The effect of pictorial depth information on projected size judgements

Emily K. Farran, Andrew Whitaker & Neha Patel

School of Psychology and Clinical Language Science

University of Reading

Address correspondence to:

Emily Farran
School of Psychology and Clinical Language Science
University of Reading
Earley Gate
Reading
RG6 6AL
UK
Tel: +44 (0)118 378 7531
Fax: +44 (0)118 931 6715
E-mail: E.K.Farran@reading.ac.uk

Abstract

When full depth cues are available, size judgements are dominated by *physical* size. However, with reduced depth cues, size judgements are less influenced by physical size and more influenced by *projected* size. This study reduces depth cues further than previous size judgement studies, by manipulating monocularly presented pictorial depth cues only. Participants were monocularly presented with two shapes against a background of zero (control), one, two or three pictorial depth cues. Each cue was added progressively in the following order: height in the visual field, linear perspective, and texture gradient. Participants made a 'same-different' judgement regarding the *projected* size of the two shapes, i.e. ignoring any depth cues. As expected, accuracy increased and response times decreased as the ratio between the projected size of the two shapes increased (range of projected size ratios, 1:1 to 1:5). In addition, with the exception of the larger size ratios (1:4 and 1:5), detection of projected size difference was poorer as depth cues were added. One-cue and two-cue conditions had the most weighting in this performance decrement, with little weighting from the three-cue condition. We conclude that even minimal depth information is difficult to inhibit. This indicates that depth perception requires little focussed attention.

The effect of pictorial depth information on projected size judgements

Introduction

When depth cues are available, these combine to enable us to perceive the *physical* size of a static object in depth. This perception of physical size remains constant despite changes in the distance of the object from the observer and the visual angle that it subtends (size constancy; see Sedgwick, 1986). In contrast to physical size, the *projected* size of an object is established by the visual angle that it subtends on the retina. When making judgements of size, the relative influence of physical size and projected size is dependent on the amount of depth information available, i.e. when depth is perceived, we expect an object which is further away to have a smaller projected size, but the same physical size, than when it is closer in depth (Epstein, 1973). Depth can be determined using the binocular cues of vergence and retinal disparity and by monocular information, available through accommodation, motion parallax and pictorial cues. We know that, in adults, when asked to make size judgements, such judgements are dominated by physical size, over projected size, even in the absence of binocular cues, accommodation and motion parallax, i.e. when only pictorial cues are available (Yonas & Hagen, 1973; Ulharik, Pringle, Jordan & Misceo, 1980). However, little is known about the effect of reducing the number of pictorial cues, on the perception of size. In this study we aim to determine the point at which depth cues begin to influence size judgements, i.e. how much depth information is required for the perception of size to be influenced by physical size information.

Yonas and Hagen (1973) investigated depth perception by manipulating accommodation (3D vs. 2D presentation) and motion parallax (present vs. absent) depth cues in a size judgement task. Two real triangles of different physical size were monocularly presented, positioned in a real textured alley and participants were asked which of the triangles was larger. The visual angle (projected size) subtended by the large triangle was either equal to that subtended by the small triangle, or was 70% or 80% of the projected size of the smaller triangle. Adult participants used the available cues, and gave judgements according to physical size. Three- and 7-year-olds responded to physical size when the projected size of the two triangles was equal. However, when the projected and physical size differences were incongruent, children required at least 3D depth information in order to respond according to physical size, and on the hardest trials (70% projected size difference), 3-year-olds also required the additional depth cue of motion parallax. These results indicate that, with development, perception of physical size is possible with progressively fewer depth cues and for adults, pictorial cues alone are sufficient for physical size to dominate. The present study further investigates this dominance by using zero to three pictorial cues.

Ulharik et al. (1980) demonstrated that pictorial depth cues impact size judgements even when participants are asked to respond according to projected size. Participants viewed a 2D photograph of a shape placed in a textured 3D alley under binocular viewing conditions. Participants were explicitly asked to judge the physical size (referred to as ‘objective size’) or ‘projected size’ of a shape, in units, relative to a standard sized shape. Whilst physical size judgements were generally accurate, projected size judgements were distorted by depth information; projected size responses were almost halfway between that predicted by physical and by projected size. This demonstrates that depth cues cannot be completely inhibited for projected size judgements and suggests that at least some depth information is processed automatically. However, as numerous pictorial cues remained present, we do not know the extent of this distorting effect. In the present study, we ask whether distortion remains with reduced pictorial cues, and if the strength of the bias is influenced by the type or number of depth cues available.

The influence of depth cues has also been demonstrated in studies of visual search. Visual search performance is affected by depth information such as 3D orientation (Enns & Rensink, 1991), direction of light in a scene (Aks & Enns, 1992) and texture gradient (Aks & Enns, 1996). It therefore appears that, in adults, depth perception is a relatively low level process, which occurs in the early stages of visual perception. That is, in common with some visual search mechanisms, depth cues are processed pre-attentively (see Treisman, 1986), and so are difficult to inhibit (Uhlarik et al., 1980).

Bennett and Warren (2002) investigated the influence of projected and physical size on performance by adapting a standard size transformation task. Standard size transformation tasks (e.g. Bundesen & Larsen, 1975; Howard & Kerst, 1978; Jolicoeur & Besner, 1987) differ from the size judgement tasks described above. A size transformation task is a mental imagery task. Participants are shown two non-uniform objects which differ in size and also, on 50% of trials, differ subtly in form. Participants must determine whether the two objects are the same or different in *form*, ignoring any differences in *size*. Successful completion is thought to rely on the participant's ability to mentally scale one object to match the size of the other, thus enabling them to make a same-different judgement of form alone; a linear increase in response time is observed with increased size ratio between the two objects.

In standard size transformation tasks, objects are presented in the same depth plane, with no background depth information. As such, projected and physical size are equivalent and their relative influence on performance cannot be differentiated.

