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Stereo and Motion Parallax Cues in Human 3D Vision: Can they Vanish Without Trace?

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ABSTRACT

In an immersive virtual reality environment, subjects fail to notice when a scene expands or contracts around them, despite correct and consistent information from binocular stereopsis and motion parallax, resulting in gross failures of size constancy (Glennerster et al. 2006). We determined whether the integration of stereopsis/motion parallax cues with texture-based cues could be modified through feedback. Subjects compared the size of two objects, each visible when the room was a different size. As the subject walked, the room expanded or contracted although subjects failed to notice any change. Subjects were given feedback about the accuracy of their size judgments, where the 'correct' size setting was defined either by texture-based cues or (in separate a experiment) by stereo/motion parallax cues. As a result of feedback, observers were able to adjust responses such that fewer errors were made. For texture-based feedback, the pattern of responses was consistent with observers weighting texture cues more heavily. However, for stereo/motion parallax feedback, performance in many conditions became worse such that, paradoxically, biases moved away from the point reinforced by the feedback. This can be explained either by assuming that subjects re-map the relationship between stereo/motion parallax cues and perceived size or that they develop strategies to change their criterion for a size match on different trials. In either case, subjects appear not to have direct access to stereo/motion parallax cues.

INTRODUCTION

There is a growing consensus that when several sensory cues contribute to a percept such as the 3D shape of an object, the combination process is well described by a weighted linear summation of cues in which the weighting of each cue is determined by its reliability (Taylor 1962; Richards 1985; Buckley and Frisby 1993; Johnston et al. 1993; Young et al. 1993; Johnston et al. 1994; Landy et al. 1995; Backus et al. 2001; Jacobs 2002). It has been argued that this combination may be 'mandatory' for cues within one sensory modality since subjects appear to be unable to access the information from individual visual cues, at least for discriminations close to threshold (Hillis et al. 2002). Nevertheless, it is possible to change the weight applied to different cues in a matter of seconds (Triesch et al. 2002) by changing the reliability of those cues. It has also been shown that training can influence the relative weighting applied to visual and haptic cue (Atkins et al. 2001). Varying the subject's task has been shown to alter subjects' responses even when the reliability of available cues remains the same. This is probably because the visual system computes quite different parameters depending on the task, rather than the effect being due to re-weighting of cues (Tittle et al. 1995; Bradshaw et al. 2000; Glennerster et al. 2006).

Here, we investigate an 'expanding room' environment presented using virtual reality in which, at first sight, subjects seem to ignore stereoscopic cues and motion parallax information altogether (Glennerster et al. 2006). The purpose was to determine whether, using feedback, we could train subjects to attend to the stereo/motion parallax cues and weight these more heavily in determining their responses. Unlike other paradigms (Hillis et al. 2002), the stereo/motion parallax signals were not near threshold, increasing the chance that subjects could learn to base their responses on those cues in isolation.

The subjective reports of people in the expanding room is that they are surrounded by a stable room, even though its dimensions (as specified by stereopsis and motion parallax) change greatly in all directions (up to fourfold in this experiment) as they walk across the room. The impression of a stable scene is equally strong when the floor and ceiling are removed, showing that it is not simply because people assume a constant eye height (Ooi et al. 2001). The relative disparities and equivalent motion parallax signals change by a factor of four (i.e. a 300% increase, substantially above a detection threshold of 10-20% for disparity increments, McKee et al. 1990) so they should be readily detected. Indeed, in our apparatus, subjects can detect the change in size of the room when they walk through a virtual wall from a small room into a large room, using only stereo/motion parallax cues. The situation in which stereo/motion parallax cues are apparently suppressed is when the room expands around them as they walk across it (the centre of expansion is the cyclopean point) so that as objects get further away they also get larger. In this case, an assumption that objects and texture elements (such as the bricks that compose the walls of the room) remain the same physical size (and the same distance) conflicts with the stereo/motion parallax cues. This assumption (which leads to what we describe as a 'texture-based cue') appears to dominate subjects' perception of the size of the room.

Despite observers' subjective reports on the apparent size of the expanding room, there is good evidence that stereo/motion parallax cues contribute to subjects' performance when they are asked to carry out certain tasks. For example, when they are asked to compare the sizes of two objects, one seen when the room is small, the other seen when the room is large, observers' matches are well described by a weighted combination of information from texture-based and stereo/motion parallax cues (Glennerster et al. 2006). The question we address in this paper is whether subjects can be trained to bias their responses in this task towards the size signalled by stereo/motion parallax cues if they are given appropriate feedback. Figure 1 illustrates three different ways in which this feedback could operate: by changing the weight applied to each cue, by changing the interpretation of each cue (the mapping from a cue value to a size) or by changing the interpretation of the combined cues. These possibilities are discussed in detail in the Model section. We find that subjects do change their responses as a result of feedback but in ways that imply that the visual system has no direct access to stereo/motion parallax cues and cannot increase the weight applied to them.

METHODS

Subjects

Five observers had normal or corrected-to-normal visual acuity aged 23-31. Two subjects were authors (SGS and AMR) and three were naïve to the purpose of the experiment (TJP, HGE, and JHP).

Equipment

The virtual reality equipment used is described in detail in (Glennerster et al. 2006). Briefly, the virtual reality system consists of a head mounted display, a head tracker, and a computer, which generate appropriate binocular images given the locations and pose of the observer's head. The Datavisor 80 (nVision Industries Inc, Gaithersburg, Maryland) head mounted display unit presents separate 1280 by 512 pixel images to each eye using CRT displays. In our experiments, each eye's image was 72° horizontally by 60° vertically with a binocular overlap of 32°, giving a total horizontal field of view of 112° (horizontal pixel size 3.4 arc min).

The location and pose of the head was tracked using an IS900 system (InterSense Inc, Burlington, Massachusetts). This system combines inertial signals from an accelerometer with a position estimate obtained from the time of flight of ultrasound signals. Four ultrasound receivers are attached to the tracker ('Minitrax'); more than 50 ultrasound emitters placed around the room send out a timed 40 kHz pulse sequence. The data are combined by the InterSense software to provide six degrees of freedom in the estimate of the tracker pose and location. These data are polled at 60Hz by the image generation program. Since the offset of the tracker from the optic centers of each eye are known, the position and pose of the head tracker allow the 3D location of the optic centres to be computed. These are used to compute appropriate images for each eye. Binocular images were rendered using a Silicon Graphics Onyx 3200 at 60Hz. We have measured the latency from movement of the Minitrax tracker to image change as 48-50 ms.

Stimulus and task

Subjects moved in a virtual room whose dimensions depended on the location of the subject in the real room. When the subject was on the left side of the room and standing within an unmarked viewing zone (0.5 x 0.5 m) a red ‘reference’ cube was visible ahead of them, presented either 0.75 or 1.5 m away from the centre of the viewing zone. (For the smallest room, the 1.5 m cube was 12.5 cm from the far wall.) Subjects were instructed to walk to their right until a comparison cube appeared (within a similar unmarked viewing zone close to the right wall, see Fig 2) and signal, by pressing one of two buttons, which cube appeared larger. The comparison cube was also at 0.75 or 1.5 m. Leaving the first viewing zone caused the reference cube to disappear, so no simultaneous comparison of the two cubes was possible.

