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Visual proprioceptive control of standing in human infants*

DAVID N. LEE† and ERIC ARONSON
University of Edinburgh, Edinburgh, EH8 9TJ, Scotland

Human infants learning to stand use visual proprioceptive information about body sway in order to maintain stable posture. Moreover, the visual proprioceptive information is more potent than the nonvisual. This is shown by an experiment in which infants were caused to sway and even fall forward or backward in response to appropriate visual stimulation.

According to the classical view formulated by Sherrington (1906), the receptor systems of the body may be classified as exteroceptors, proprioceptors, or interoceptors. It is assumed that each receptor system subserves a *unique* function, exteroceptive, proprioceptive, or interoceptive.

J. J. Gibson (1966) has questioned this assumption. He argues that if exteroception is defined to be the obtaining of information about events extrinsic to the organism, and proprioception the obtaining of information by the organism about its own actions, then vision, in particular, is not only exteroceptive, as is classically assumed, but is also proprioceptive.

The proprioceptive function of vision seems apparent enough in driving a vehicle; the driver clearly uses visual information about his and the vehicle's movement to guide the vehicle. Does vision also function proprioceptively in the control of more basic activities? The activity we chose to study is standing.

Standing involves continuous compensatory adjustments of the musculature. It is a process of feedback control. Any sway of the body away from the vertical has to be registered and compensatory muscular adjustments made else balance is lost.

The classical view is that the information about body sway that is used in standing comes from receptors ("proprioceptors," in classical terminology) in the vestibular canals and in the joints and muscles, particularly of the ankles and hips (Eldred, 1960). We may refer to these as *mechanoreceptors*, since they are responsive to mechanical force.

The question of whether vision too functions proprioceptively in standing does not seem to have been considered. There is, however, some suggestive evidence in the literature. For example, Wood (1895) reported that people standing on a stationary "haunted swing" while the surrounding room was rotated about a horizontal axis tended to be unsteady. Also, when normal vision is impaired by imposing an impoverished or unstable visual field or by blindfolding a person, body sway tends to increase (Edwards, 1946; Witkin & Wapner, 1950). While the available evidence is suggestive, it is not conclusive. For example, the increase in body sway with impaired vision may simply be due to increased tension in the person, as Edwards (1946) in fact suggested. However, if it could be shown that balance can be disturbed by visual stimulation *in a direction specific to that stimulation*, this would furnish direct evidence that vision functions proprioceptively in standing.

Visual information about movement of the body relative to the environment is available in the optic array at the eye. When the head is moving, as when the body is swaying, there are certain properties of the optic flow pattern at the eye that specify that movement (Gibson, 1958; Lee, 1973). The question is whether or not this visual proprioceptive information is actually used in maintaining balance.

We chose to use as Ss human infants with limited experience in standing and walking. There were several reasons for this. First, the standing posture in humans is manifestly less stable in the early stages of its development; we therefore expected that any effect on balance that our experimental procedure might produce would be more pronounced, and so more easily measured, in infants than in adults. Second, the naivete of infants should militate against their inadvertently complying with the E's expectations. Finally, the present study is part of an ongoing series using both infant and adult Ss, and here we were particularly interested in determining whether or not, and if so to what extent, visual proprioception is an integral part of the postural control system in the early stages of development.

METHOD

The standing S was presented, for short periods, either with an optic flow pattern similar to what normally would accompany backward body sway or with the opposite. This was done by

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†Requests for reprints should be addressed to D. N. Lee, Department of Psychology, University of Edinburgh, Edinburgh EH8 9TJ, Scotland.

