Perception, 2001, volume 30, pages 167 – 176

DOI:10.1068/p2789

Development of infants' sensitivity to surface contour information for spatial layout

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Received 19 May 1998, in revised form 17 May 2000

Abstract. The development of sensitivity to a recently discovered static-monocular depth cue to surface shape, surface contours, was investigated. Twenty infants in each of three age groups (5, $5\frac{1}{2}$, and 7 months) viewed a display that creates an illusion, for adult viewers, that what is in fact a frontoparallel cylinder is slanted away in depth, so that one end appears closer than the other. Preferential reaching was recorded in both monocular and binocular conditions. More reaching to the apparently closer end in the monocular than in the binocular condition is evidence of sensitivity. Infants aged 7 months responded to surface contour information, but infants aged 5 and $5\frac{1}{2}$ months did not. In a control study, twenty 5-month-old infants reached consistently for the closer ends of cylinders that were actually rotated in depth. As findings with other static-monocular depth information suggest, infants' sensitivity to surface contour information appears to develop at approximately 6 months.

1 Introduction

Attempts to describe the information that make static-monocular perception of three-dimensional space possible have a long history. In the 15th century Leonardo da Vinci catalogued the depth cues, such as cast and attached shadows, and linear and aerial perspective, that a painter could use to create the experience of a scene in depth on a flat canvas (Richter 1970). In the centuries that followed, the list of cues grew to include texture gradients, relative size, height in the picture plane, familiar size, and interposition (see Goldstein 1996). To understand how spatial perception takes place, we must first describe the information to which we are sensitive. Therefore, the discovery of a new source of information for spatial layout is an important contribution to the science of perception. Stevens (1981) describes a powerful new cue for spatial layout based on the form of the contours that cover a surface. He pointed out that, when objects have surface markings or cracks that are intrinsic to the structure of the surface, rather than caused by shadows or reflections on a surface, curvature of these markings could indicate surface layout (see figure 1). The name given to this new static-monocular depth cue was *surface contours*.

Surface contours are surface markings (eg reflectance edges) that are assumed to be constrained by the three-dimensional shapes of the surface on which they lie. Earle (1986) demonstrated that, for adults, surface contours can produce an illusion of cylinders slanted in depth. Two versions of the assumptions or constraints involved in making the retinal shape of these contours informative have been proposed in the computer vision literature. Stevens (1981) suggested that any parallel surface markings are taken to be contours that follow lines of curvature on the cylindrical portions of the surfaces. Knill (1992) proposed that the visual system assumes a more general form of constraint on

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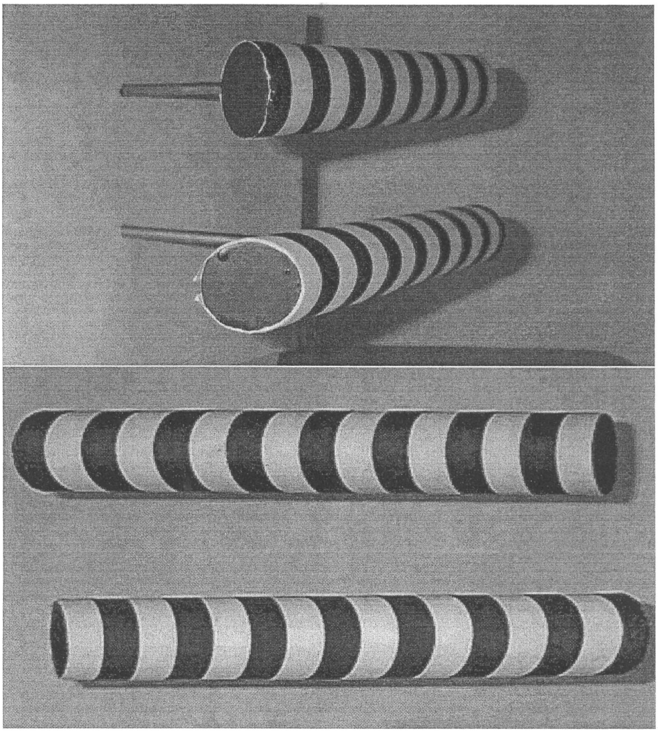

Figure 1. The surface contour display (front and side views).

surface markings: that they tend toward being geodesic (ie they follow paths of minimal length between points on a surface). For developable surfaces, of which cylindrical ones are a special case, assuming that surface markings are geodesic amounts to assuming that the markings on a surface would become straight lines were the surface to be unfolded to be flat.