Bennett and Warren (2002) introduced progressive amounts of depth information in their size transformation study. This enabled them to investigate the relative influence of projected and physical size on participant's judgements of form. Displays were viewed monocularly from behind a reduction screen, and depth information decreased across three conditions; a textured corridor with shadow information; a textured corridor with no shadow; and a vertical textured wall (forms could still differ in height in the picture plane). Stimuli were presented at different simulated distances, using five projected and physical size ratios (range, 1:1 to 1:3). Results demonstrated significant linear increases in RT for both physical and projected size ratios in all conditions. The authors suggest that, before mental size scaling and thus form matching proceeds, size is coded by pooling all available size information. For both of the 3D 'corridor' conditions, the linear increase in RT was comparable across physical and projected size ratios. This suggests that the influence of projected and physical size was roughly equal. This is surprising, given that *size* judgement studies report physical size dominance in similar conditions. This could relate to additional 'projected size' information from the flat screen (accommodation, motion parallax), as suggested by Bennett and Warren (2002), or could be related to the difference in task demands (form vs. size judgement). Performance on the 2D condition, however, showed a stronger influence of projected than physical size. Importantly, this indicates that manipulating pictorial depth cues influences the relative influence of physical and projected size on *form* judgements and that with only very minimal cues, projected size dominates. This is investigated further in the present study by using a *size* judgement task. To our knowledge, this is the first study to investigate the effect of manipulating pictorial depth cues on same-different judgements of projected size.

In summary, previous studies have shown that, with reduced depth cues, provided there are numerous pictorial depth cues, physical size remains dominant over projected size (Yonas & Hagen, 1973; Uhlarik et al.,1980). However, Bennett & Warren (2002) provide evidence to suggest that projected size might dominate if pictorial cues are also reduced. To investigate this, we asked participants to make size judgements with reduced pictorial cues only. Stimuli were viewed monocularly, in an environment in which objects rested on the ground plane, the ground plane was flat and the horizon was at eye-level. The first cue added was height in the visual field (Wallach & O'Leary, 1982). For this cue, the angle between eye level (assuming this is at the horizon) and the location of the base of the object (assuming that this is below eye level) determines the distance of the object from the observer: objects that are further away appear higher in the visual scene, and thus subtend a smaller angle. The second depth cue added was linear perspective. Sedgwick (1986) explains that this indicates size and depth in two ways. First, as a direct indication of size (see Wraga, 1999), there is a constant relationship between the height of an object resting on a surface and the vertical distance between eye-level (assuming this is at the horizon) and that surface. From this the ratio between the visual angles subtended from the point of observation between the top and bottom of the object and between the horizon and bottom of the object can be calculated, known as the horizon-ratio relationship (Sedgwick, 1973). The second way in which linear perspective indicates size and depth is also specified by the third depth cue added, texture gradient. For both linear perspective and texture gradient, depth is indicated by the angular separation between the projection of converging horizontal surface lines (edges or texture) which provide a constant scale factor towards the horizon (Gibson, 1950; Sedgwick, 1986).

For each condition, participants were explicitly asked to make same-different size judgements according to *projected size* only. The influence of *physical size* was determined by the negative effect on performance, relative to the control condition where no depth cues were available. We aimed to determine when depth cues begin to affect projected size judgements and the relative weighting of each of the depth cues employed.

Method

Participants

Forty participants, 22 female and 18 male, aged from 18-29 years (Mean: 19.43 years, S.D: 0.29) were recruited. Participants were undergraduate students at the University of Reading. All participants had normal or corrected to normal vision. Twenty-two (55%) participants were left eye dominant and 18 (45%) participants were right eye dominant (45%) (eye dominance tests are described in the procedure).

Eye Dominance tasks

Eye dominance was determined by employing two methods cited in Roth, Lora & Heilman (2002). The first was a variation of the Porta test (Porta, 1593): participants were asked to extend one arm and align their index finger vertically with the corner of the testing room, with both eyes open. Participants then had to close one eye at a time, and report which eye closure caused the least change in the alignment of their index finger with the corner of the wall. This eye was recorded as the dominant eye. The second test was a variation of the Miles test (Miles, 1930). Participants were asked to make a small hole between both of their extended hands and view a small object (a piece of metal) through the hole. They were then asked to move their hands towards their face, whilst fixating on the object in the hole. The eye that participants brought their hands nearest to was recorded as the dominant eye. All participants gave the same eye dominance for both tests.

Experimental task

Design

Viewing was made monocular by asking participants to wear an eye patch over their less dominant eye. Viewing distance from the screen was controlled using a chin rest, fixed at 39.10 cm from a screen 33.00 cm in width, and 21.00 cm in height (resolution: 1920 x 1200 pixels). Thus, the screen subtended a visual angle of 45.76 ^{o} by 30.06^{o}.

Each image depicted two shape stimuli (either two black triangles or two black squares, see Figure 1) on a background of zero to three monocular depth cues (created using Paint Shop Pro, v.7.0 and Alice, v.2.0). Control trials contained no depth information. One-cue trials employed the depth cue of height in the visual field. Two-cue trials employed height in the visual field and linear perspective. Three-cue trials used height in the visual field, linear perspective and texture gradient. The texture employed was a texture depicting a typical concrete-type surface (surface.bmp from Corel Draw 9). Five projected shape sizes were employed, with an area of 1cm^2, 2cm^2, 3cm^2, 4cm^2, and 5cm^2 respectively. The left hand shape was positioned at X: 75 mm, Y: 30 mm throughout. The right hand shape was positioned at X: 175 mm, Y: 30 mm for control trials, and X: 175 mm, Y: 185 mm for depth cue trials. The two presented shapes were either the same projected size or different projected sizes (50% of trials for each). As these corresponded to correct participants responses of ‘same’ or ‘different’ respectively, corresponding trials are henceforth referred to as ‘same’ or ‘different’ trials. There were 10 possible size combinations of different sized shapes

($2cm^2:1cm^2$, $3cm^2:1cm^2$, $4cm^2:1cm^2$, $5cm^2:1cm^2$, $3cm^2:2cm^2$, $4cm^2:2cm^2$, $5cm^2:2cm^2$, $4cm^2:3cm^2$, $5cm^2:3cm^2$, $5cm^2:4cm^2$) and 5 possible combinations of same sized shapes ($1cm^2:1cm^2$, $2cm^2:2cm^2$, $3cm^2:3cm^2$, $4cm^2:4cm^2$ and $5cm^2:5cm^2$). ‘Same’ trials were presented twice, for each shape, in each condition to give equal amounts of ‘same’ and ‘different’ trials. The projected size ratio of these shapes varied from 1:1 (same trials) to 5:1 ($5cm^2:1cm^2$). In ‘different’ trials, the projected size of the left hand shape was larger than the right hand shape.