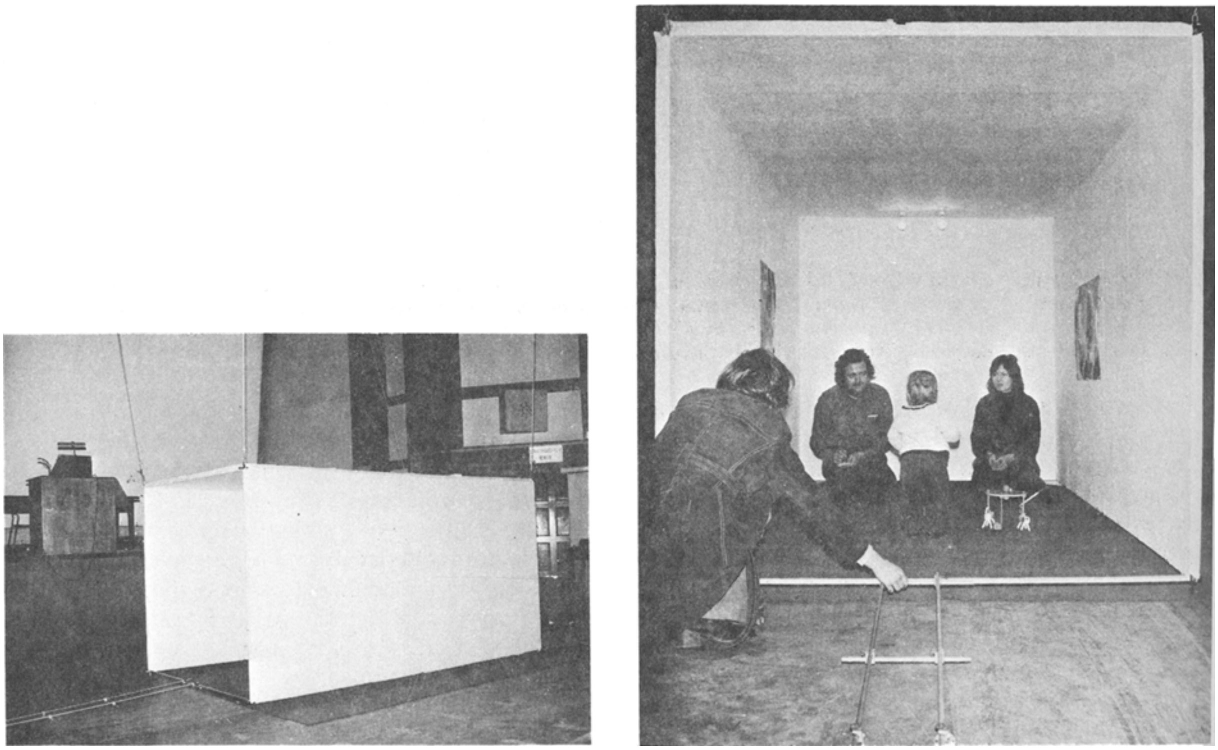

Fig. 1. The moving room and the experimental situation just prior to moving the room past the infant S.

moving an experimental "room," comprising three walls and a ceiling, forward or backward past the S standing on a stationary floor (see Fig. 1). The "room," 3.6 m long x 1.8 m wide x 2 m high, was constructed of rigid white polystyrene on a metal frame and was open at one end. It was suspended in a horizontal position by four ropes, one to each upper corner, from the 7.2-m-high ceiling of a lecture theater, so that the bottoms of the walls were about 1 cm above the floor of the theater. The room could be swung noiselessly along its length from one lockable position 47 cm to one side of its stable hanging position to another lockable position the same distance the other side. The time for such a swing was about 2.5 sec, and the motion was approximately simple harmonic, with a maximum velocity, in the middle, of about 40 cm/sec. During its swing, the room remained horizontal and the variation in its height above the floor was only about 4 cm. The room was lit by two 60-W bulbs rigidly attached to its ceiling 30 cm from the closed end. Pictures were stuck on the walls to make the room more interesting.

Consider a S standing still in the room facing the closed end. Motion of the room forward, in the direction he is facing, will produce optic flow patterns at his eyes that are similar, except for the lower sector corresponding to the stationary floor, to what would normally accompany backward sway of his body (see Fig. 2). If he uses visual proprioception in maintaining posture, the visual information for backward body sway should induce muscular action to produce a compensatory forward torque about his feet. If this torque were maintained, he would sway forward until he lost balance. However, once he was swaying forward, a conflict between visual and mechanical proprioception should arise; vision would be still specifying backward body sway and so calling for the maintenance of the forward torque, while his mechanoreceptors should be registering the actual forward sway of his body and so calling for a compensatory backward torque. The converse holds for backward motion of the room. Thus, any abnormal sway or loss of balance in the direction the room is moved would indicate dominance of the visual proprioceptive information over the mechanical proprioceptive information.

Subjects

Seven normal healthy human infants served as Ss in the experiment. They ranged in age from 13 to 16 months, and in walking experience, according to their mothers' accounts, from 1 to 22 weeks (see Table 2).