When either cube was visible, the room remained stable. However, in the region between the two viewing zones the room size was directly related to the lateral component of the subject’s location. On some trials the room expanded while on others it contracted: the expansion factors were 0.25, 0.5, 1, 2 and 4. The point of expansion was the cyclopean point (half way between the eyes) so that, as objects got larger they also got further away. Thus, no single image would allow the observer to know whether they were in a large or a small room. Only comparison of two or more views (and a knowledge of the separation of the optic centres from which the images were obtained) would reveal the size of the room. The dimensions of the non-expanded virtual room were 3 m wide by 3.5 m deep. At this scale the virtual floor was at the same level as the subject’s feet. The smallest size of the room was 1.5 by 1.75 m and the largest 6 by 7 m. The walls were textured with a brick pattern and the floor with regular tiles (see Fig 2). No other objects were present in the room.

Psychometric Procedure

20 independent psychometric functions were randomly interleaved in one run of trials (2 distances of the reference cube, 2 distances of the comparison and 5 room expansion factors). Each psychometric function consisted of 40 trials, i.e. a total of 800 trials in a run. Subjects were encouraged to take breaks about every 100-150 trials. (800 trials took

in total approximately 3-4 hours, required 4.8 km walking and could be spread across more than one day.) Other properties of the cubes were also randomized but did not define separate psychometric functions. These were the heights of the reference and comparison cubes and the size of the reference cube. If g is the room expansion factor on a given trial (0.25, 0.5, 1, 2 and 4) then the reference cube size was 0.75, 1 or 1.5 times a 'standard' cube size (constant with respect to the virtual room) of sqrt(g) x 10 cm while the heights of the cubes were sqrt(g) x 9, 18 or 36 cm below eye level.

On each trial the size of the comparison object relative to the reference was determined according to a standard staircase procedure (similar to Cornsweet 1962; Levitt 1971; Johnston et al. 1993). Each psychometric function was gathered using four randomly interleaved staircases, two starting from a high value and two from a low one. The two staircases starting from a high value were a 1-down, 3-up staircase (i.e. one correct answer and the cube size would be made smaller, three errors and it would be made larger) and a 3-down, 1-up staircase (i.e. converging more slowly and steadily). The two staircases starting from a low value were the same but in reverse (1-up, 3-down and 3-up, 1-down). The stepsizes reduced over the first 6 trials per staircase (step size was 6/N, where N is the trial number on that staircase until N >= 6 after which stepsize remained constant). The starting ranges were such that they included both a real size match (as specified by stereo/motion parallax) and a texture- or room-based match (equal size relative to the room). Since the experimental cue was a size ratio, the scale used in both the staircase and psychometric fitting was logarithmic. The size of the comparison object at the point of subjective equality was obtained by fitting each psychometric function with a cumulative Gaussian by probit (Finney 1971). In figures 3 and 4, size matches show the bias (50% correct point). The error bar in each plot shows the mean s.e.m. for those data. Details of the feedback given to subjects are described with each experiment. In figures 3 and 4, the data for feedback conditions show the fits obtained for the last 400 trials within each run in order to allow the effect of feedback to show after at least 400 trials.

RESULTS

Size-matches without feedback

The left hand column of figures 3 and 4 show the size matches that subjects made before they were given feedback in each experiment. For those subjects who had not received feedback before (i.e. this was their first experiment: HGE in experiment 1; TJP, SGS, JHP in experiment 2), the data generally lie between the horizontal dashed line (a physical match as specified by stereo/motion parallax cues) and the diagonal (a match assuming texture elements and the room stay constant size). The lines show fits according to a weighted linear sum of the two cues (see Model section). Glennerster, Tcheang, Gilson, Fitzgibbon and Parker (2006) also used this simple model, where the weight applied to the stereo/motion parallax cue was smaller for more distant comparison cubes. Although a much narrower range of distances was used here, these data show the same trend (data for comparison distances of 1.5 m are closer to the diagonal, see Model section). All subjects reported that that the room appeared to be a constant size in all conditions, before and after feedback.

Experiment 1: Texture-Based Cue Feedback

The goal of experiment 1 and 2 was to determine whether subjects could change their responses in the size matching task according to a criterion set by the computer.
In the first experiment, the ‘correct’ size match for any given trial was a comparison object that was the same size as the reference object in relation to room size. Texture-based cues such as brick size signal the correct estimate of stimulus size in this experiment, because the size of texture elements is scaled directly with room size. (Thus, if the reference cube is two bricks high then the correct match of the comparison cube is also one that is two bricks high, no matter what size the cubes appeared to be.) The goal of feedback in this experiment was to drive observers to a size match based on these texture cues. The experiment was slightly different for the two naïve observers (HGE

and JHP) than for the two experienced observers (authors AMR and SGS). The naïve observers did not know what rule was being used by the computer to determine feedback, while the experienced observers did.

Fig 3 shows the results (right hand column). If observers changed their responses according to the feedback their data should lie along the diagonal (matched size scaled directly with the expansion factor of the room). As can be seen in Fig 3, observers' responses moved closer to a texture-cue based match during texture-cue based feedback, though never quite obtaining it. The subjects' success at minimizing their errors can be measured by the deviation from the texture-based match, where deviation is calculated as the sum of squared logarithmic distances between the observers size-match and the matches expected from texture-cues alone. Across all subjects, the average deviation decreased by a factor of 3.9 from pre-feedback to feedback blocks. By this criterion, observers AMR and SGS, who knew the purpose of the experiment, were more successful than naïve observers HGE and JHP (average decreases in deviation of 7.9 and 2.6 times respectively). The slopes of the data increased, while matches made in the static room (room expansion factor = 1) remained unaffected. This is the pattern expected if subjects weight the texture cue more heavily in determining their responses.

Experiment 2: Veridical (stereo/motion parallax) Feedback

In this second experiment, the 'correct' size match was one in which the comparison object was the same physical size as the reference object regardless of the room expansion factor. Stereo/motion parallax cues signal the correct estimate of stimulus size in this experiment. In Fig 4, this would be reflected as data lying along the horizontal dotted line (i.e. matched size is always equal to 1). As in experiment 1, the naïve observes (JHP and TJP) were not told the rule by which the computer determined its feedback, while observer SGS knew. However, in this case, knowledge of the feedback rule appeared not to help.

Fig 4 show the data during the feedback run (right hand column). For all subjects, feedback about the veridical size of the cube (as specified by stereo and motion parallax) caused size matches to become less dependent on the room expansion factor (matches moved towards the horizontal, as expected). The improvement can again be quantified by the difference between observers' size match and that expected for stereo/motion parallax cues alone. The average deviation was a factor of 4.1 smaller than it was prior to feedback. One might assume that this reduction in errors implies that the subject has access to the stereo/motion parallax information in the stimulus and changes their responses accordingly. However, a distinctive pattern of the data, which is present for all three subjects, suggests this is not the case. When the reference and comparison objects were presented at different distances, matches spread away from the horizontal line that defines physical size-matches. When the reference object was at 1.5 m and the comparison at 0.75 m, all observers produced a larger matched size (i.e. comparison objects were judged as smaller than they should have been) than when the reference was at 0.75 m and the comparison at 1.5 m, where all observers produced a smaller matched size than they should have. This led to increased error rates from pre-feedback to feedback blocks for certain conditions, most clearly when the room expansion factor was 1 (a static room) with reference and comparison objects at different distances: in this condition the deviation was on average 1.63 times larger during feedback than in pre-feedback. In other words, size constancy had been lost in a static room, since subjects no longer matched similar sized objects presented at different distances, despite being given appropriate feedback that should help them to do so. (The failure of size constancy is in the opposite direction to that predicted by retinal size matching.) This trend continued in the third block of trials (post-feedback; not shown), where the average deviation was 2.04 times larger than that in the pre-feedback block.