The centre of the display was at participants’ eye level and therefore the vertical mid-point of the back wall of the alley equated to where a true horizon would be. If depth was judged from the height of the object in the scene, this equates to the angular subtense of each object at the eye. This can be calculated from the vertical distance between the "horizon", and the base of each object (left shape, 9cm: right shape, 3.5cm), and the distance of the observer from the screen (39.1cm). Physical size ratios were calculated based on the ratio between these vertical distances (and thus the visual angle that they subtend), which was 1: 2.57 (9.00cm / 3.5cm). Thus, where tan θ1 and tan θ2 are calculated from the projected size of the object on the left (physically near) and the projected size of the object on the right (physically far) respectively, the physical size ratio is: 1:x, where $x = 2.57 \tan \theta 2 / \tan \theta 1$. Corresponding projected and physical size ratios are shown in Table 1. Physical size ratio varied from 1:2.57 to 1:1.15. There were 160 experimental trials in total: four monocular cue conditions, each with 40 trials (10 same, 10 different for each of the two shapes: square, triangle).

Table 1 about here

Procedure

Participants were informed that the study was concerned with how certain depth cues affect ones perception of the size of an object. They were instructed to judge whether the size of two objects was the ‘same’ or ‘different’, whilst ignoring the depth cues. They responded by pressing one of two keys labelled ‘same’ and ‘different’ respectively. Participants were told that there was no time limit, but that response times would be recorded. Participant responses were followed by a 200msec inter-stimulus-interval and a 200msec fixation mask before the next trial began. Participants took part in a practice block of eight trials to ensure that they understood the procedure. This comprised two existing trials drawn from each of the four cue conditions. Following this, the 160 experimental trials were presented in a randomised order. Feedback was given on the practice trials only.

Figure 1 about here

Results

Projected and Physical size ratios

‘Same’ and ‘different’ responses were recorded and the proportions of ‘different’ responses analysed. For the projected size ratio of 1:1, a ‘different’ response corresponds to an incorrect response and for projected size ratios from 1.25:1 to 5:1, a ‘different’ response is correct.

The data set was not normally distributed for projected size ratios from 1.25:1 to 5:1 (Kolmogorov-Smirnoff , $p<.05$ for all) and so all data underwent arcsine transformation before analysis. A two-way ANOVA of proportion of ‘different’ responses was carried out, with monocular cue (4 conditions: control, one-cue, two-cue, three-cue) and projected size ratio (10 levels: 1:1, 1.25:1, 1.33:1, 1.5:1, 1.67:1, 2:1, 2.5:1, 3:1, 4:1, 5:1) as factors. The main effects of monocular cue (linear contrast: $F(1, 39) = 83.17$, $p<.001$, partial $\eta^2= .68$) and projected size ratio (linear contrast: $F(1, 39)=281.89$, $p<.001$, partial $\eta^2=.88$) were mediated by an interaction between these two factors ($F(27, 1053)=25.97$, $p<.001$, partial $\eta^2=.40$). This is illustrated in Figure 2, which shows that, when a ‘different’ response was a correct response (all projected size ratios, except 1:1), for small size ratios, as the number of monocular cues increased it became increasingly more difficult to determine that the projected sizes of the two shapes were different (ratios of 1.25:1 to 3:1, $p<.001$ for all). This was not the case for the larger projected size ratios, where the proportion of ‘different’ responses was high across all monocular cue conditions (4:1 ($F(3, 117)=2.02$, $p=.11$, partial $\eta^2=.01$; 5:1, $F<1$). When a ‘different’ response was an incorrect response (a projected size ratio of 1:1), the pattern of responses differed from other projected size ratios. For the control, no-cue, condition, participants were, as expected, unlikely to incorrectly report a size difference. Similarly, only a small proportion of different responses were given in the one-cue condition and this was in-line with the steady increase in the proportion of ‘different’ responses across increases in projected size ratio. However, for the two-cue and three-cue conditions, the proportion of different responses was high, and was not in line with the trend in ‘different’ responses across increasing projected size ratios. This suggests that there is something special about ‘same’ trials which differentiates them from ‘different’ trials. This is returned to in the discussion.

Further analysis determined the point at which a projected size difference could no longer reliably be detected. As described above, a response of ‘different’ was an incorrect response for ‘same’ trials (1:1 projected ratio), but a response of ‘different’ was a correct response for ‘different’ trials (1.25:1 to 5:1 projected ratios). As we were interested in the ability to detect projected size difference only, ‘same’ trials were not included in this analysis. For each condition, the projected size ratio at which ‘different’ responses were given on 25% of trials was employed as a threshold. This is the 75% threshold for incorrect (non-projected) responses, and thus the threshold at which the influence of depth information is too strong to inhibit. Proportion of ‘different’ responses was converted to z-scores, and plotted against x^{-1} where x represents an x:1 projected size ratio. Using x^{-1} transforms performance on each condition into a straight line (linear regression of mean z-scores of each cue condition against x^{-1}: control condition: $F(1, 7) = 16.844$, $p=.01$; 1-cue condition: $F(1, 7)=90.33$, $p<.001$; 2-cue condition: $F(1, 7)=139.24$, $p<.001$; 3-cue condition: $F(1, 7)=40.06$, $p<.001$). Individual linear functions of the z-score against x^{-1} were calculated for each participant for each condition. The mean of these functions is plotted in Figures 3a, b, c and d, alongside the actual mean z-scores, to illustrate the linear fit. From each linear function, each participant’s 75% threshold (25% correct) at which depth information could not be inhibited, was determined for each depth condition. 75% and 25% thresholds of correct responses are illustrated in Figures 3a, b, c and d. This shows that performance on the control condition was always above 75%, thus differences can be detected from at least a projected ratio of 1.25:1. For cue conditions, projected size differences could be detected from a ratio 1.36:1 with one cue, 1.79: 1 with two cues, and 1.82:1 with three cues.

