Depth Perception and Stereoacuity

Introduction

Humans use many visual cues in order to determine depth of objects away from them. Most of these cues are monocular in nature, meaning that only one eye or one image is required in order to determine depth from them. These exist in large part as the context of objects rather than the objects themselves. The most relevant for this investigation consist of retinal size, shadows and motion parallax. The remaining cues are binocular, and as such they require both eyes to provide depth information. The two main binocular cues are disparity and convergence, although disparity is the more powerful of the two (Howard and Rogers, 2002).

The Howard (1919) ‘two needle’ test protocol in general involves judging the relative depths between two needles, and is designed in such a way as to attempt to remove, in a simple manner, as many depth cues as possible, leaving (nearly) only the cue that is to be measured. Although humans do not excel at absolute depth perception (Howard and Rogers, 2002), their relative depth perception has fine resolution, depending somewhat on the cues used. As a result, the equipment used to test relative perception, as undertaken by this investigation, does not have to be particularly large, and so can be performed adequately in a standard-sized room. The 2 needle stimuli are ‘disjoint’ (separate), which should be appreciated to improve relative depth perception in comparison to contiguous stimuli (McKee, 1983).

Different cues have differing impacts on how well humans can assess depth. The aim of this investigation was to evaluate the threshold at which depth information could be perceived using primarily the 3 different cues of retinal size, motion parallax and binocular disparity based on the two needle test protocol.

Method

A different variant of the protocol was used depending on the cue being tested, but almost all of the main features remained the same. The method was based on the protocol described by Howard (1919), although some changes had to be made. The participant was a 19 year old male.

Apparatus

The apparatus was consistent between conditions, and consisted of:
- A chair
- A tape measure
- A ruler
- 2 needles of equal diameter and height
- A block with 2 parallel lines of holes, with the holes in a line 1cm apart
- A solid white background board
- A white front board with a window
- A hyperstereoscope

Procedure

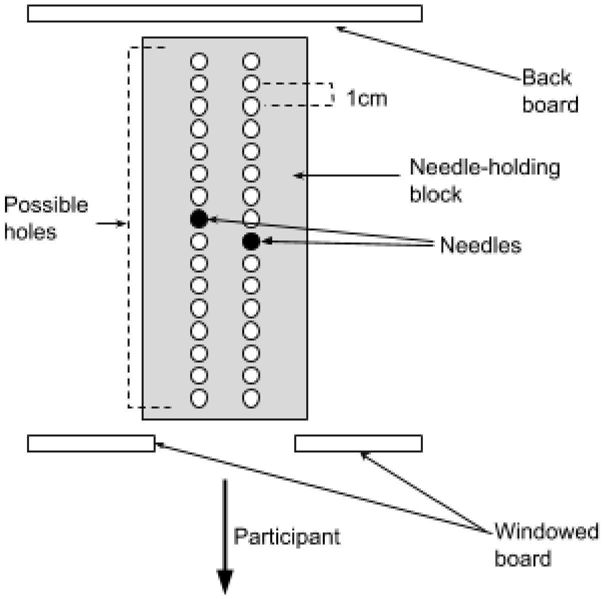

Figure 1A: Apparatus setup

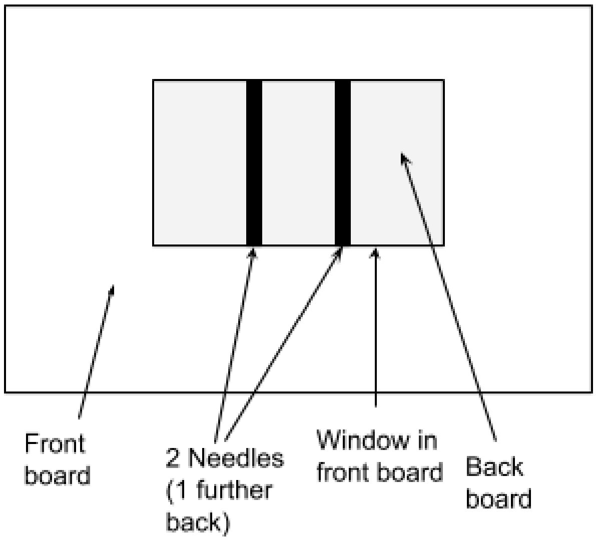

Figure 1B: Setup from participant's view

The distance testing apparatus was set up as shown in Figures 1A and 1B, with the needles set in the holes of the block, which would have the solid board behind it and the windowed board in front. The holes were aligned such that the needles could be moved directly forward and backward with respect to the participant, perpendicular to the boards.
The basic procedure involved the participant sitting on the chair with his head a measured distance from the front needle. The start position for the back needle was in the hole 1cm further back than the front needle. The participant had to state which of the needles was farther back with 2 Alternative Forced Choice method - they had to choose 1 of the 2 options, and could not 'pass'. After each choice, the researcher randomly chose whether the left or right needle would be behind. If the participant failed once in determining which was the farther back, they were considered to have failed that stage, conversely they had to correctly answer 7 successive times to be considered to have successfully completed a stage. This was to minimise the possibility that the correct answers were by chance, and so ensure that the participant was consistent in depth discrimination. The probability of correctly guessing 7 times in a row is 1 in 2^7, or 1 in 128, which is very unlikely.

Still Monocular

The participant sat in the chair with his head 308cm from the first needle, and covered his non-dominant eye with the corresponding hand. They followed the procedure as described above while keeping his head still. For every failure the back peg was moved back 1cm until the participant could complete the stage by correctly stating which needle was farther back 7 consecutive times. At this point, the trial was finished, and the distance between needles was recorded along with the distance of the participant's head from the front needle.