The unexpected pattern of results with veridical feedback suggests observers could not simply ignore texture-based cues. It seems that whatever mechanism or strategy allows the subject to reduce their errors during feedback causes, as a bi-product, increases errors in particular conditions. In the following section, we explore two types of models that could explain this pattern of responses. Briefly, one model assumes that rather than re-weighting cues, in which case the combined output would be constrained to lie somewhere between the values signalled by the two cues, the visual system can instead 're-map' one or both cues to signal a quite different size of the comparison (or reference) cube. The other model assumes that subjects use a conscious strategy to change their criterion on different trials. Because they cannot identify the trials with different expansion factors, which would allow them to respond to the feedback appropriately, they instead use other parameters, such as the perceived distance of the reference and comparison cubes. These signals correlate to a limited extent with the room expansion factor and hence allow them to reduce their errors overall, but at the cost of introducing systematic biases.

MODEL

Figures 3 and 4 show that feedback, whether it be in relation to texture-based or stereo/motion parallax cues, causes observers to adjust their responses and minimize the errors they make. What perceptual mechanisms underlie this? In this section we consider a simplified model of cue combination in 3D visual perception, illustrated in Figure 1 and based largely on that of Landy et al (1995). We assume that the size-matching task requires three stages of analysis: first, compatible ("promoted") estimates of size are made independently for texture-based and stereo/motion parallax cues; second, these estimates are combined linearly to form a unified sensory representation; third, this sensory representation is filtered in relation to the observers task to form the report. Feedback could exert its influence at any or all of these stages.

Size-matches before feedback

Our task requires observers to match the size of two objects, with information available from texture-based and stereo/motion parallax cues. The model postulates that for each object the observer perceives size, S, as a summation of independent texture-based (T) and stereo/motion parallax (P) estimates. Thus perceived size,

$$S = Tw_T + Pw_P \qquad (1)$$
$$w_T + w_P = 1.$$

where w_T and w_P are the weights given to texture-based and stereo/motion parallax cues at one distance from the observer. The estimate of size from stereo/motion parallax cues, *P*, is always veridical, and the estimate of size from texture-based cues, *T*, is always inversely proportional to the size of the room (all texture elements scale with the room). The weights of texture-based and stereo/motion parallax cues are allowed to vary with distance reflecting the decline in accuracy of stereo/motion parallax cues at larger distances. We assume that the weights of texture-based and stereo/motion parallax cues at a given distance are independent of the size of the room.

Equation (1) can give us predictions for the perceived size of the reference cube, on the left side of the room, S_L, and for the comparison cube on the right of the room, S_R. In our task the size match, M, is the inverse of the ratio of perceived size of the two objects[1]:

$$M = \left[S_R / S_L \right]^{-1} \qquad (2)$$

The left-hand panels of Figs 3 and 4 show that for all observers, the size-match depended on the size of the room (the size match is approximately proportional to the room expansion factor) and, to a lesser extent, the distance of objects from the observer (for most expansion factors, the size-match depends on the relative distance to the two objects). The model in Eqns (1) and (2) was able to accommodate the pattern of size matches in each case (lines in Figs 3, 4 and 5), with two parameters allowed to vary, namely the relative weights of texture-based and stereo/motion parallax cues at the two object distances tested. For every observer, size matches could be accounted for best by assuming that texture-based cues are weighted more at larger distances: average w_T was 0.43 (SD 0.12, n = 5) at a distance of 0.75 m and was 0.56 (SD 0.19) at 1.5 m ($p < 0.05$, paired Students *t*-test).

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1 M is the inverse of the S_R/S_L because if an object appears smaller when the room is made larger, then the observer should increase the size of the comparison object in the larger room to match perceived size. We assume that changing the size of the comparison object leads to proportional changes in perceived size.

Incorporating the influence of feedback

We consider three ways in which feedback could exert its influence, illustrated in fig 1. First, there might be a re-weighting of mechanisms in the process of combining the two size estimates (Fig 1–A), i.e. allowing the relative weights of cues to vary in the same way as described above for the model applied to the pre-feedback data. Second, feedback could cause a re-mapping between the input and size estimate for either texture or stereo/motion parallax cues or both (Fig 1–B). Finally, the observer may adopt a strategy to minimize errors by varying their criterion for an equal sized match from trial to trial (Fig 1–C). In the following, we discuss each of these models and concentrate on the responses under veridical feedback, which proved the best at differentiating the model predictions (Fig 5).

For each model, best-fitting predictions were obtained by minimizing the mean-square distance between the logarithms of the size-match, M, and the model's predictions. In the case of the re-mapping and strategy models, cue weights at each of the two object distances were estimated from the pre-feedback size-matches. The most obvious way to reduce errors under feedback is to increase the use of the target cue by re-weighting its input to the size estimate. We describe this model first.

Cue re-weighting

If observers could learn to ignore the irrelevant cues, they would eliminate any errors. In the case of texture-based feedback, observer's responses should then lie along the diagonal, and most observers tended towards this (Fig 3). The re-weighting model is able to account for this well, by reducing the weight of the stereo/motion parallax cues contributing to the size estimate (w_P) from 0.66 to 0.29 at 0.75 m and from 0.59 to 0.21 at 1.5 m ($n = 4$). In Fig 3, this results in a rotation about the origin towards the diagonal. The best fit for this and all subsequent models was found by minimizing the squared error between the model predictions and the observer's responses.

For veridical feedback (experiment 2), the re-weighting model was less successful. The top right panel in Fig 5 shows for one observer the size-matches made during veridical feedback (symbols) and the corresponding predictions of the model (lines). The model is unable to account for the vertical spreading of responses. This can be best understood for the static room, where any amount of re-weighting will still generate the same size-match, because $T = P = 1$ in Eqn (1) and w_T and w_P always sum to 1.

Cue re-mapping

Adams et al. (2001) found that a re-mapping of binocular disparity cues provided a simple explanation for perceptual adaptation to slant, and we asked if it can also explain the impact of feedback in the size-matching task (Fig. 1—B). We define re-mapping as a change in each size estimate (*T* or *P* in Eqn (1)), but in the model it is only the ratio T/P that matters. Arbitrarily, we have assumed in the following that the re-mapping applies only to the cue for which feedback was given. We allow size-estimates to vary independently at the two object distances. The key difference between this and the previous model is that for the re-weighting model changing the weights applied to one cue must be accompanied by reciprocal changes in the weights to the other cue. This is not the case for re-mapping: changing the size-estimate for one cue source has no impact on that for the other cue.

The lines in the right-hand panels of Fig 3 show the predictions of the re-mapping model under texture-based feedback. As with the re-weighting model, re-mapping can predict the rotation towards the diagonal; it accomplishes this by increasing the size-estimate *T* at both object distances–by an average of 6.4 (SD 2.3, n = 8). There was no difference between the increases at the two object distances ($p = 0.29$; paired t-test on the ratio between the changes at the two distances). Consequently both S_L and S_R tend towards the product Tw_t . Perceived size is thus dominated by the texture-based component and the size-match tends towards the room expansion factor, *g*.