We also calculated the cumulative weighting of each cue on the ability to judge projected size. To explain how this was calculated, consider the hardest ‘different’ trials, i.e. where the projected size ratio is the smallest, 1.25: 1. On these trials, if depth cues could not be inhibited at all, then the participant would perceive physical size only and the right-hand object would appear 2.30 times larger than the left-hand object (see Table 1). Thus, we calculated each individual’s 75% threshold *projected* size ratio, i.e. the point at which physical size differences could not be inhibited, as a proportion of 2.30 (100% influence). This showed that depth information was weighted at 67.47 (20.83) %, 80.25 (13.59) % and 87.31 (40.16) % for one-cue, two-cue and three-cue conditions respectively. This corresponded to significantly higher weightings for two and three cues compared to one cue ($p<.001$ for both), but no difference between the weightings towards two and three depth cues ($p=.23$).

Figures 2 and 3a, b, c and d about here

Response times

Response times for correct responses only were analysed. Response time data is illustrated in Figure 4, and is consistent with the proportion correct data. As with the proportion correct data, a two-way ANOVA was carried out with monocular cue and projected size ratio as factors. Consistent with the proportion correct data, the main effects of monocular cue ($F(3, 117) = 21.17$, $p<.001$, partial $\eta^2=.35$) and projected size ratio ($F(1, 39) = 95.27$, $p<.001$, partial $\eta^2=.71$) were mediated by an interaction between these two factors, $F(27, 1053)=6.62$, $p<.001$, partial $\eta^2=.15$. This was due to differences in the main effect of cue as the projected size ratio increased. For size ratios of 1:1 to 1: 2:1, 3:1 and 4:1, responses were faster, the fewer cues there were (1:1 to 1.67:1, 4:1 $p<.001$; 2:1, 3:1, $p<.05$); for the size ratio of 2.5: 1, this main effect was marginally significant ($p = .06$); whilst for the largest size ratio of 5:1, the number of cues present had no significant effect on RTs ($p=.55$).

Figure 4 about here

Discussion

We were interested in the level of monocular pictorial depth information required to affect the ability to perceive the projected size of an object. The results demonstrate that participants were able to respond to projected size as requested, rather than physical size ratios: as projected size ratio increased, performance became more accurate and responses quicker. The main effect of monocular cues, however, clearly demonstrates that it was effortful to inhibit the influence of depth cues. Relative to the no-cue control condition, performance became increasingly less accurate and responses slower, with the addition of each depth cue. Even for the single monocular depth cue of height in the visual field, physical size had to be actively inhibited for participants to respond in line with projected size. This finding is consistent with and expands on the results of Yonas and Hagen (1973) and Uhlarik et al. (1980), who showed a dominance of physical over projected information with numerous pictorial depth cues.

We also estimated the threshold at which a difference in projected size could no longer be accurately detected due to sensitivity to depth information. On the control (no-cue) trials, small projected size ratios were relatively difficult to detect, but accuracy was consistently above the 75% level of performance. This was not the case for trials which included depth cues. Participants could only reliably detect a projected size difference from a projected size ratio of 1.36:1 for one-cue trials, 1.79:1 for two-cue trials and 1.82:1 for three-cue trials. Below these ratios, the interference from depth cues was great enough to reduce detection of projected size difference to below 25%. The addition of each depth cue was not equally detrimental. The addition of the cue of height in the visual field strongly influenced performance. There was also a substantial additional influence of adding linear perspective as a cue. At this point, sensitivity to depth cues showed a plateau: the inclusion of texture gradient as a depth cue had little additional effect on performance.

Cues were added in a fixed order, thus one cannot determine the extent to which the weightings reflect the number of cues available. Also, studies have shown that the reliability of an individual cue changes according to factors such as viewing distance and the slant of a surface, and that this dictates the relative influence of each cue (e.g. Ernst & Banks, 2002; Hillis, Watt, Landy & Banks, 2004; Bradshaw, Glennerster & Rogers, 1996). As such, the weightings of the three cues observed in this study are not fixed, and could vary with differences in viewing distance or if slant was introduced to the flat ground plane.

It is possible that the relatively small additional weighting observed for texture gradient, relative to the two-cue condition, relates to the nature of the texture, a concrete-type texture. Texture gradient is not a singular depth cue as it involves the gradients of size, density and compression. The texture employed clearly depicted a receding texture with size, density and compression gradients; however, it did not have any defined texture units. This was intentional as we did not want the depth cue of relative size to govern performance (see Cutting & Vishton, 1995; Gillam, 1995). However, it is possible that a texture with visible texture units might have commanded a higher weighting on performance. Participants might have shown more interference, as size would be ‘measured’ against the size of texture units.

Overall, it appears that with only two pictorial cues, performance is heavily influenced by physical size information despite instructions to ignore this information. This suggests that below a certain projected size ratio, depth cues cannot be ignored. This supports the suggestion that depth information is perceived at a preattentive level (Aks & Enns, 1992; 1996; Enns & Rensink, 1991).

The effect of monocular depth diminished as the projected size ratio between shapes increased. Indeed, when the projected size ratio was 5:1, there was no effect of cue for either proportion of ‘different’ responses or RT. This was also true for proportion of ‘different’ responses when the projected size ratio was 4:1. Performance on these trials was no different whether there were no depth cues or all three depth cues present. Thus, given a large enough projected difference in size, conflicting information from depth cues is relatively inconsequential and can be ignored.

