



INTERHEMISPHERIC DEPTH JUDGEMENT

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Abstract—Interhemispheric depth comparisons were studied by requiring subjects to align in depth two textured plates, one presented to the left hemifield and the other to the right. Callosal agenesis subjects and neurologically-normal control subjects adjusted the plates so that they appeared to be at the same distance. Subjects viewed the plates monocularly or binocularly while keeping their head still, moving it side-to-side or moving it up and down. Subjects fixated a target located between the two plates while performing the task. For all subjects, the results showed that the deviations from veridical settings were significantly smaller for the binocular than for the monocular viewing conditions. Moreover, there were no significant differences among the three binocular viewing conditions (horizontal, vertical or no head movement), indicating that neither vertical nor horizontal motion parallax improves the precision of depth judgement when binocular disparity is available. These results further suggest that the precision of interhemispheric comparison for binocular depth is not affected by the absence of the corpus callosum. Looking at the plates monocularly, the control subjects judge the relative depth between the plates more precisely when they moved their head than when they kept it still. These results show that motion parallax is a useful depth cue when relative motion is extracted from different hemifields. Unlike the control subjects, the callosal agenesis subjects did not judge the relative depth between the plates more precisely when they moved their head than when they kept it still. These results show that interhemispheric comparison of depth using relative motion is not possible without the corpus callosum.

INTRODUCTION

THE CORPUS CALLOSUM seems essential for processing depth perception from binocular disparity when largely disparate stimuli presented on each side of the vertical meridian must be compared rapidly. MITCHELL and BLAKEMORE [12] reported that callosotomized patients cannot judge depth between bars presented to different hemifields when the bars were simultaneously exposed for 100 msec. It was concluded that section of the corpus callosum impairs midline coarse stereopsis. This conclusion was supported by JEEVES [5] who found equivalent impairments with callosal agenesis patients. HAMILTON and co-workers [2–4] presented data indicating deficient binocular stereopsis in the vertical meridian region in patients with surgical callosal sections. LASSONDE and co-workers [8, 9] showed that an intact corpus callosum is essential to judge the distance between two objects presented in different hemifields for 120 msec. JEEVES [6] showed that one partial callosotomy patient could judge at a level above chance that a stimulus was in front of a fixation point (crossed disparity) when presented at the midline during 150 to 200 msec whereas the patient could not make his judgement when the stimulus was presented behind the fixation point

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(uncrossed disparity). Another partially-callosotomized patient performed above chance level in both crossed and uncrossed disparity conditions. However, performing the same task, two acallosal subjects performed at chance level for crossed disparity and could not make systematic judgements in the uncrossed disparity condition.

LASSONDE [7] stated that acallosal subjects, as well as commissurotomized and callosotomized patients did not have any difficulties accomplishing a binocular task during prolonged viewing. LASSONDE [7] proposed that callosal agenesis subjects can compare depth between relatively complex visual stimuli presented across hemispheres, but they require more time to accomplish such comparisons than do neurologically normal subjects. Interhemispheric comparison of binocular depth information may thus be possible without the corpus callosum when the stimuli are presented long enough.

Accurate depth judgement with longer presentation time may not be solely attributable to a lengthened processing of depth using binocular disparity. An alternative explanation could be that subjects use monocular depth cues that become apparent with longer presentation duration. For example, observers could have slightly moved their head providing them with motion parallax to judge depth. The corpus callosum may not be essential to compare monocular depth cues interhemispherically, and therefore depth judgements could be performed correctly with longer presentation times. We addressed this question by investigating the role of the corpus callosum for the interhemispheric comparison of depth using both motion parallax and binocular disparity.

In the experiment reported here, subjects could take as much time as they felt necessary to make their judgement. Performance was measured for neurologically normal subjects as well as for callosal agenesis subjects. Two textured plates were presented at different distances in the left and right hemifields. Subjects judged the depth between the plates, and adjusted the plates until they appeared to lie in the same plane. Six different conditions were tested in the experiment: subjects viewed the plates monocularly and binocularly while keeping their head still, moving it side-to-side or moving it up and down.

Different depth cues were available in each of these different conditions. When subjects viewed the stimulus binocularly without moving their head, binocular disparity was available. When the subjects moved their head up and down or side-to-side while viewing the display binocularly, both binocular disparity and vertical or horizontal motion parallax, respectively, were available. When subjects viewed the stimulus monocularly while moving their head up and down or side-to-side, vertical or horizontal motion parallax was available, respectively. Finally in a baseline condition, subjects did not move their head and looked at the display monocularly. Precision of depth judgement was expected to be low in the baseline condition and it was expected to improve when binocular disparity and/or motion parallax were available.