The re-mapping model is also capable of explaining observers' responses under veridical feedback. Its predictions are shown in the right-hand panels of Fig 4 and the middle-right panel of Fig 5. As in the case of texture feedback, the model can account for any rotation of the data about the origin by increasing the stereo/motion parallax size estimate, P, at both distances. It can also account for vertical spread by increasing P more at the further distance (a separate mapping is allowed at each distance). On average, the stereo/motion parallax size estimate, P, at a distance of 0.75 m was increased by a factor of 4.1 (SD 1.9), and at 1.5 m by 7.9 (SD 4.7, $p < 0.05$). [2]

Strategic scaling of size-matches

Error minimization during feedback may reflect neither re-weighting nor re-mapping at early stages of visual processing. In the case of texture-based feedback, the experienced observers knew the rule for feedback and could apply a strategy accordingly (Fig. 1—C). They could, for example, relate object size to the size of the nearest wall bricks, ignoring the perceived sizes S_L and S_R when making their match. This strategy would nevertheless be equivalent in our model to increasing the weight of texture-based cues. For veridical feedback there is no such obvious strategy that would lead to the correct size match, but there are others that would nevertheless help, more often than not, to give the correct answer. If observers could learn to distinguish the size of the room they were in they would be able to choose an appropriate size-match and so provide perfect responses in the feedback conditions. No observer reported being aware of the change in room size but any cue that co-varies with room size, even with a moderate correlation, would provide a valuable signal.

For example, if the reference and comparison objects had always been presented at 0.75 m, the perceived distance of either cube would have co-varied with the room expansion factor on each trial (because the distance of the cube relative to the room would have differed). This would have enabled subjects to change their criterion for an equal size match from trial to trial. Because the cubes were presented at two different distances,

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[2] Observers SGS and JHP were participants in both texture-based and veridical feedback experiments. Both observers completed the veridical feedback trials before undertaking the texture-based feedback trials; the pre-feedback size-matches of SGS (Fig 3-D) are similar to those obtained under veridical feedback (Fig 5), one month earlier. To obtain model fits in this case, we estimated simultaneously the pre-feedback cue weights and the impact of feedback on size-estimates.

perceived distance of the comparison cube was not a wholly reliable correlate of the room expansion factor but it would nevertheless provide subjects with a useful signal to determine how to adjust their criterion so as to reduce their errors. In fact, this was not the strategy that best fitted our data: it predicts, for example, that in the static room performance should depend on the distance of the comparison cube alone. Instead, for all of our subjects, the relative distance of the reference and comparison cubes was a better predictor of size matches made in the static room. (Subjects also reported that they used the relative perceived distance of the two cubes to help decide how to adjust their size matches.) We calculated the predictions of subjects using this strategy as follows.

We assume that feedback has no effect on the perceived sizes of the reference or comparison cubes, S_L and S_R . Instead, feedback allows the subject to change their matched size, M, from trial to trial according to a cue, in this case the relative perceived distance of the comparison and reference cubes, D_R / D_L. In order to fit the data, the exponent, k, applied to this ratio was allowed to vary:

$$M = \left[{}^{D_R}\!/_{D_L} \right]^k \cdot \left[{}^{S_R}\!/_{S_L} \right]^{-1} \qquad (3)$$

The perceived distances of the reference and comparison cubes, D_L and D_R, were calculated from the pre-feedback data. In fitting the model, the exponent k was allowed to vary between 0.1 and 2.

The fit of the strategy model to one data set is shown in the bottom-right panel of Fig 5. The main characteristics are similar to the re-mapping model, i.e. a vertical spread of the lines fitting data for conditions in which the reference and comparison cubes were at different distances and lines with different slopes through the origin for conditions in which the two cubes were at the same distance. For all three observers, the exponent k in Eqn (3) was less than 1 (0.33, 0.55 and 0.54). This was the only free parameter, since the ratio D_R / D_L was obtained from each subject's pre-feedback data.

Comparison of model performance

Fig 6 plots the residual error of each model for all subjects and for both types of feedback (experiments 1 and 2). To aid comparisons between the models, errors in the re-weighting and strategy models have been normalized by the error for the re-mapping model in each condition. The re-mapping model fits the data best in all cases. It should be remembered that the re-weighting and re-mapping models each have two free parameters while the strategy model only has one, so a slightly worse fit would be expected in the latter case. However, we compared the Akaike Information Criterion (AIC, Akaike 1974) returned for each model during veridical feedback (experiment 2): for two observers the re-mapping model minimized AIC (evidence ratios 9.4 and $>10^6$), and for the other observer, the strategy model was best, though the evidence ratio was lower (4.8).

We also measured, in separate blocks of trials, size-matches following veridical feedback. No feedback was given during these blocks (see Fig 6C). Subjects were asked to match the sizes of the reference and comparison cubes as they perceived them and to ignore any strategy they may have adopted during feedback. The trends that were apparent during feedback were nevertheless more prominent in these post-feedback trials, with greater vertical spread. This suggests that, if subjects used a cognitive strategy of the sort proposed here then at least some aspects of the strategy must have become automatic and difficult to 'switch off' by the end of the feedback run.

DISCUSSION

Despite our best attempts, we have found no convincing evidence that subjects have direct access to information from stereopsis and motion parallax when performing our size matching task. Subjects appear unable to change their responses appropriately when given feedback about the size of objects as specified by these cues. Disparity and motion parallax are clearly used in the task, but these cues appear to be combined with others before the stage at which they can be used to determine the subject's response. This contrasts with the result we found for texture-based cues (which we have used as shorthand to mean the information provided about the distance and size of objects if it is assumed that texture elements do not change size over time). Here, subjects were able to change their responses in accordance with the feedback provided, especially in the case of subjects who knew in advance the rules on which the feedback was based. This is what would be expected if subjects could choose to base their responses predominantly on texture-based cues. Accordingly, a re-weighting model provides a good account of the data (Fig 6 A). The fact that the same was not true of stereo and motion parallax cues indicates that these cues must be combined with others 'mandatorily' (Hillis et al. 2002) without the subject having access to the individual cues.

Instead of the pattern expected from a re-weighting of cues, subjects all produced a distinctive and, at first sight, perplexing pattern of biases in their size matches. Size constancy even in the normal, non-expanding room was disrupted. We have presented two kinds of model that could explain this pattern of responses. According to one ('re-mapping'), the relationship between the distance signalled by stereo/motion parallax and perceived size is changed (Adams et al. 2001). This predicts a pattern of responses similar to our data, including a loss of size constancy in the static room. However, there are some problems with this type of explanation. In order to fit our data, the re-mapping between stereo/motion parallax signals of distance and size were quite extreme (see table 1). It would be straightforward to test whether such re-mapping had occurred in a general way and hence affects other tasks. One informal piece of evidence that this is not the case is that subject SGS maintained the same pattern of biases after more than a month. During this time, any re-calibration between stereo/motion parallax and perceived size that might have occurred during the experiment is likely to have disappeared or at least substantially diminished. In fact, SGS's biases had barely altered over this period (compare SGS data post feedback in Fig 4 with pre-feedback data in Fig 3).

The second model that could explain the peculiar pattern of our feedback data (Fig 4) is that subjects used a strategy to try and identify the trials on which the room was expanding and those on which it was contracting. If they used this information to shift their criterion in the size matching task (for example, choosing apparently smaller cubes as a match when they had evidence that the room was large on that trial) it could help explain why subjects lose size constancy in the static room. The model we have used (Fig 6), based on the relative perceived distance of the reference and comparison objects, does well at fitting the data but it is by no means the only such strategy that would be effective at reducing feedback errors.

There are two advantages of models based on strategies to shift the criterion for a size match. First, there is no need to propose large re-calibration in the size or distance signalled by cues such as stereo and motion parallax. Second, the strategies are similar to those that subjects report they are following during the experiment. They describe choosing matches around a smaller criterion size on some trials and a larger one on other trials. The methods by which subjects distinguish such trials are likely to vary but they commonly report using the perceived distance to the reference and comparison cubes to help disambiguate the trials on which they should use different matching criteria.