For ‘same’ trials, the effect of two and three cues was out of line with responses to ‘different’ trials in these conditions. One might argue that this reflects the relationship between projected and physical size ratios. The 1:1 projected size ratio trials represented the largest physical size ratio, and thus it is possible that these trials were the most likely to elicit a ‘different’ response if responding was strongly driven by physical size. However, if this were the case, one would predict an interaction between increasing projected size difference and decreasing physical size difference, which would produce a U-shaped function for the two-cue and three-cue conditions. Inspection of Figure 2 does not support this; performance at a projected size ratio of 1:1 is distinctly different from the pattern of performance for the other ratios. Thus, we conclude that there is something special about the influence of depth cues on performance, when the projected size of two objects is identical. If so, then it appears that participants do treat identical projected size trials differently from other trials, which suggests some subconscious awareness, but that this results in a stronger influence of conflicting depth information, rather than the reduced influence that one might predict. Data from previous studies shed little light on this effect. Yonas and Hagen (1973) did not specify that participants judge projected size, and Bennett and Warren’s (2002) task was a size transformation (form judgement), rather than a size judgement task. Uhlurik et al. (1980) did ask participants to judge projected size, and in contrast to the present findings, showed that responses to a projected size ratio of 1:1 were in line with the trend across projected size ratios. Participants were asked to judge the size of one block, in units, relative to another block. As this type of responding is along a continuum, perhaps the binary, same-different, responding required in the present study was the root of the unusual effect for ‘same’ trials. This could be determined through further investigation of different response types.

In this study, depth was manipulated at the level of pictorial monocular depth cues. As such, the amount of depth information available was reduced relative to previous size judgement studies, as both Uhlarik et al. (1980) and Yonas and Hagen (1973) included numerous pictorial monocular depth cues across all depth conditions. By asking adult participants specifically to make judgements of projected size, we revealed a differentiation in the extent to which depth information affects size judgements. It appears that even one pictorial depth cue affects a projected size response, but also that this effect is cumulative with depth cues, with a plateau at two cues. Previous studies of size judgement did not find this differentiation as the lowest cue condition already contained the ceiling amount of cues to encourage the complete dominance of physical size ratios over projected size ratios in adults.

Similar to the present study, pictorial depth cues were manipulated in the *form* judgement study employed by Bennett and Warren (2002). Their pattern of results is similar to the pattern observed here, with a stronger influence of physical size for texture and height in the visual field, compared to the latter cue alone. However, projected size remained influential across conditions, thus the extent of effect is attenuated compared to the current study. Comparison between their form judgement study and our size judgement study suggests that physical size is easier to inhibit in a form judgement task than a size judgement task, although differences in the influence of the flat presentation screen cannot be ruled out.

In summary, even minimal depth information has some influence on projected size judgements in adulthood, provided the size judgements are sufficiently difficult. These results illustrate the preattentive nature of depth processing, even at the level of pictorial monocular cues.

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Table 1: Corresponding projected and physical size ratios for depth-cue trials

Size ratio										
Projected	1:1	1.25:1	1.33:1	1.5:1	1.67:1	2:1	2.5:1	3:1	4:1	5:1
Physical	1:2.57	1:2.30	1:2.23	1:2.10	1:1.99	1:1.82	1:1.63	1:1.48	1:1.28	1:1.15

Author Note

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Figure captions

Figure 1: Example stimulus images

Figure 2: Proportion of ‘different’ responses for projected size judgements at each cue condition

Figure 3a: Z-scores of proportion of ‘different’ responses for the control condition, plotted against transformed projected size judgements (x^{-1}: 1). Open shapes show mean (s.d.) participant z-scores, plotted for each transformed projected size judgement. Closed shapes indicate the mean (s.d.) participant linear function between z-scores and transformed projected size judgements. Linear functions were employed to determine the weighting of each depth cue.

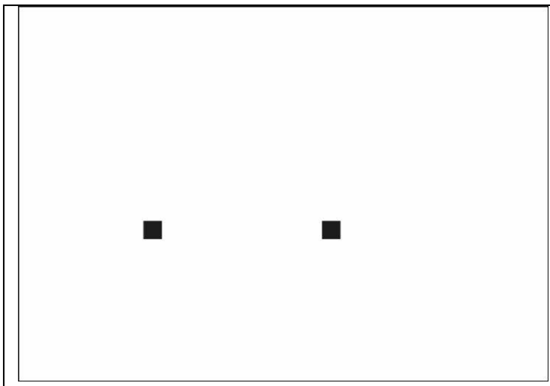
Figure 3b: Z-scores of proportion of ‘different’ responses for the one-cue condition, plotted against transformed projected size judgements (x^{-1}: 1). Open and closed shapes indicate z-scores and linear functions of z-scores as in Figure 3a.

Figure 3c: Z-scores of proportion of ‘different’ responses for the two-cue condition, plotted against transformed projected size judgements (x^{-1}: 1). Open and closed shapes indicate z-scores and linear functions of z-scores as in Figure 3a.

Figure 3d: Z-scores of proportion of ‘different’ responses for the three-cue condition, plotted against transformed projected size judgements (x^{-1}: 1). Open and closed shapes indicate z-scores and linear functions of z-scores as in Figure 3a.

Figure 4: Response times for projected size judgements

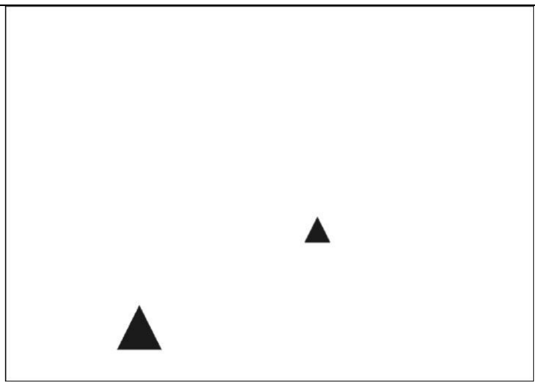
Figure 1



a. Condition: control (no cue)

Retinal size ratio: 1:1.