METHOD

Subjects

Three callosal agenesis subjects participated in the experiment. The three acallosal subjects are siblings out of a family of four children from Québec. (1) M.G. is the youngest child. He is a 23-year-old left-handed male. He has a full-scale IQ of 77 on the WISC—R. He finished high school and is presently unemployed. At the age of 4, M.G. was seen by a neurologist because of chronic enuresis, motor incoordination and delayed acquisition of speech. A complete agenesis of the corpus callosum was revealed by a pneumoencephalography (PEG), and later confirmed by a computer tomography (CT scan). (2) L.G. is the second of the four siblings. She is a 30-year-old right-handed woman. She has a full-scale IQ of 78 on the WISC—R. She is married and is gainfully employed. L.G. was first hospitalized at the age of 3 because she suffered from a mild concussion and was hospitalized later because she

showed ataxia and mutism. A complete agenesis of the corpus callosum was revealed by a PEG, and later confirmed by CT scan and by magnetic resonance imaging (MRI). The MRI also showed an intact anterior commissure. (3) S.G. is the oldest sister of M.G. and L.G. She is a 31-year-old, right-handed woman. She has a full-scale IQ of 84 on the revised WAIS. She has finished high school and works presently at a home for the elderly. Apart from the slow acquisition of walking, her development was considered normal. She volunteered to a CT scan only in order to assess the distribution of the congenital abnormality in the family. The examination showed a complete callosal agenesis.

Nine control subjects (four subjects with a mean IQ matched to the mean IQ of the acallosal subjects and five students recruited from the university community) participated in the experiment. All subjects had normal stereoscopic acuity as measured by the TNO [18] test of stereoscopic vision and by the Titmus stereo fly test [17].

Apparatus

See Fig. 1 for an illustration of the apparatus. The apparatus consisted of two equally illuminated vertical plates moving in depth when a rod was rotated. A fine random dot surface was placed on each plate. The random dot density was 871.8 dots per cm^2 , half of the dots being black and the other half being white. Only the inner edges of the

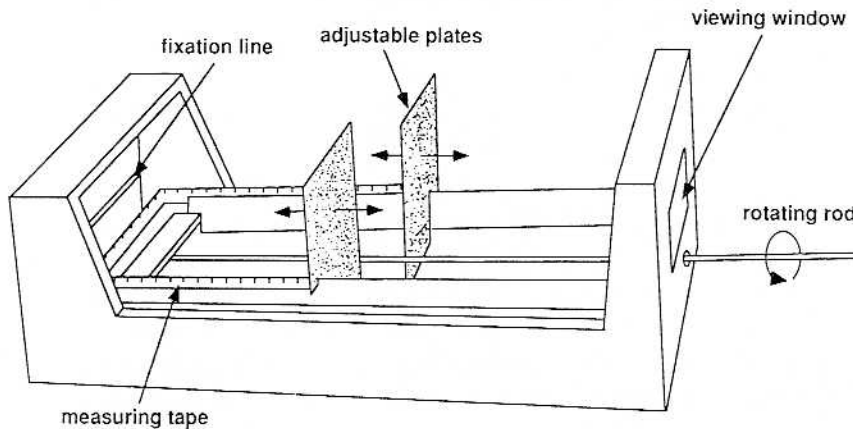


Fig. 1. Schematic illustration of the apparatus. The two plates could be adjusted in depth as the subjects rotated a long rod connected to the apparatus. A measuring tape was connected to the two plates such that a change in the position of the plates would result in a proportional change in the position of the measuring tape.

plates were visible to the subject. The top, bottom and outer edges were occluded by a small opening that restricted the size of the field of view (the visible surface of each plate sustained 3.05 wide and 3.52 high). The small opening was at 28.9 cm in front of the plates when positioned at the same distance such that the top, bottom and outer edges of the plates were always occluded even when subjects moved their head. A thin white horizontal line was placed on the inside back wall of the apparatus to provide a fixation line positioned between the two plates. The horizontal distance between the plates when they were aligned in depth was 0.6 of visual angle. The subject controlled the relative offset in depth of the two plates by rotating a long rod connected to the apparatus. The plates were viewed from a distance of 95 cm at eye level with the fixation line in the center of the visual field. The relative position of the plates was given on a measuring tape mounted on the apparatus. A head restraint was mounted on the viewing chair when subjects kept their head still and when they moved up and down. The head restraint allowed head rotation only around the axis passing through the subject's ears.