It might be argued that with a more careful experimental design we could have eliminated any correlation between the perceived distance or size of objects and expansion factor of the room in order to prevent subjects using any such strategies. We do not believe this to be the case. Our results suggest that subjects have access both to the perceived size of objects (a combination of stereo/motion parallax and texture cues) and to the size of the object with respect to the elements in the room such as bricks (equivalent to the 'texture cue' alone). As a consequence, it is not possible to devise a set of stimuli that are equivalent for each room expansion factor. A similar argument has been made by (Hillis et al. 2002), who found evidence for 'mandatory fusion' of disparity and texture cues in signaling the slant of a surface. Although successful in explaining much of the data, the mandatory fusion model failed where it predicted very large thresholds. The authors' explanation was that another cue (in their case the apparent homogeneity of the texture elements) was used by subjects and that in their paradigm, as in ours, it was not possible to eliminate both cues simultaneously.

Hillis et al (2002) and Backus (2002) used an odd-one-out task to find evidence of metamerism and hence mandatory fusion of cues. (Metamerism is the inability to discriminate mixtures of stimuli when the components alone would be easily distinguishable, such as confusing yellow with a mixture of red and green light.) In our experiment, when the room is not static it seems that texture-based and stereo/motion parallax cues are not fused 'mandatorily' in the way that has been found close to threshold by Backus and Hillis et al 2002. Instead, our data suggest that observers have access to two distinct signals, one texture-based and the other a combination of texture-based and stereo/motion parallax cues. The second of these, we suggest, gives rise to the perceived size of the object.

CONCLUSION

Our results show that the visual system cannot re-weight stereo/motion parallax cues in the way that it apparently can do for texture-based cues. We conclude that stereoscopic and motion parallax cues about the distance of objects become inextricably combined with other cues so that, by themselves, they can no longer be used to influence a subject's responses.

Acknowledgements

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Figure Legends

Figure 1. **Illustration of the 3 models described in the Model section**. Feedback could: (A) modify (Δ) the relative weight applied to texture versus stereo/motion parallax cues ('re-weighting' model); (B) cause a change in the size estimates provided by individual cues ('re-mapping' model); or (C) encourage subjects to shift their criterion for a size match on different trials ('strategy' model)

Figure 2. **Illustration of the relationship between the virtual and physical rooms.** As the observer moves from side to side within the physical room, the size of the virtual room changes size. Here the room expansion factor is 4, meaning that the size of the virtual room gradually expands by a factor of 4 as the observer moves from left to right. The centre of expansion is the cyclopean point, so any single view of the room cannot reveal the changed size of the (as can be seen from the images shown above). Subjects had to judge whether a cube visible when they were on the right side of the room ('comparison') was larger or smaller than a cube that was visible when they were on the left side ('reference'). On other trials, the room could remain static or decrease in size.

Figure 3. **Results of Experiment 1 (texture-based feedback).** The ratio of the physical size of the comparison object to the physical size of the reference object at the point of subjective equality (i.e. the subject's size match) is plotted against the expansion factor of the virtual room for all four observers. Data are plotted separately for different distances of reference and comparison objects, as described in the key. The horizontal and diagonal dotted lines show the expected size matches using only stereo/motion parallax or texture-based cues respectively. The left and right columns show matches made before and during feedback. The unusual pattern of pre-feedback data for subject SGS arises from the fact that he carried out experiment 2 before experiment 1 (see text).

Figure 4. **Results of Experiment 2 (stereo/motion parallax feedback).**
Data are plotted in the same way as for fig 3.

Figure 5. **The 3 models illustrated for one data set.** Data for one observer is shown before (left) and after (right) stereo/motion parallax feedback (experiment 2). The pre-feedback data is fitted with a weighted linear summation model (see Model section). Of the three models, the re-mapping model fits the data most closely (see Fig 6 and Model section for details).

Figure 6. **Performance of the 3 models compared.** The residual mean squared errors (MSEs) for each model (see Figs 1 and 5) are shown for the texture-based feedback above (A) and the stereo/motion parallax based feedback below (B). The 'strategy' model for observer AMR performed so poorly it was excluded from plot A. To help comparisons across conditions, we normalized by the MSE for the re-mapping model. The bottom right plot (C) shows MSEs for data collected without feedback, measured after the run in which stereo/motion parallax based feedback was given.

Table 1. **Parameters of the models used to fit the data in figures 3, 4, 5 and 6.** Pre-feedback, re-weighting and re-mapping models were fitted to the data using equation 1. For these models, values of the free parameter are given for comparison object distances of 0.75 and 1.5 m. The strategy model is defined in equation 3. In this case, one parameter, k, applies to the data for comparison cubes at both 0.75 and 1.5 m.

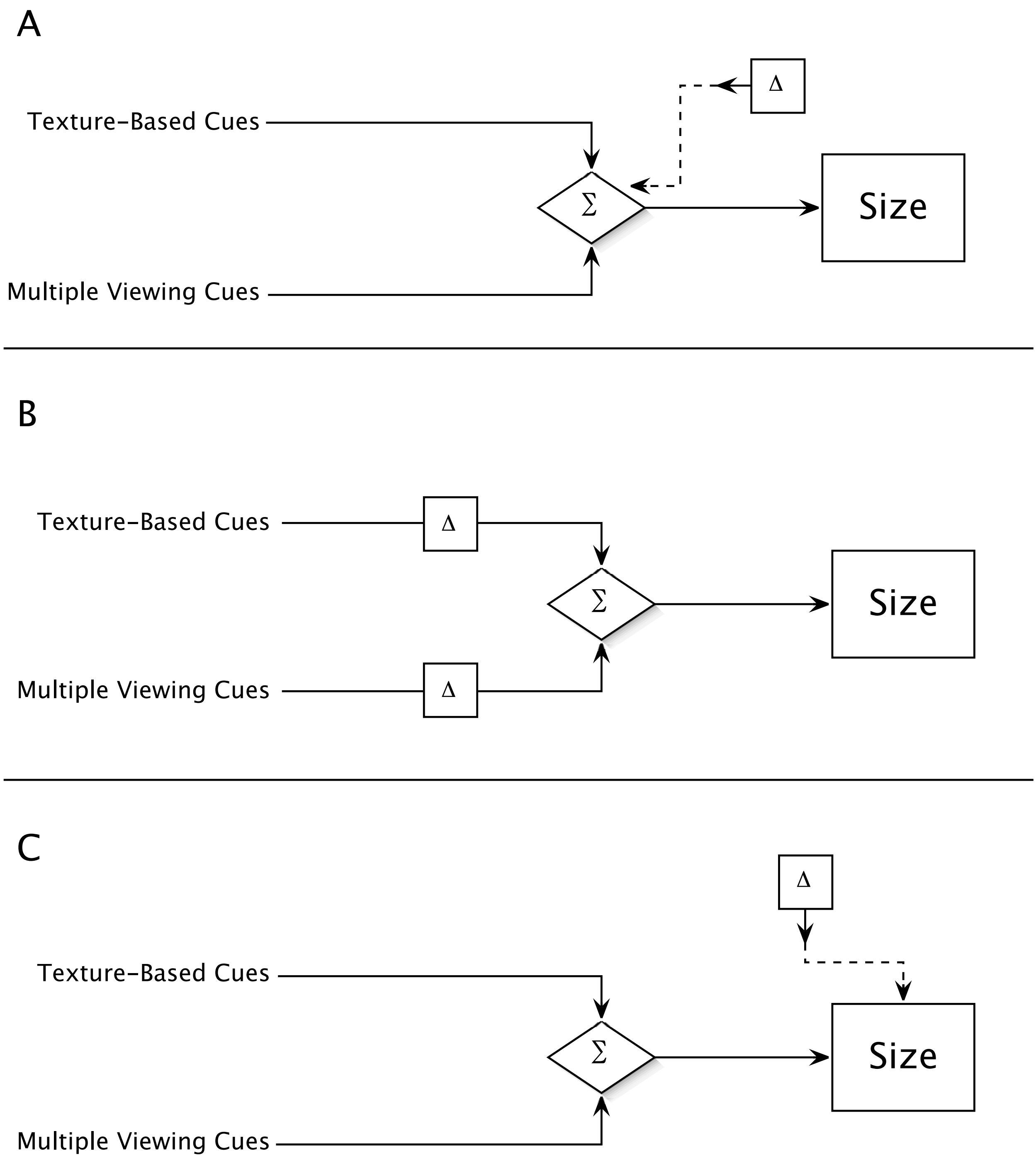

A
Texture-Based Cues
Δ
Σ
Size
Multiple Viewing Cues
B
Texture-Based Cues
Δ
Σ
Size
Multiple Viewing Cues
Δ
C
Δ
Texture-Based Cues
Σ
Size
Multiple Viewing Cues