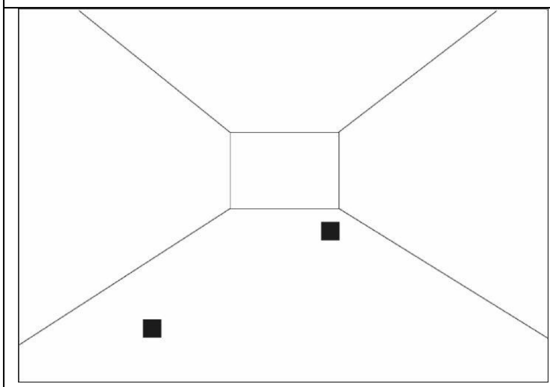
Environmental size ratio: 1:1



b: Condition: one-cue (height in the visual field)

Retinal size ratio: 3:1

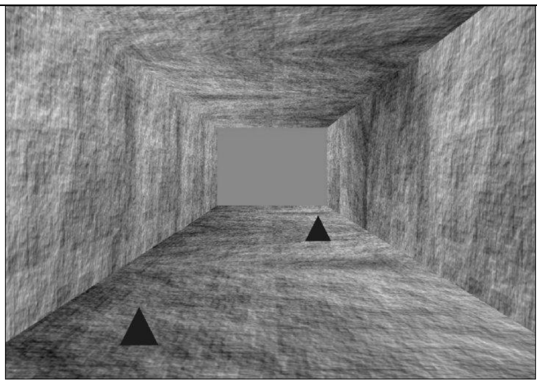
Environmental size ratio: 1: 1.48



c: Condition: two-cue (height in the visual field, linear perspective)

Retinal size ratio: 1:1

Environmental size ratio: 1:2.57



d: Condition: three-cue (height in the visual field, linear perspective, texture)

Retinal size ratio: 2:1

Environmental size ratio: 1: 1.82

Figure 2

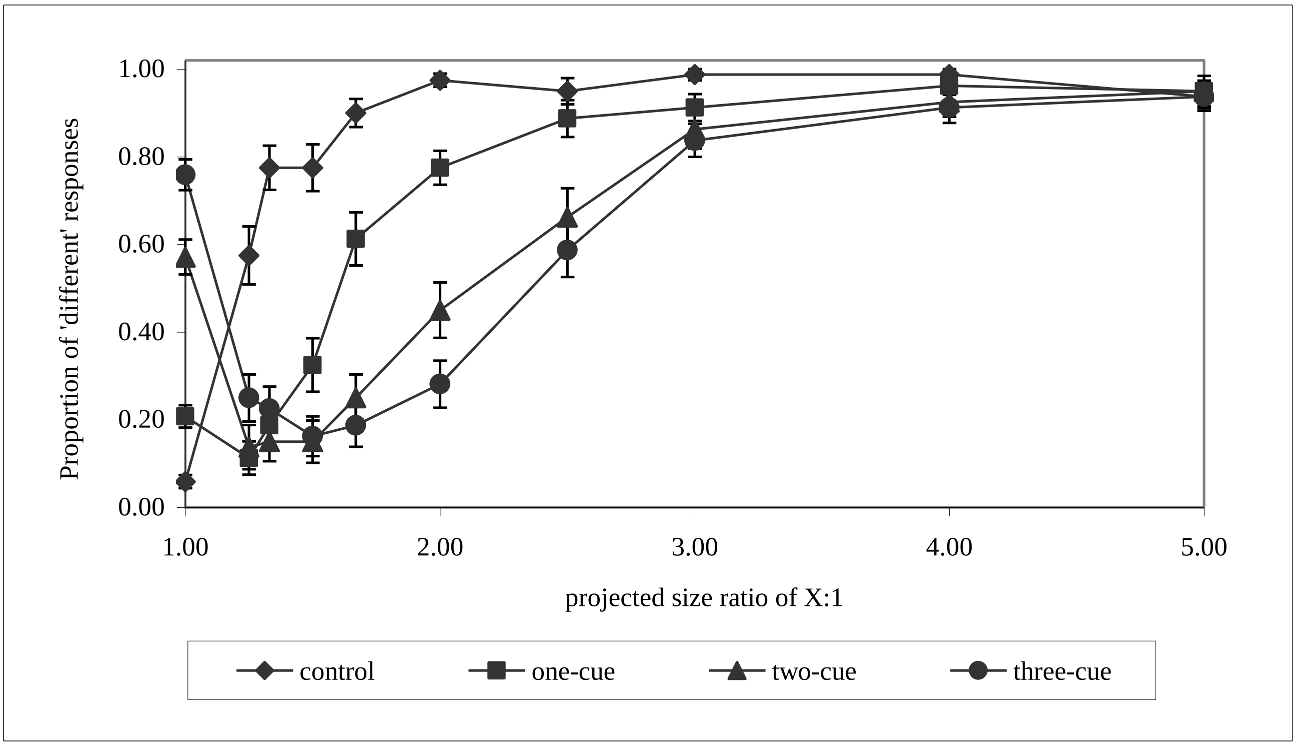

1.00
0.80
0.60
0.40
0.20
0.00
Proportion of 'different' responses
1.00
2.00
3.00
4.00
5.00
projected size ratio of X:1
control
one-cue
two-cue
three-cue