The monocular depth cues available in the display were reduced maximally — the plates were equally illuminated and the distal size of the random dots on the plates remained constant at all relative distances. The difference in relative proximal size of the random dots was a monocular cue that could not be eliminated in this experiment. However, this depth cue was kept constant across all experimental conditions.

Procedure

Six experimental conditions were used. For three conditions, subjects viewed the stimuli monocularly when their head (1) moved side-to-side, (2) moved up and down or (3) remained still. For the other three conditions, subjects viewed the stimuli binocularly when their head (1) moved side-to-side, (2) moved up and down or (3) remained still. When head movement was required, subjects moved their head at a speed and extent that felt comfortable. However,

all subjects were instructed to move the head through a distance of at least 6 cm up and down or side-to-side. Any trials in which subjects did not move their head to a large enough extent were discarded and repeated at the end of the series. Subjects used their preferred eye when they looked at the display monocularly. In all conditions, they manually varied the relative distance between the two plates until the two plates appeared to lie in the same plane. The deviations from veridical settings were recorded.

Subjects were instructed to maintain fixation on a stationary horizontal line placed between the two plates while performing the task. The experimenter observed the subject's eye movements during the task to verify that fixation was maintained. An eye movement corresponding to about 1° of visual angle could be detected reliably. Trials in which fixation was not maintained were discarded and repeated at the end of the series. In all conditions, subjects could take as much time as they felt necessary to make the adjustment. There were 26 depth adjustments for each condition. For one half of the adjustments, subjects performed the task with their left hand, for the other half, they performed the task with their right hand. The order of starting hand was counterbalanced across subjects and across conditions for each subject. For one half of the adjustments, the left plate was placed nearer to the subject, and for the other half, the right plate. The choice of the nearest starting plate was randomized across trials within a condition. The order of the conditions was randomized among subjects except for the starting condition which was counterbalanced across subjects.

In all conditions, assuming good fixation and little or no binocular overlap, the depth information from the left and right plates had to be compared across the hemispheres in order to make the adjustments. Consequently, the task required commissural connections.

RESULTS

The means and standard deviations were calculated for each subject in each condition. The root mean squared deviations (RMSD) were computed from the means and standard deviations. The RMSD were used to perform the analysis since it reflects both the variability of the depth setting and the deviation between the mean setting and the true value. The RMSD for each condition and for the control and callosal agenesis subjects are illustrated in Fig. 2. The average RMSD were transformed using a natural logarithmic function and were analyzed in three separate analyses. We first conducted an analysis in which results for binocular and monocular viewing conditions were analyzed together, then we performed separate analyses for the binocular viewing conditions and for the monocular viewing conditions.

Binocular vs monocular viewing conditions

A three-way analysis of variance was performed with Group (three levels: students, IQ matched and callosal agenesis) as a between-subject variable, and Head Condition (three levels: up and down movement, side-to-side movement, and no movement) and Viewing Condition (two levels: monocular and binocular) as repeated measurements. The triple interaction $\text{Group} \times \text{Head Conditions} \times \text{Viewing Conditions}$ was significant [$F(4, 18) = 3.38, P < 0.05$]. In order to explore this interaction, separate analyses were performed for the binocular and monocular viewing conditions. The results of the two groups of control subjects (students and IQ matched subjects) did not differ. Therefore, in the following two analyses, the factor Group has only two levels: control subjects including both the students and IQ matched, and the callosal agenesis subjects.

Binocular viewing conditions

A two-way analysis of variance was performed with Group as a between-subject variable (two levels: control and callosal agenesis), and Head Condition (three levels: up and down movement, side-to-side movement, and no movement) as a repeated measurement. Neither the double interaction [$F(2, 20) = 2.85, P > 0.05$] or the main effects were significant