Fig 1

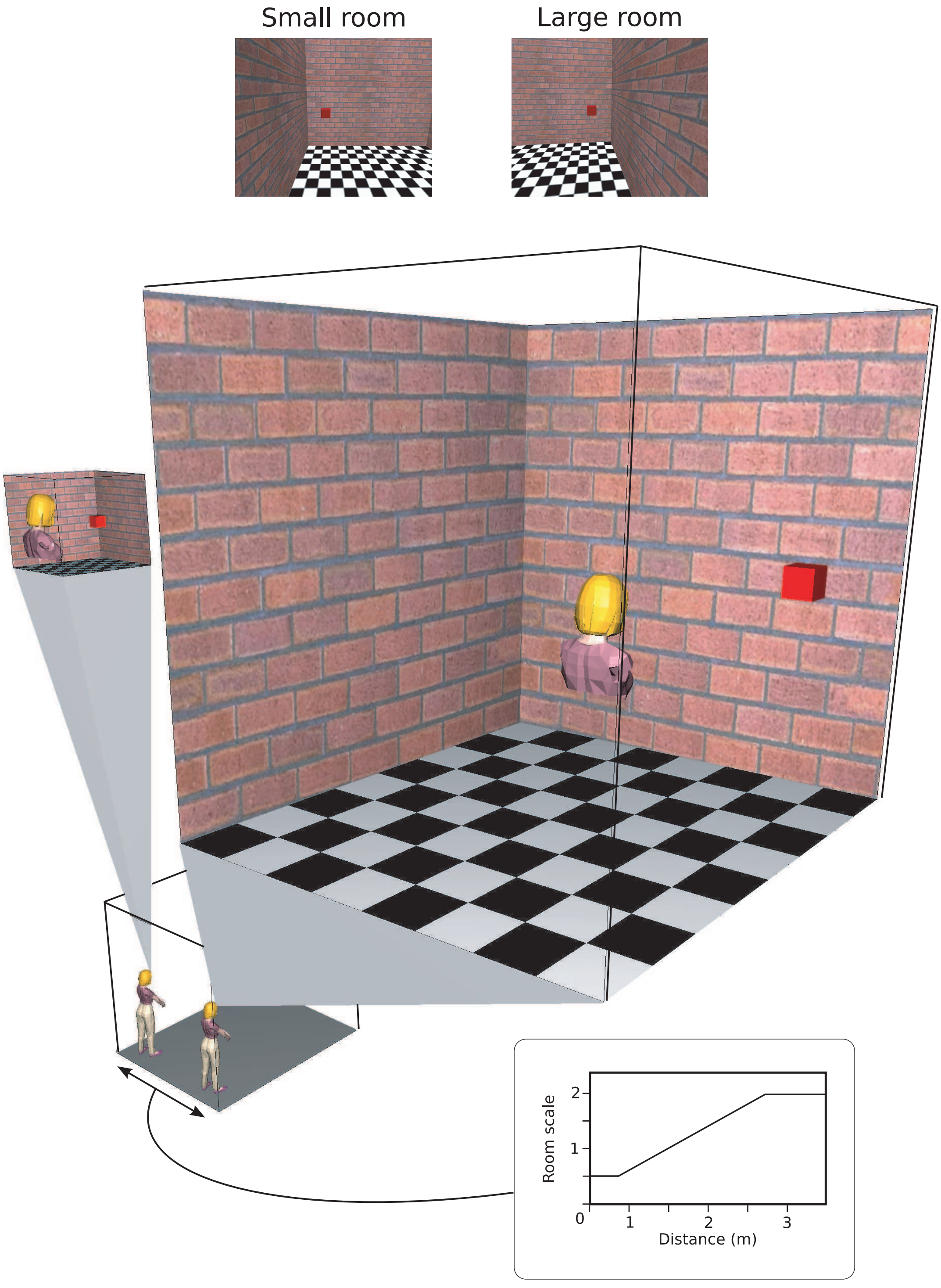
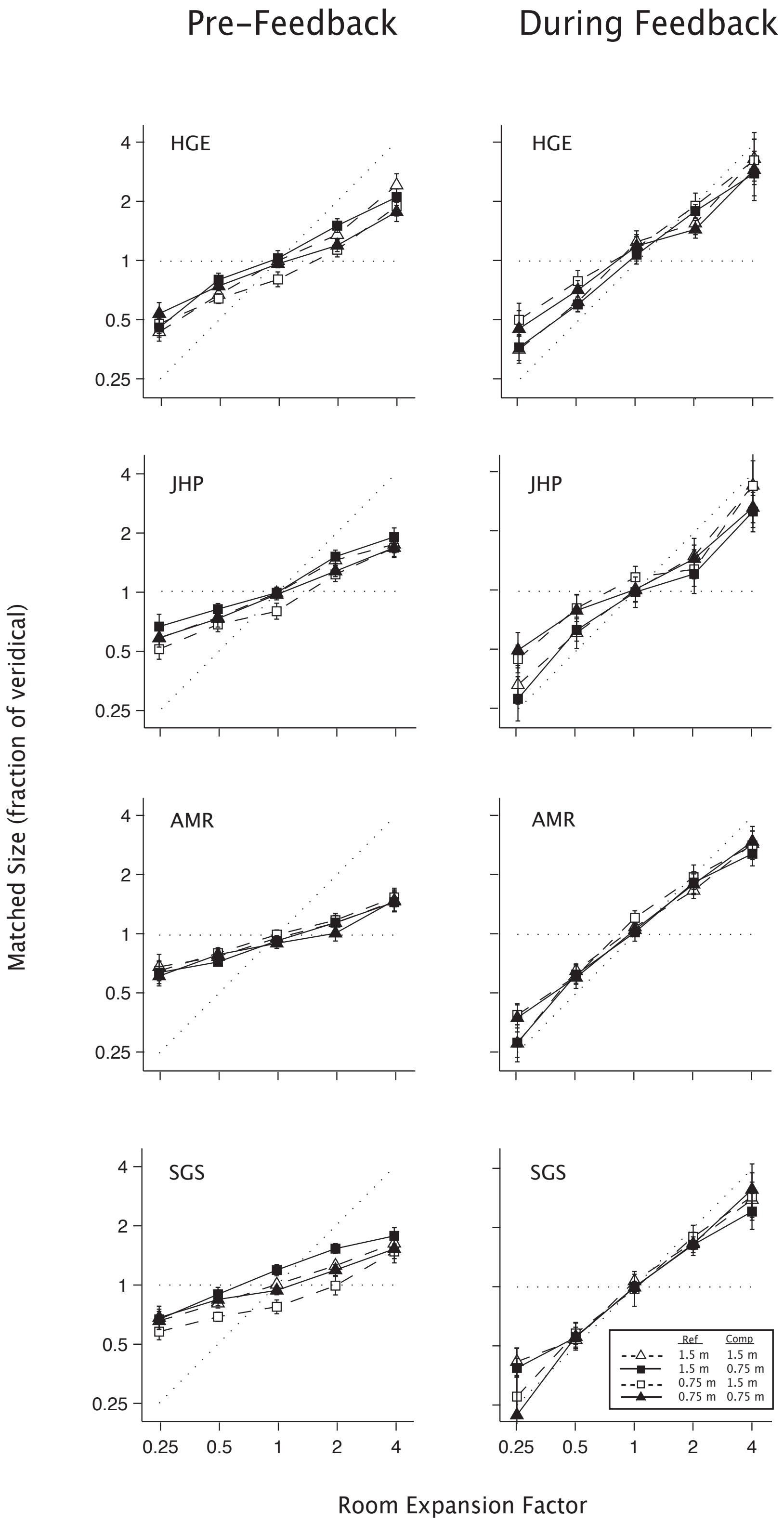