Moving Monocular

The procedure followed was the same as for the Still Monocular trial, except the participant was permitted to move his head from side to side to aid in determining depth. If they succeeded with 1cm between needles they were moved backwards by 50cm at a time until they were no longer capable of completing the stage, at which point the distance from his head to the front needle was recorded for the last point at which they were successful.

Stereopsis

The procedure remained the same as for the Moving Monocular condition, except the participant was permitted to use both eyes to judge depth, but was not permitted to move his head.

Inter-pupillary distance (IPD) was measured by asking the participant to fixate on a pencil in front of the researcher's left eye; the researcher used this eye to zero the ruler in front of the left edge of the participant's right eye; the pencil was moved in front of the researcher's right eye with the participant maintaining fixation and a measurement was taken with that eye on the left edge of the participant's left eye. The researcher's non-measuring eye was closed to minimise parallax problems.

A hyperstereoscope was also briefly used to attempt to informally/qualitatively compare normal binocular disparity to the equivalent of having eyes twice the distance apart.

Results

Table 1: Comparison of results in different conditions

Condition	Inter-Needle Distance (Threshold) (cm)	Eye-Needle Distance (cm)	Threshold:Eye-Needle Distance Ratio
Still Monocular (SM)	8	308	1:38.5
Moving Monocular (MM)	1	408	1:408
Binocular Disparity (BD)	1	558	1:558

As seen in Table 1, the threshold:eye-needle ratio for MM is over 10 times greater than for SM, and BD is 36% greater than that.

The IPD was measured at 5.8cm.

The participant's stereoacuity - the ability to discriminate distances based on a binocular disparity between retinal angles - can be calculated following Howard (1919) or Howard and Rogers (2002). The simplified method can be used, as stimuli were approximately on the 'median plane' (Howard and Rogers, 2002:12). The calculations were as follows:

$$half\ the\ interpupillary\ distance\ r = 5.8cm \div 2 = 2.9cm$$
$$distance\ from\ eyes\ to\ front\ needle\ p = 558cm$$
$$distance\ from\ eyes\ to\ back/rear\ needle\ s = 559cm$$
$$eye,\ midpoint\ angle\ at\ front\ needle\ a = arctan\ (r \div p) = 0.29777108356° = 1071.97590083''$$
$$eye,\ midpoint\ angle\ of\ back\ needle\ b = arctan\ (r \div s) = 0.29723840782° = 1070.05826818''$$
$$stereoacuity = (a - b) \times 2 = 0.001065° = 3.835'' \rightarrow \textbf{\textit{3.835 seconds of arc}}$$

The hyperstereoscope unfortunately appeared to this researcher to be not quite correctly calibrated. The angles of the mirrors were not precisely enough at 45 degrees, which meant that the image in each eye was too different to fuse, and so no attempts at depth perception could be carried out.

Discussion

Multiple visual cues are used simultaneously to determine depth (Landy et al., 1995). As such, it would be expected that the still monocular condition would elicit a poorer threshold than the other 2 conditions, as retinal size/angle can still be incorporated into the determination of depth along with cues from motion parallax or binocular disparity. It is clear from the results that the strength of retinal image size as a cue at approximately 4m is much less significant than the other motion parallax or binocular disparity, presuming these are the primary cues actually in play here, considering the order of magnitude difference between the results. The influence of retinal image size may even be exaggerated by these results, as it was suggested by the participant that once the back needle was at a certain threshold, it began to cast easily visible shadows on the back board, giving a definite cue as to the positioning. A different lighting setup to change the amount and angles of lights compared to the setup could prevent this in further studies.

Rogers and Graham (1982) found that motion parallax and binocular disparity were similar in characteristics and sensitivity, and propounded that they operated using a similar mechanism. The results obtained did not strongly deviate from this. It is notable that here, binocular disparity provided a more powerful cue for depth perception than motion parallax, particularly as the distance between extremes of the head movement during MM was multiple times the size of the interpupillary distance, which would have resulted in a greater parallax effect between extremes than between the eyes. The participant may not have moved his head as fast or as far between extremes as those in said study, as these improve motion parallax depth perception; this may be at least partially explained by the additional motion processing that must be done (Holmin and Nawrot, 2015). More speculatively, the difference may be because the earlier position has to be stored/buffered to be compared with the latter position, and its internal representation may have lost clarity.

It appears difficult to obtain a reliable and valid mean inter-pupillary distance (IPD) score due to significant differences in sex, race, age and measurement technique (the distance of the fixation point can vary the IPD score by around 3mm (Evereklioğlu et al. 1999)). Dodgson (2004) compiled a number of different scores based on different datasets, and for adult males the average (median or mean as determined appropriate) was between 61mm and 65mm. The participant's IPD can thus be determined to be slightly smaller than average, which means a reduced stereo separation (Dodgson, 2004), resulting in a larger threshold than someone with the same stereoacuity but a greater IPD.

Howard (1919) concluded that any stereoacuity score below 8 seconds of arc was considered 'normal'. The participant scored well below this at 3.835 seconds of arc. The value of 8" was calculated using a more lenient method, in which 75% of (20) answers had to be correct rather than 100% (of 7), which, by contrast shows that the participant has good stereoacuity.

The difficulties with the hyperstereoscope demonstrated the necessity of similarity of images between eyes for proper binocular image fusion, as initially demonstrated by Wheatstone (1838).

To conclude, previous research was corroborated, with the participant showing a similar level of depth perception using binocular disparity and a monocular motion parallax cues. Both of these cues were stronger than monocular retinal size, despite methodological issues making that condition easier than it should have been. The participant's stereoacuity was better than 'normal'.

References

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