent tension, through multiple stages of visual processing, between sensitivity to elementary properties of the visual input, and invariance to or tolerance of irrelevant variations in these properties (Gutmann & Hyvärinen, 2013). In the case of binocular disparity, this is seen in the sensitivity of simple cells to the location of stimuli within their receptive fields, and the invariance of complex cells to location seen as the hallmark of ideal disparity detectors, tuned to a particular binocular disparity (Ohzawa, DeAngelis & Freeman, 1990). In a similar vein, higher stages of binocular processing appear sensitive to relative disparity variations that are important for object recognition (Orban, Janssen & Vogels, 2006), while losing sensitivity to those aspects that vary with viewer-dependent factors such as viewing distance.

CRediT authorship contribution statement

Rebecca E. Ranson: Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Peter Scarfe:** Writing – review & editing, Software, Conceptualization. **Loes C.J. van Dam:** Supervision, Writing – review & editing. **Paul B. Hibbard:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

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.

Acknowledgements

This research was funded by a Leverhulme Trust Research Project Grant (RPG-2016–361) to PBH.

Data availability

Data will be made available on request.

References

Baird, J. W. (1903). The influence of accommodation and convergence upon the perception of depth. *American Journal of Psychology, 14*, 150–200.
Bradshaw, M. F., Elliott, K. M., Watt, S. J., Hibbard, P. B., Davies, I. R., & Simpson, P. (2004). Binocular cues and the control of prehension. *Spatial Vision, 17*(1–2), 95–110.
Bradshaw, M. F., Parton, A. D., & Eagle, R. A. (1998). The interaction of binocular disparity and motion parallax in determining perceived depth and perceived size. *Perception, 27*(11), 1317–1331.
Bradshaw, M. F., Parton, A. D., & Glennerster, A. (2000). The task-dependent use of binocular disparity and motion parallax information. *Vision Research, 40*(27), 3725–3734.
Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10*(4), 433–436.
Brenner, E., & van Damme, W. J. (1999). Perceived distance, shape and size. *Vision Research, 39*(5), 975–986.
Chopin, A., Levi, D., Knill, D., & Bavelier, D. (2016). The absolute disparity anomaly and the mechanism of relative disparities. *Journal of Vision, 16*(8), 2.
Dodgson, N. A. (2004) Variation and extrema of human interpupillary distance. In *Stereoscopic Displays and Virtual Reality Systems XI* (Vol. 5291, pp. 36-46). SPIE.
du Lac, S., & Knudsen, E. I. (1990). Neural maps of head movement vector and speed in the optic tectum of the barn owl. *Journal of Neurophysiology, 63*(1), 131–146.
Erkelens, C. J., & Collewijn, H. (1985a). Motion perception during dichoptic viewing of moving random-dot stereograms. *Vision Research, 25*(4), 583–588.
Erkelens, C. J., & Collewijn, H. (1985b). Eye movements and stereopsis during dichoptic viewing of moving random-dot stereograms. *Vision Research, 25*(11), 1689–1700.
Field, A. (2017). *Discovering statistics using IBM SPSS statistics* (5th ed.). London: Sage.
Foley, J. M., & Held, R. (1972). Visually directed pointing as a function of target distance, direction, and available cues. *Perception & Psychophysics, 12*, 263–268.
Frisby, J. (2009). Optic arrays and retinal images. *Perception, 38*(1), 1–4.
Glennerster, A., Rogers, B. J., & Bradshaw, M. F. (1998). Cues to viewing distance for stereoscopic depth constancy. *Perception, 27*(11), 1357–1365.
Gregory, R. L. (1973). *Eye and brain: The psychology of seeing*. McGraw-Hill.
Gutmann, M. U., & Hyvärinen, A. (2013). A three-layer model of natural image statistics. *Journal of Physiology-Paris, 107*(5), 369–398.
Harris, J. M., Chopin, A., Zeiner, K., & Hibbard, P. B. (2012). Perception of relative depth interval: Systematic biases in perceived depth. *Quarterly Journal of Experimental Psychology, 65*(1), 73–91.
Hibbard, P. B., Bradshaw, M. F., Langley, K., & Rogers, B. J. (2002). The stereoscopic anisotropy: Individual differences and underlying mechanisms. *Journal of Experimental Psychology: Human Perception and Performance, 28*(2), 469.
Orban, G. A., Janssen, P., & Vogels, R. (2006). Extracting 3D structure from disparity. *Trends in Neurosciences, 29*(8), 466–473.
Jaschinski, W., Bröde, P., & Griefahn, B. (1999). Fixation disparity and nonius bias. *Vision Research, 39*(3), 669–677.
Johnston, E. B. (1991). Systematic distortions of shape from stereopsis. *Vision Research, 31*(7–8), 1351–1360.