Fig 2



Pre-Feedback
During Feedback
HGE
JHP
AMR
SGS
4
2
1
0.5
0.25
Matched Size (fraction of veridical)
0.25
0.5
1
2
4
Room Expansion Factor
Ref
Comp
1.5 m
1.5 m
1.5 m
0.75 m
0.75 m
1.5 m
0.75 m
0.75 m

Fig 3

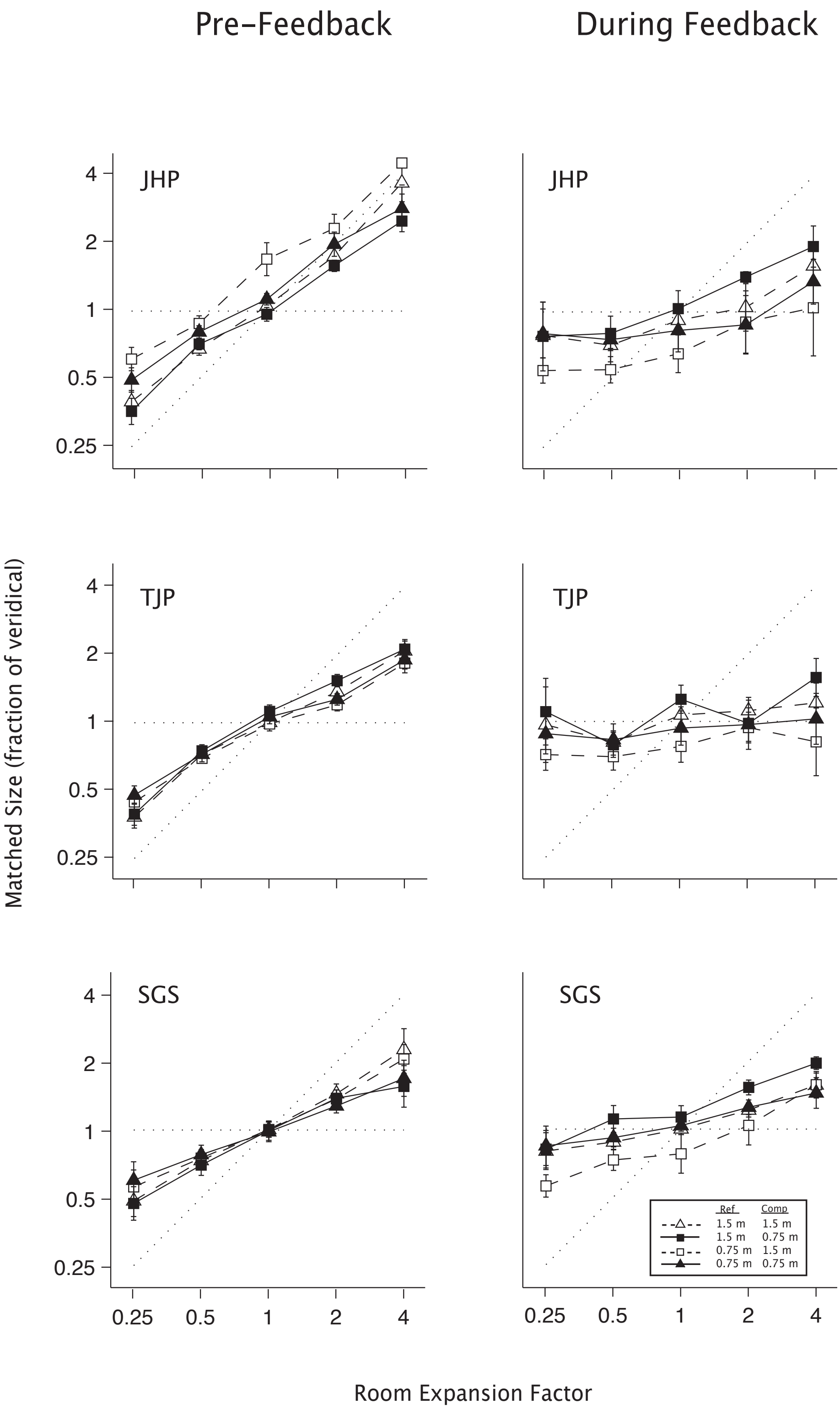
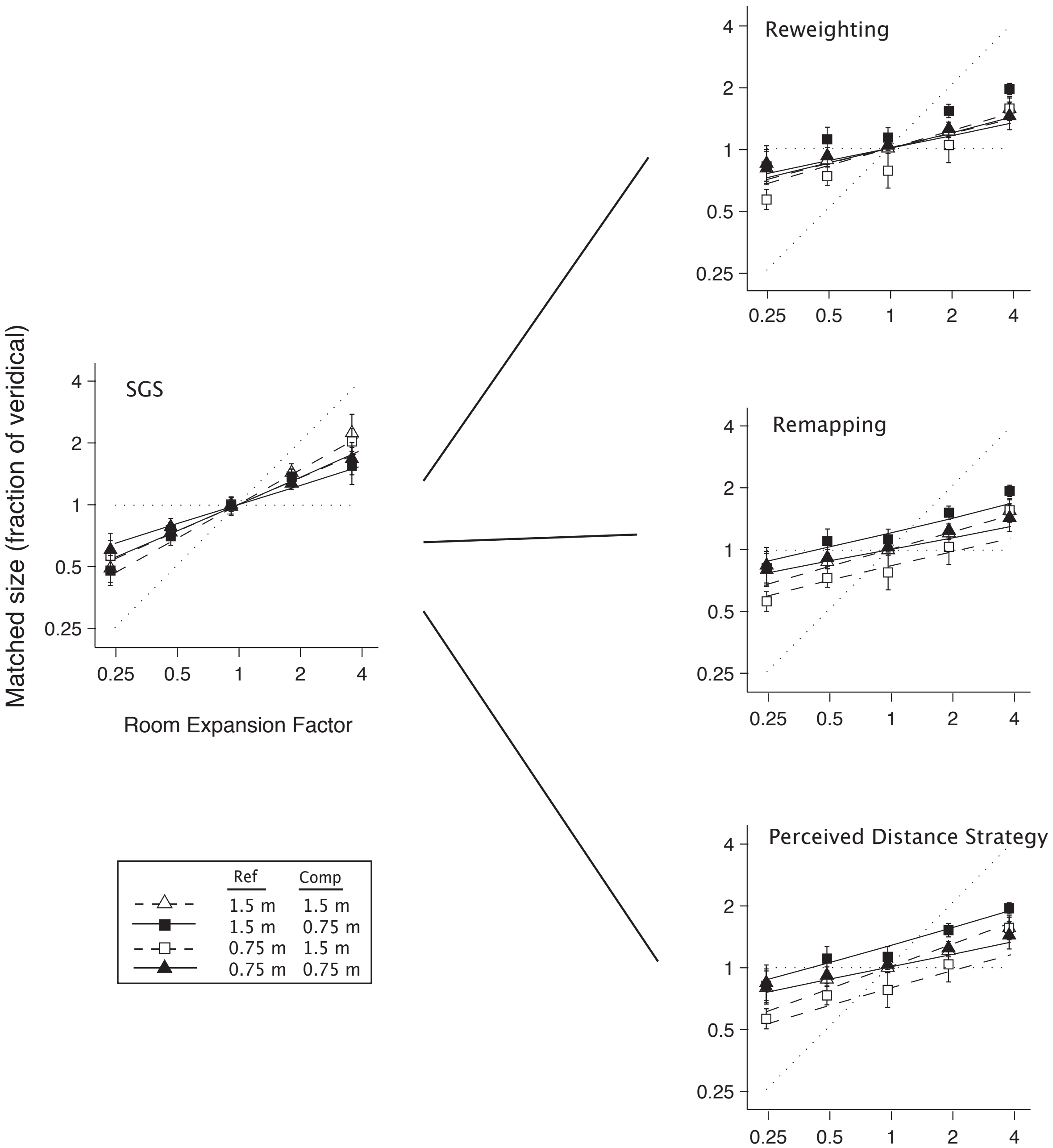