Figure 3a

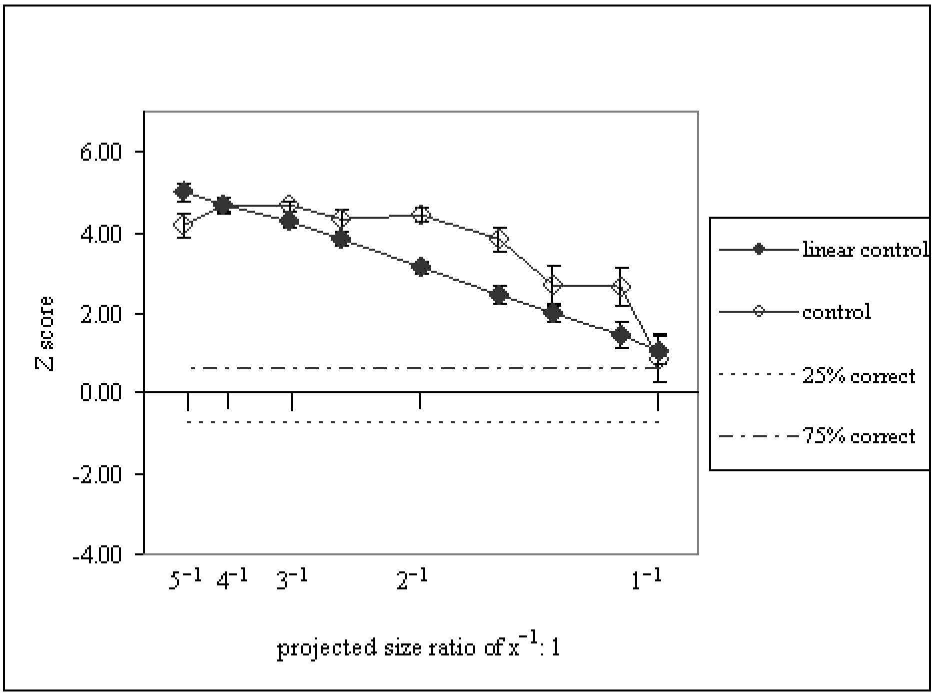


Figure 3b

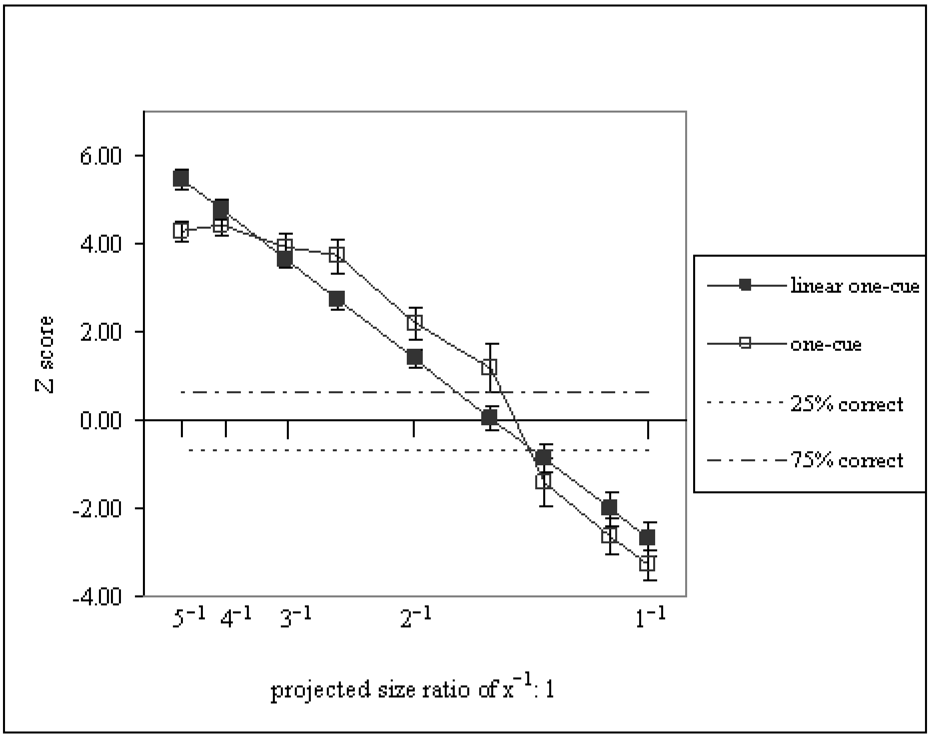


Figure 3c

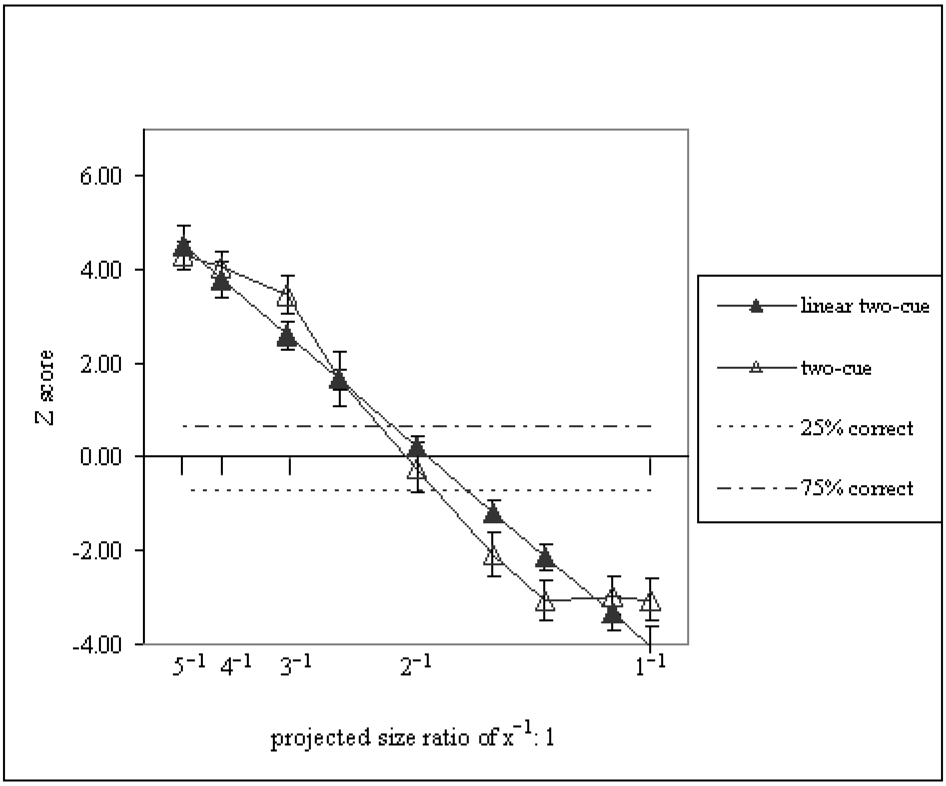


Figure 3d

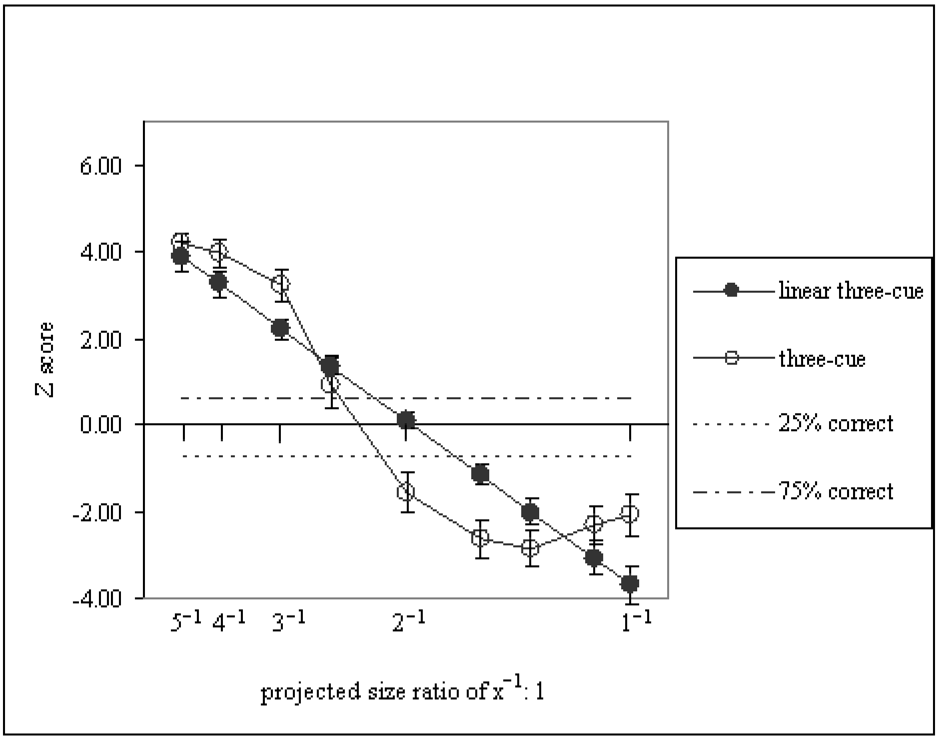