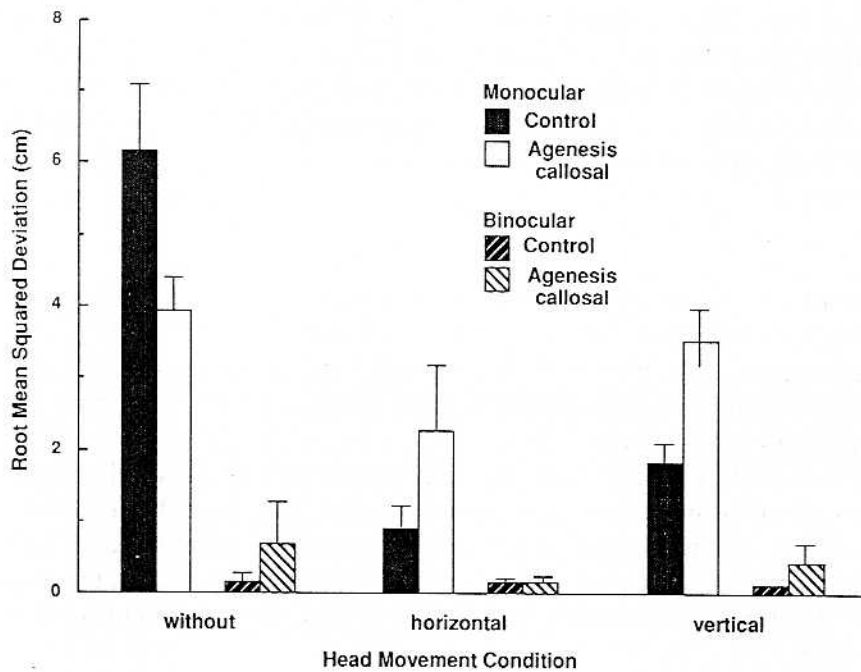


Fig. 2. Average root mean squared deviation in centimeters for callosal agenesis subjects and control subjects in the binocular and monocular viewing conditions.

[$F(1, 10) = 1.57, P > 0.05$ for Group and $F(2, 20) = 2.19, P > 0.05$ for Head Condition]. For all subjects, when the plates were viewed binocularly, the average deviation from the veridical settings did not differ significantly among the conditions in which the head was kept still, moved up and down or side-to-side. These results are important because they indicate that when binocular disparity is available, neither vertical nor horizontal motion parallax improves the precision of depth judgement. The average deviation from the veridical settings did not differ significantly between the control subjects and the callosal agenesis subjects. These results indicate that when acallosal subjects are allowed to take as much time as needed to judge the relative distance between information presented binocularly to each hemisphere, the precision of their depth judgements is not degraded by the absence of the corpus callosum.

Monocular viewing conditions

A two-way analysis of variance was performed with Group as a between-subject variable (two levels: control and callosal agenesis), and Head Condition (three levels: up and down movement, side-to-side movement, and no movement) as repeated measurements. The Group \times Head Condition interaction was significant [$F(2, 20) = 4.43, P < 0.05$]. Tukey HSD tests were performed to compare the results between different head movement conditions. For the control subjects, the deviation from the veridical settings was larger when the subjects did not move their head than when they moved it up and down (HSD, $q_{(1, 20)} = 7.02, P < 0.01$). These results suggest that vertical motion parallax provides depth information even when relative motion is presented to different hemifields. However, monocular depth judgement based on vertical parallax was less precise than that based on

horizontal parallax. The average deviation was larger when subjects moved their head up and down than when they moved it side-to-side (HSD, $q_{(1,20)} = 5.07$, $P < 0.01$).

For the callosal agenesis subjects, on the other hand, there were no significant differences among the three conditions, suggesting that relative motion cannot be compared across hemispheres in the absence of the corpus callosum.

CONCLUSIONS

For the normal subjects, neither vertical nor horizontal motion parallax improved the precision of binocular depth perception. However, both horizontal and vertical motion parallax did improve the precision of monocular depth perception. The precision of monocular depth judgement was lower when subjects moved their head up and down than when they moved it side-to-side.

We cannot conclude from our results that horizontal motion parallax alone provides more precise depth information than vertical motion parallax since more depth cues were present on the horizontal condition than in the vertical condition. In particular, when subjects moved their head side-to-side, the width of the gap between the two plates changed when they were at different depths, which may have provided depth information in addition to motion parallax.

Despite the fact that these additional cues may have improved the precision of horizontal parallax compared to vertical parallax in our experiment, we do not think that these cues are the sole contributors to the better precision observed in the horizontal conditions. There is evidence of an anisotropy in the precision of depth judgements based on parallax when these additional cues are removed [16, 19]. In these experiments, judgements did not involve interhemispheric comparisons and the relative motion was always a shearing motion along the boundary between the two surfaces so that there were no additional cues such as accretion or deletion. Yet, horizontal parallax was consistently more precise than vertical parallax.