As an account of how the surface contour constraint could be acquired, Stevens pointed to the high frequency of constructed objects with corners and edges that are straight. When a surface is folded, such edges, while no longer straight, remain geodesics of the now curved surface. Thus, learning could be essential for the constraint to be used. However, natural objects also have straight contours. It is possible that the geodesic constraint was incorporated into visual processes over evolutionary history and is inherent to the visual system. If so, we could expect that very young infants would show the ability to use this constraint in perceiving the spatial layout of objects. Alternatively, this constraint may require a minimal amount of experience in the environment for maturation to take place. Finally, the constraint may be learned but its use may be dependent on a certain level of neurological maturity.

In this study we investigated the development of sensitivity to the surface contour cue in human infants. Although previous work has shown that adults are sensitive to surface contour information (Stevens 1981; Earle 1986; Todd and Reichel 1990; Knill 1992), nothing is known about the ontogeny of sensitivity to this information.

Prior research on the development of sensitivity to other static-monocular depth cues has found that responsiveness to this class of information appears relatively late in development. Whereas infants in the first weeks of life respond to motion-carried information for collision (Yonas et al 1979; Pettersen et al 1980; Nañez 1988), and 5-month-old infants use binocular information to guide reaching (Gordon and Yonas 1976; Granrud et al 1984; Yonas et al 1987), infants under 6 months of age do not appear to use any static-monocular depth cues to control their reaching. However, 7-month-old infants are able to use this information effectively (see Yonas and Owsley 1987 for a review of early work; Arterberry et al 1991; Yonas and Arterberry 1994). It is important to investigate the onset of this new type of static-monocular depth information because knowing whether a perceptual ability appears at the same time as other abilities may indicate that a common process is shared by the mechanisms underlying these abilities. In addition, the early onset of an ability suggests that extensive experience is not required for its development. The task of understanding the role of experience in the development of an ability is difficult because of the altricial nature of human newborns and their slow development. For example, although maturation rather than learning is required for the appearance of secondary sex characteristics, such features usually do not appear until adolescence.

An important problem in fixing the onset of sensitivity to any kind of information is that evidence of sensitivity allows us to draw a firm conclusion (eg that 7-month olds are sensitive to linear perspective), whereas the absence of evidence of sensitivity in 5-month-old infants does not warrant the conclusion that they are insensitive. Although no study of static-monocular depth sensitivity to date has found evidence of responsiveness in 5-month olds, we cannot conclude the null hypothesis. It is possible that, if a more sensitive method were employed, responsiveness to the information would be apparent. The tactic that must be employed is to investigate sensitivity in the younger age group repeatedly, with a variety of cues, displays, and methods. If we find that 5-month-old infants do not show evidence of sensitivity to any of the static-monocular depth cues, the conclusion that they are insensitive becomes more secure.

To investigate the development of sensitivity to surface contour information, we created a display in which two real cylinders were presented perpendicular to the line of sight. When the cylinders are viewed monocularly by adults, curved surface contours produce the experience that one end of each cylinder is closer than the other (see figure 1).

Infants are known to reach preferentially toward the closer side of an object or the closer of two objects. Previous studies have relied on this tendency to assess depth sensitivity. For example, reaching to the large and small side of a trapezoidal window was used to assess sensitivity to linear perspective (Yonas et al 1978). When adults view this display monocularly, linear perspective information makes the window appear to be slanted in depth. The tendency to reach for the larger side of the window was taken as evidence of sensitivity. To rule out the possibility that reaching was motivated by some other factor other than perceived depth, the display was viewed both monocularly and binocularly. If infants simply preferred to reach for the larger side of the window, the apparent slant in depth of the display should not have mattered. In the control condition, binocular information specified that the two sides of the window were equidistant, and, for adults, linear perspective was overriden; they perceived a trapezoidal window in the frontoparallel plane. Infants sensitive to linear perspective and binocular information for depth reached more often to the apparently closer side of the display in the monocular viewing condition than in the binocular condition. This difference was the evidence of their sensitivity to the depth cue.