Pre-Feedback
During Feedback
JHP
TJP
SGS
4
2
1
0.5
0.25
0.25
0.5
1
2
4
Matched Size (fraction of veridical)
Room Expansion Factor
Ref
Comp
1.5 m
1.5 m
1.5 m
0.75 m
0.75 m
1.5 m
0.75 m
0.75 m

Fig 4



SGS
Matched size (fraction of veridical)
Room Expansion Factor
0.25
0.5
1
2
4
Ref
Comp
1.5 m 1.5 m
1.5 m 0.75 m
0.75 m 1.5 m
0.75 m 0.75 m
Reweighting
Remapping
Perceived Distance Strategy

Fig 5

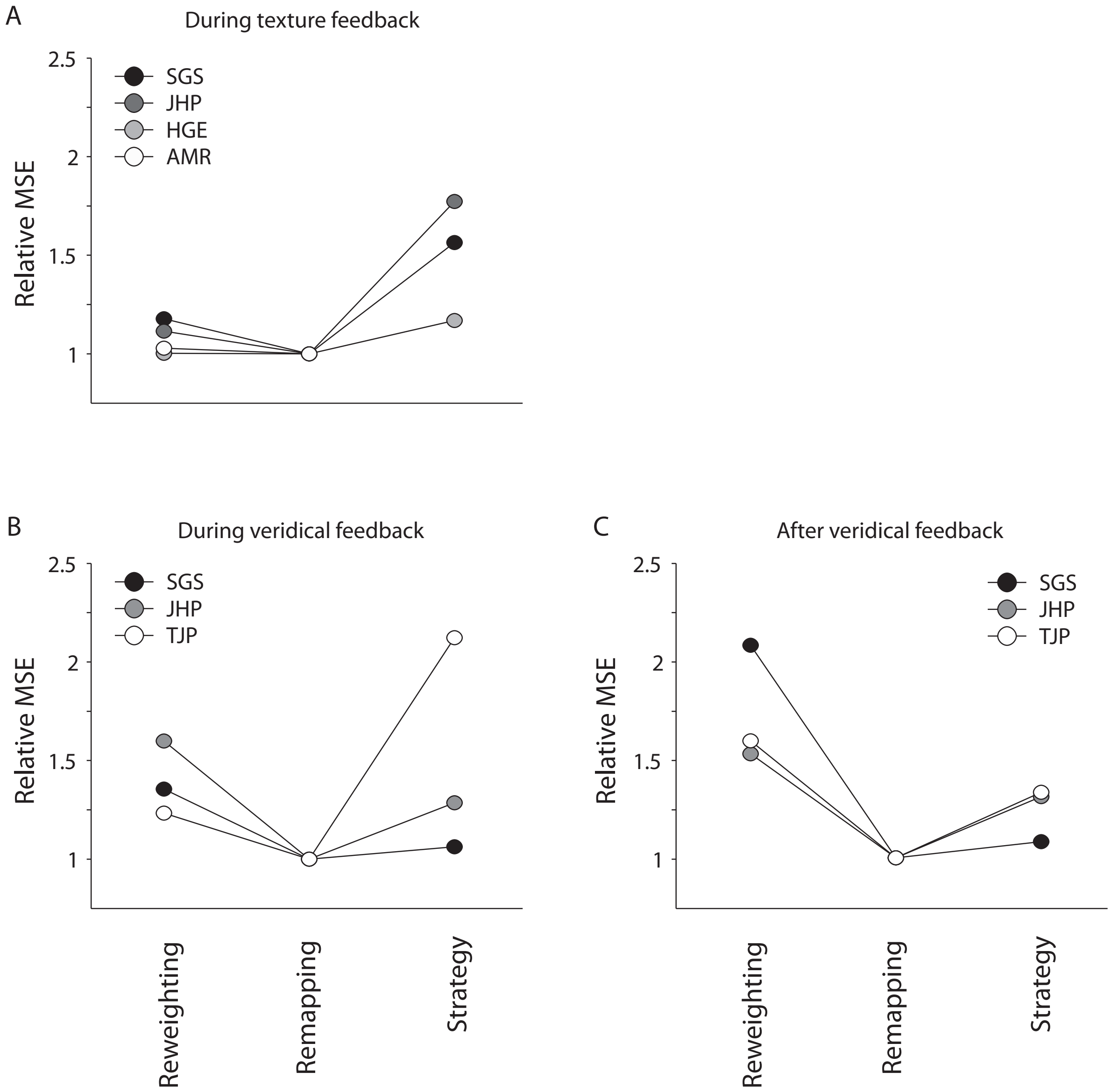

A
During texture feedback
2.5
2
1.5
1
Relative MSE
SGS
JHP
HGE
AMR
B
During veridical feedback
2.5
2
1.5
1
Relative MSE
SGS
JHP
TJP
C
After veridical feedback
2.5
2
1.5
1
Relative MSE
SGS
JHP
TJP
Reweighting
Remapping
Strategy
Reweighting
Remapping
Strategy

Fig 6

		PRE-FEEDBACK		DURING FEEDBACK				
		All Models		Strategy	Re-map		Re-weight	
Ver		**Wp,0.75**	**Wp,1.50**	**k**	**P,0.75**	**P,1.50**	**Wp,0.75**	**Wp,1.50**
	SGS	0.63	0.46	0.33	1.94	2.95	0.77	0.69
	TJP	0.52	0.41	0.55	5.61	8.46	0.97	0.85
	JHP	0.39	0.19	0.54	4.87	12.28	0.82	0.68
Tex		**Wt,0.75**	**Wt,1.50**	**k**	**T,0.75**	**T,1.50**	**Wt,0.75**	**Wt,1.50**
	SGS	0.21	0.29	-0.45	12.21	7.26	0.1	0.31
	AMR	0.7	0.72	-0.49	8.26	9.56	0.26	0.18
	HGE	0.59	0.4	-0.27	1.82	4.06	0.36	0.2
	JHP	0.62	0.58	-0.39	2.62	4.8	0.44	0.17

Table 1