Procedure

At the start of a session, the experimental room was stationary at one of its two lockable positions. (Four of the Ss started the experiment with the room in one position, and the other three with it in the other position.) The infant S was then brought into the room by its mother and an E, who remained there throughout the experiment. They sat on the carpeted floor at the closed end of the room, facing the open end, while the infant was free to move around in the room and play with toys for about 3 min. If necessary, the infant was encouraged to stand and/or walk during this 3-min pretest period, and any falls were recorded, providing a measure of the infant's normal stability. As throughout the whole experiment, three independent records were taken: one by the E inside the room, one by an E outside the room, and one by a TV camera directed through the open end of the room, the video record subsequently being analyzed by a third person. On the great majority of trials there was consensus among the three indepenent records, and when there was not consensus, a majority criterion was applied.

The main experiment followed immediately after the pretest and comprised up to 20 trials. Before starting a trial, the S was required to be standing still, unsupported, facing the closed end of the room. Normally, the E simply waited until the S was in this position before starting a trial; on occasion, the S was manoeuvred into the position. On a few trials, the S started to walk just as the trial was starting, and when this lead to uncertainty in categorizing his behavioral response, a "zero" response was recorded (see Table 1).

On each trial, the room was swung by an E behind the S from one stationary locked position to the other. It was swung back again on the next trial, and so on. At the start of a trial, the S was usually standing near the middle of the room, and during no trial was the closed end of the room ever closer to him than 1 m. The interval between trials was usually 30-60 sec. Whenever possible, a 3-min posttest, similar in form to the pretest, was given immediately after the main experiment.

RESULTS

The behavioral response to a swing of the room was categorized according to the scheme shown in Table 1. Unless there was a clear change in posture during the 2.5 sec that the room was moving, a "zero" response was recorded. The experimental results and S data are presented in Table 2. Three of the Ss (2, 4, and 5) became very distressed during the main part of the experiment, and the experiment had to be curtailed. Since these Ss had appeared quite content during the pretest period, their distress was presumably due to their instability when the room was moved. The remaining four Ss, however, showed no undue distress throughout the experiment, though their instability during trials was just as marked. The experiment had to be stopped after the 10th trial for one of these Ss (No. 1) due to the S's becoming sleepy.

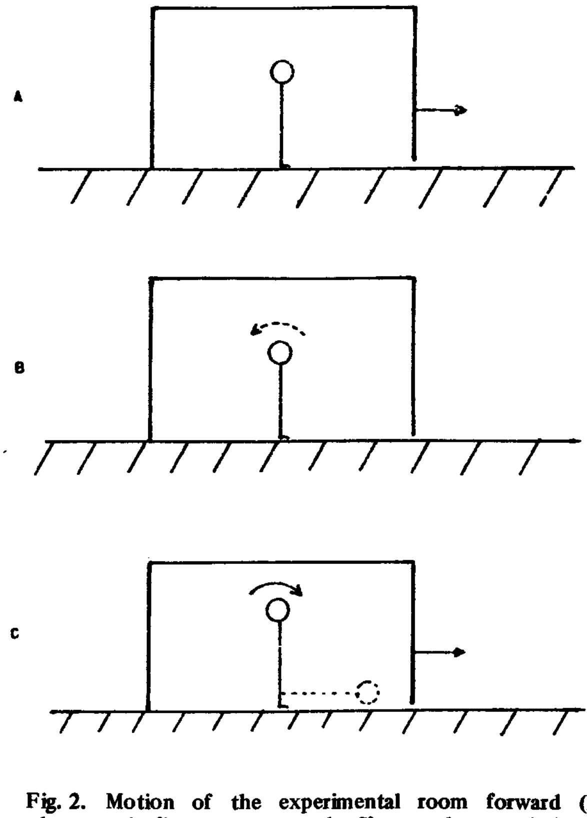

Fig. 2. Motion of the experimental room forward (A) produces optic flow patterns at the S's eyes that are similar to what would normally accompany backward body sway (B). Postural adjustment to counteract this apparent backward body sway would result in the S's swaying forward and possibly losing balance (C). The opposite holds for backward motion of the room.