Kindgom, F. A. A., & Prins, N. (2010). *Psychophysics: A practical introduction*. London UK: Academic Press.
Kleiner, M., Brainard, D., Pelli, D., Ingling, A., Murray, R., & Broussard, C. (2007). What's new in psychtoolbox-3. *Perception, 36*(14), 1–16.
Komoda, M. K., & Ono, H. (1974). Oculomotor adjustments and size-distance perception. *Perception & Psychophysics, 15*(2), 353–360.
Linton, P. (2020). Does vision extract absolute distance from vergence? *Attention, Perception, & Psychophysics, 82*, 3176–3195.
Melmoth, D. R., Storoni, M., Todd, G., Finlay, A. L., & Grant, S. (2007). Dissociation between vergence and binocular disparity cues in the control of prehension. *Experimental Brain Research, 183*, 283–298.
Mon-Williams, M., & Dijkerman, H. C. (1999). The use of vergence information in the programming of prehension. *Experimental Brain Research, 128*, 578–582.
Mon-Williams, M., & Tresilian, J. R. (1999). Some recent studies on the extraretinal contribution to distance perception. *Perception, 28*(2), 167–181.
Morgan, M., Chubb, C., & Solomon, J. A. (2008). A 'dipper'function for texture discrimination based on orientation variance. *Journal of Vision, 8*(11), 9.
Morrell, C. H., Pearson, J. D., Carter, H. B., & Brant, L. J. (1995). Estimating unknown transition times using a piecewise nonlinear mixed-effects model in men with prostate cancer. *Journal of the American Statistical Association, 90*(429), 45–53.
Morrison, J. D., & Whiteside, T. C. (1984). Binocular cues in the perception of distance of a point source of light. *Perception, 13*(5), 555–566.
Nagata, S. (1991). How to reinforce perception of depth in single 2-D pictures. *Pictorial Communication in Virtual and Real Environments*, 527–545.
Nefs, H. T., O'Hare, L., & Harris, J. M. (2010). Two independent mechanisms for motion-in-depth perception: Evidence from individual differences. *Frontiers in Psychology, 1*(155), 1–8.
Ohzawa, I., DeAngelis, G. C., & Freeman, R. D. (1990). Stereoscopic depth discrimination in the visual cortex: Neurons ideally suited as disparity detectors. *Science, 249*(4972), 1037–1041.
Ono, H. (1967). Difference threshold for stimulus length under simultaneous and nonsimultaneous viewing conditions. *Perception & Psychophysics, 2*, 201–207.
Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10*, 437–442.
Peterzell, D. H., Serrano-Pedraza, I., Widdall, M., & Read, J. C. (2017). Thresholds for sine-wave corrugations defined by binocular disparity in random dot stereograms: Factor analysis of individual differences reveals two stereoscopic mechanisms tuned for spatial frequency. *Vision Research, 141*, 127–135.
Prins, N. (2013). The psi-marginal adaptive method: How to give nuisance parameters the attention they deserve (no more, no less). *Journal of Vision, 13*(7), 3.
Scarfe, P., & Hibbard, P. B. (2006). Disparity-defined objects moving in depth do not elicit three-dimensional shape constancy. *Vision Research, 46*(10), 1599–1610.
Scarfe, P., & Hibbard, P. (2017). A Bayesian model of distance perception from ocular convergence. *Journal of Vision, 17*(10), 159.
Schor, C.W,. & Ciuffreda, K.J. (1983) Vergence eye movements: Basic and clinical aspects, 199–295. Butterworth Boston.
Solomon, J. A. (2009). The history of dipper functions. *Attention, Perception, & Psychophysics, 71*(3), 435–443.
Swenson, H. A. (1932). The relative influence of accommodation and convergence in the judgment of distance. *The Journal of General Psychology, 7*(2), 360–380.
Tittle, J. S., Todd, J. T., Perotti, V. J., & Norman, J. F. (1995). Systematic distortion of perceived three-dimensional structure from motion and binocular stereopsis. *Journal of Experimental Psychology. Human Perception and Performance, 21*(3), 663.
Todd, J. T., Christensen, J. C., & Guckes, K. M. (2010). Are discrimination thresholds a valid measure of variance for judgments of slant from texture? *Journal of Vision, 10*(2), 20.
van Damme, W., & Brenner, E. (1997). The distance used for scaling disparities is the same as the one used for scaling retinal size. *Vision Research, 37*(6), 757–764.
van der Willigen, R. F., Frost, B. J., & Wagner, H. (1998). Stereoscopic depth perception in the owl. *Neuroreport, 9*(6), 1233–1237.
Viguier, A., Clement, G., & Trotter, Y. (2001). Distance perception within near visual space. *Perception, 30*(1), 115–124.
von Hofsten, C. (1976). The role of convergence in visual space perception. *Vision Research, 16*(2), 193–198.
Wilmer, J. B. (2008). How to use individual differences to isolate functional organization, biology, and utility of visual functions; with illustrative proposals for stereopsis. *Spatial Vision, 21*(6), 561–579.