The precision of the acallosals for making binocular depth judgement was not statistically different from that observed in neurologically normal subjects. These results are consistent with the findings of LASSONDE [7] who showed that callosal agenesis subjects can perform binocular interhemispheric depth judgements when the stimuli were presented for a period longer than 200 msec. However, they are different from the results of JEEVES [6] and of LASSONDE *et al.* [8] showing that subjects without a corpus callosum could not perform binocular interhemispheric depth judgements when the stimuli were presented for 150 msec and for 120 msec, respectively. They are also inconsistent with the results of HAMILTON and co-workers [2-4] and MITCHELL and BLAKEMORE [12], showing that binocular stereopsis is impaired in the veridical meridian region for patients who had their corpus callosum sectioned surgically.

The discrepancy between the results may be due to the difference in the intrahemispheric information available in the task. In our task, each plate extended far enough in the pericentral field such that each hemisphere might have had enough information to extract the absolute distance of each plate. Once the absolute distance of each plate was extracted intrahemispherically, the relative distance between the two plates could be inferred interhemispherically. This is unlike the experiments of HAMILTON and co-workers [2-4], JEEVES [6], LASSONDE *et al.* [8, 9] and MITCHELL and BLAKEMORE [12], in which the information available to only one hemisphere could not contribute to extraction of distance.

However, it is also possible that information provided to each hemisphere was insufficient to provide an accurate judgement of absolute distance in our experiment. While some precautions were taken to reduce cues of absolute distance, observers were not specifically asked to report the absolute distance of each plate.

A seemingly apparent discrepancy between our results and those of others may alternately be due to the difference in exposure time. Our stimuli were presented as long as required by the observers, whereas in the other experiments they were presented for less than 200 msec (e.g. Refs [6], [9], and [12]).

Our results show that binocular information can be compared interhemispherically. These results suggest that the brain of acallosal patients may be so organized that extra-callosal structures can mediate the comparison of information emanating from each hemisphere. We know that one of our callosal agenesis subjects has an intact anterior commissure, but we do not know whether this is the case with the other two acallosal subjects. It is probable that their anterior commissure is also present. The work of LOESER and ALVORD [11] provides evidence that the anterior commissure is usually present when the corpus callosum is absent. The recent MRI studies of RAUCH and JINKINS [14] also indicate that the anterior commissure is generally present in the acallosal brain. Thus the anterior commissure could provide the substrate for binocular interhemispheric integration in the absence of the corpus callosum. This could be a result of its connection with inferotemporal (IT) cortex, an area thought by COWEY [1] and others [10, 13] to be involved with binocular depth perception.

Although binocular depth information can be compared between the two hemifields in the absence of the callosum, monocular depth information from parallax cannot. Neither horizontal nor vertical parallax improved depth judgements significantly when relative motion was presented to different hemifields and the corpus callosum was absent. These results show that the corpus callosum plays an essential role in depth perception using relative motion. These results suggest that motion parallax may rely on different cortical mechanisms than binocular disparity such as movement analysis possibly carried out by the middle temporal (MT) area, at least in monkeys. Interestingly, MT is not interconnected by the anterior commissure. Therefore, the presence of the anterior commissure in our acallosal subjects would not have been useful to compare relative motion interhemispherically.

Finally, RAMACHANDRAN *et al.* [15] showed that the corpus callosum is not required to judge the temporal order of flashing stimuli producing apparent motion. In their experiment, the motion signals were not sent to each hemisphere, whereas in our experiment, motion signals were provided intrahemispherically. Therefore, the cortical mechanism involved in these two experiments may well be different.

One alternative explanation for the lack of improvement in the precision of depth judgements with head movement for the callosal agenesis subjects is that they do not use motion parallax at all, whether the relative motion is compared interhemispherically or intrahemispherically. We tested this possibility by running one acallosal subject (SG) with an intrahemispheric presentation of the two plates (fixating on one plate so that parts of both plates fell in one hemifield) under a condition in which she kept her head still and under a condition in which she moved it up and down. Her results showed that the average deviation from veridical settings was larger when she kept her head still than when she moved it up and down. Thus, vertical motion parallax does seem to be a useful depth cue for callosal agenesis subjects when the relative motion is compared within one hemisphere.

This finding allows us to conclude that the corpus callosum is an essential structure for

comparing depth using relative motion across hemispheres. These results are the first experimental attempts to study the role of the corpus callosum in the processing of motion parallax. Other results collected with callosotomized patients should provide further information about this issue.

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