Table 1
The Response Categories Used in the Experiment

Category	Code	Behavior
	+++	Initial sway WR and fall WR
Positive	++	Initial sway WR and stagger WR
	+	Initial sway WR
Mixed	−+	Initial sway OR and stagger or fall WR
	+−	Initial sway WR and stagger or fall OR
	−−−	Initial sway OR and fall OR
Negative	−−	Initial sway OR and stagger OR
	−	Initial sway OR
Zero	0	No abnormal sway

Note–"WR"/"OR" (with room/opposite room) mean in the same/opposite direction as the room was moving.

As argued above, a "positive" response (i.e., a sway, stagger, or fall in the direction the room was moved) would indicate that the S was making compensatory adjustment to his posture in accord with the visual proprioceptive information about body sway produced by the motion of the room. The results (Table 2) indicate that such occurred on the great majority of trials, frequently resulting in loss of balance. Overall, 82% of responses were positive–26% sway, 23% stagger, and 33% fall.

We discount two other possible explanations of the results. First, it might be argued that a backward positive response may simply be an avoidance response to the "looming" of the room. However, this would leave unexplained the *forward* positive responses that occurred when the visible end of the room was moved *away* from the S. Secondly, the draught produced by the motion of the room, while consistent in direction with a positive response, was so slight as to make it a most unlikely cause of such a response, particularly one involving loss of balance.

DISCUSSION

It is, therefore, evident that an infant learning to stand uses visual proprioception in maintaining his posture. Furthermore, since the conflict created in our experiment between mechanical and visual proprioception was, in the majority of cases, dominated by the visual, it may be concluded that, for infants at least, visual proprioceptive information is more potent than mechanical proprioceptive information. If one compares the mechanical and visual proprioceptive information likely to be available to an infant, it is, indeed, not surprising that visual proprioception should play a dominant role in the maintenance of standing.

The most sensitive mechanical proprioceptive information for standing is probably that from the mechanoreceptors in the ankle joints and associated muscles, and those in the soles of the feet. The vestibular system appears to be insensitive to fine body movements

Table 2
Subject Data and Experimental Results

	S 1	S 2	S 3	S 4	S 5	S 6	S 7
Weeks walking	1	4	8	8	9	10	22
Age (months : weeks)	16 : 0	15 : 3	14 : 1	15 : 2	14 : 3	13 : 1	16 : 2
Sex	F	M	F	F	F	F	M
Number falls in 3-min pretest	0	0	0	1f	0	0	0
Number falls in 3-min posttest			1b	0		0	0
Main Experiment							
Number trials	10	12	20	6	4	20	20
Number (+++) responses forward : backward	3 : 3	0 : 5	4 : 4	0 : 1	1 : 1	5 : 1	0 : 2
Number (++) responses forward : backward	0 : 0	2 : 1	1 : 1	1 : 1	0 : 0	4 : 1	3 : 6
Number (+) responses forward : backward	1 : 2	3 : 0	3 : 4	0 : 0	1 : 0	0 : 5	3 : 2
Total number positive responses	9	11	17	3	3	16	16
Number mixed responses	0	0	0	0	0	0	0
Number negative responses	0	0	1	0	1	0	0
Number zero responses	1	1	2	3	0	4	4

(Birren, 1945). However, for an infant, these mechanoreceptors are necessarily sensitive to the growth changes in lengths and weights of his body parts, and so probably can be kept finely calibrated only by means of continual practice in some controlled activity that utilizes them. But few, if any, of the activities that an infant engages in before standing are of this type, and so when he begins to stand, his mechanical proprioceptive system will afford only rudimentary and imprecise information, being essentially still in embryonic condition (see Trevarthen, 1973, for a discussion of behavioral embryology).

The infant's visual proprioceptive system, on the other hand, should be more developed and considerably more reliable. There seems no reason why its calibration should be affected by skeletal growth, and the eye is quite close to its final form. Moreover, the infant will have had much visual proprioceptive feedback from his prestanding activities, e.g., sitting, rocking, crawling, and being carried.

In some more recent experiments, to be reported in detail elsewhere, it has been found that adults show similar behavior to that of infants in the experimental room. Body sway is generally greater when the room is moving forward and back than when it is stationary or when the eyes are closed, the body sway tending to be in phase with the motion of the room. However, the effect on balance of the motion of the room is not as pronounced as in infants, indicating that an adult has a more finely tuned mechanical proprioceptive system.

We would suggest, therefore, that when an infant is learning to stand he relies heavily on visual proprioception, and only later, as a result of practice, does his mechanical proprioceptive system approach the same degree of efficiency as his visual proprioceptive system.

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