In the present study, infants may prefer to reach toward one side of a cylinder because it appears closer. However, it may be that they prefer to reach toward one side for some other reason; for example, they may prefer to reach for the side toward which the markings are curved. Contrasting reaching under monocular and binocular viewing conditions rules out this possibility. When viewed binocularly, stereo information overrides the surface contour cue and specifies that the ends of the cylinders are equidistant, while having no effect on the non-depth-related properties of the displays. Thus, we contrasted preferential reaching in monocular and binocular conditions to test whether infants use surface contour information to perceive depth. Finding that infants reach more often to the apparently closer ends in the monocular condition than they do in the binocular condition would constitute evidence that they have some sensitivity to the surface contour cue.

In experiment 1, sensitivity to surface contour information for layout was investigated. If sensitivity to surface contours develops at the same age as other static-monocular depth cues, responsiveness to this cue should emerge between 5 and 7 months of age.

2 Experiment 1

2.1 *Method*

2.1.1 *Participants.* Three groups of twenty full-term infants completed the surface contour study: a 5-month-old group (age range, 134 – 151 days; mean age, 141 days), a $5\frac{1}{2}$-month-old group (age range, 153 – 174 days; mean age, 161 days), and a 7-month-old group (age range, 200 – 225 days; mean age, 215 days). Twenty-seven additional infants (ten 5-month olds, eleven $5\frac{1}{2}$-month olds, and six 7-month olds) were excluded from the sample because they failed to reach the criterion of 10 reaches in one or more conditions.

2.1.2 *Apparatus.* The surface contour display (depicted in figure 1) consisted of two parallel cylinders that were constructed of tubing 3.5 cm in diameter, cut to 24 cm lengths. The ends of the cylinders were cut at a 60° angle to the long central axis (on a prototypical cylinder the ends are cut at 90°). The cylinders were covered with 14-mm-wide stripes that were sine waves parallel to the curve of the cylinder ends. The sine waves were created according to the formula $y = [\sin(2x/D)]/(D\cos q)$, where D is the diameter of the cylinder, q is the angle away from the symmetry axis made by the end-cuts, and x and y are coordinates in which the stripes are drawn on the paper (see figure 2). Substituting the parameters for the cylinders used in the experiment, we obtained as the equation for the stripes, $y/\text{cm} = 0.875\sin(0.571x/\text{cm})$.

When viewed monocularly, these curved markings produced the illusion that the cylinders were not parallel, but slanted in opposite directions. The sine waves were computer-generated and printed with a laser printer. These stripes were then copied onto colored paper (blue or green) to make them more attractive to the infants. Rods positioned out of sight of the infant were used to mount the cylinders on the apparatus. They were placed 13 cm in front of a white background with the central axes 6 cm apart, and were connected to a bell, masked by the background, that jingled when the cylinders were touched.

Figure 2. The sine waves that covered the cylinders.

2.1.3 *Procedure.* Each infant viewed the cylinder display both in the monocular and in the binocular condition. The order of these conditions was counterbalanced, as was the left – right orientation of the cylinders.

Infants viewed the cylinders from their parent's lap. The display was placed on a table in front of the infant, at shoulder level, but beyond reaching distance (approximately 45 cm away from the infant's shoulder). The experimenter tapped the cylinders to ring the bell, drawing the infant's attention to the display. The cylinders were then moved within the infant's reach (approximately 30 cm away from the infant's shoulder), and the infant's reach was scored. The movement of the apparatus took approximately 1 to 2 s. In this initial study, contact of the hand with the cylinder while the infant was looking at the display was defined as a reach. Only the first contact on each trial was scored.

The cylinders were moved into and out of reach until 10 reaches had been scored. The infant was then given a short break, during which an eye patch was either applied or removed. The experiment then continued until 10 more reaches had been recorded. The left–right position of the cylinders was reversed every 5 trials. Changing the position of the cylinders controlled for any handedness or position preference.

A video camera positioned at the side (at the height of the cylinders) was used to record reaching behavior on each trial for later scoring. The cylinders were divided into three 8-cm-long regions and scored as reaches to the 'near' end, middle region, and 'far' end. Only the display and the infant's reaching behavior were visible on the tape. The presence or absence of the eye patch on the infant was not visible to reduce the chance that experimenter bias influenced scoring.