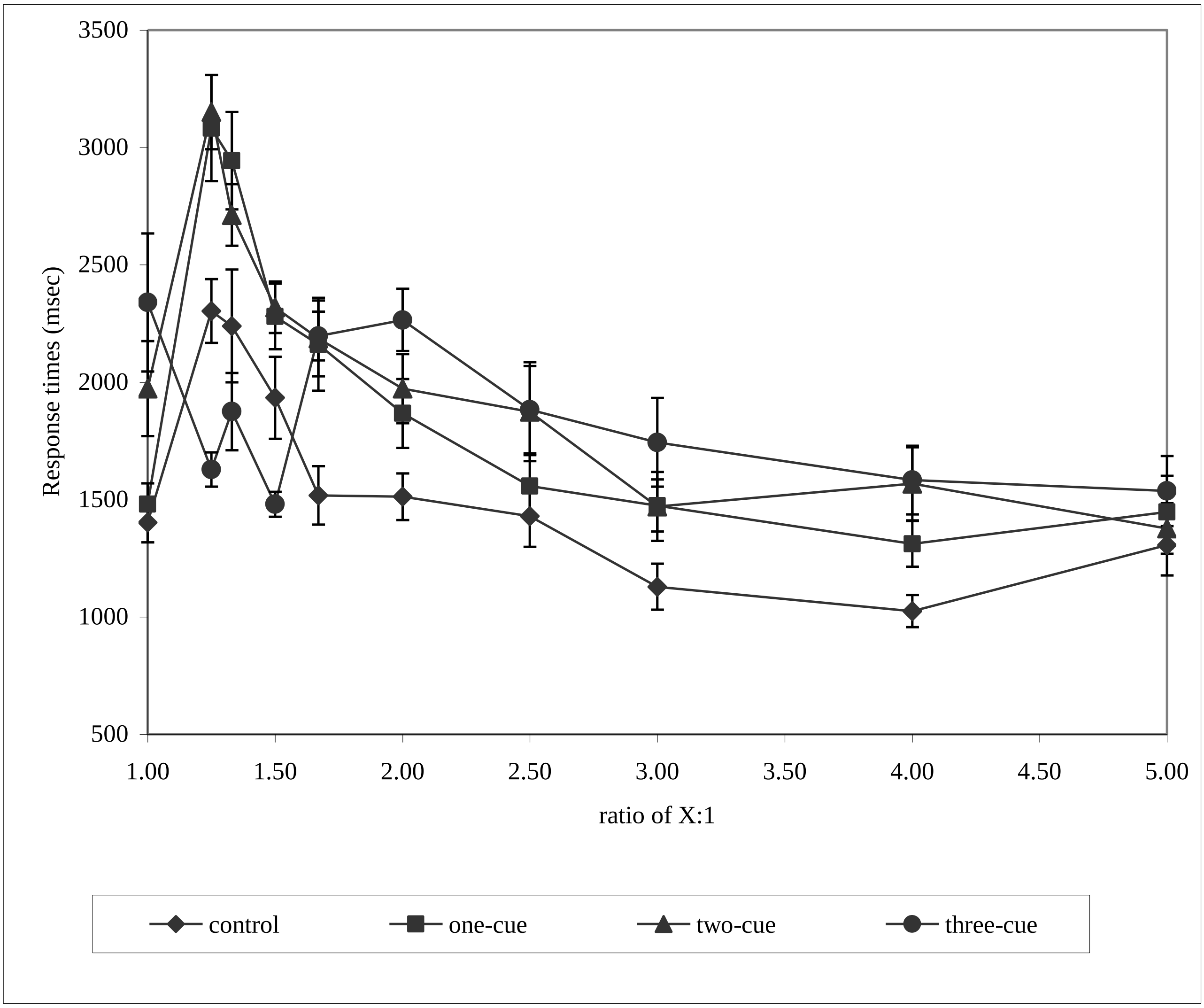


Figure 4


3500
3000
2500
2000
1500
1000
500
Response times (msec)
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
ratio of X:1
control
one-cue
two-cue
three-cue