2.2 *Results*

The mean numbers of reaches to the 'near', middle, and 'far' regions of the cylinders are presented in table 1. The number of reaches to the 'near' end of the cylinders was analyzed in a 3×2 repeated-measures ANOVA with Age (5, $5\frac{1}{2}$, and 7 months) as the between-subjects factor and Condition (monocular and binocular) as the within-subjects factor. There was a main effect of Condition ($F_{1,57} = 7.08$, $p < 0.05$), indicating that overall the infants reached more consistently for the 'near' ends of the cylinders in the monocular condition than they did in the binocular condition. Although there was no main effect of Age ($F_{2,57} = 1.88$, $p > 0.05$), there was an Age by Condition interaction ($F_{2,57} = 8.90$, $p < 0.001$). Therefore, we performed a Tukey's HSD contrast to determine for which age group the infants' reaching varied by viewing condition (see figure 3). 7-month-old infants reached more often to the 'near' ends of the cylinders in the monocular condition than they did in the binocular condition. Neither 5-month nor $5\frac{1}{2}$-month olds showed an effect of viewing condition on reaching. There was no significant difference between the younger infants' reach in the monocular and binocular conditions (see figure 3). In fact, the 5-month-old infants reached for the apparently closer end of the cylinder more frequently in the binocular control condition.

Table 1. Mean number of reaches out of 10 to the 'near', middle, and 'far' sections of the cylinders for infants aged 5, $5\frac{1}{2}$, and 7 months in the monocular and binocular conditions in experiment 1. Standard deviations are shown in parentheses.

Age/months[a]	Condition	Cylinder section		
		'near'	middle	'far'
5	monocular	3.75_a (1.52)	1.70 (1.92)	4.55 (1.54)
	binocular	4.45_a (1.32)	1.95 (1.54)	3.55 (1.50)
$5\frac{1}{2}$	monocular	4.10_a (2.02)	2.90 (1.77)	3.00 (1.78)
	binocular	3.25_a (1.97)	2.75 (1.97)	4.00 (1.26)
7	monocular	5.45_a (1.82)	1.70 (1.42)	2.85 (1.46)
	binocular	3.65_b (1.50)	2.45 (2.01)	3.90 (1.45)

[a] $n = 20$ for each group.

Note: Means for the same age group that have different subscripts differ at $p < 0.01$ in the Tukey honestly significant difference comparison.

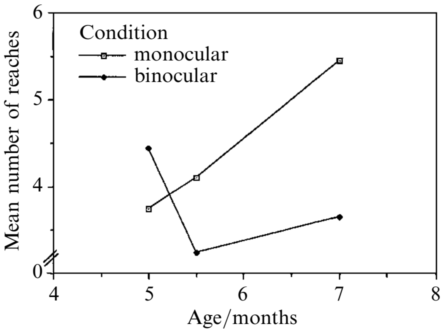

Figure 3. Mean number of reaches by age to the 'near' ends of the cylinders (out of 10 possible) in the monocular and binocular conditions in experiment 1.

2.3 *Discussion*

The finding of more reaching to the apparently closer ends of the cylinders in the monocular than in the binocular condition by 7-month-old infants argues that they are responsive to surface contour information for layout. The absence of an effect of viewing condition in 5-month-old infants suggests that they are insensitive to this information. It is possible, however, that 5-month-old infants are sensitive to the cue, but they reach equally to the 'near' and 'far' ends of the cylinders simply because they lack motor control. To explore this possibility, 5-month-old infants were presented with cylinders that were actually slanted in depth to determine if they could direct their reaching to the closer end of a cylinder when binocular depth information was available. If 5-month-old infants show sufficient motor skills to reach consistently to the actually closer ends of the cylinders, we can rule out an explanation based on poor motor control.

3 Experiment 2

3.1 *Method*

3.1.1 *Participants.* Twenty full-term 5-month-old infants (age range, 130–152 days; mean age, 142 days) participated in the actual slant study. Eight others were excluded from this sample because they failed to complete the criterion of 10 reaches.

3.1.2 *Apparatus.* The actual slant display was constructed of the same tubing as the surface contour display, and was also 24 cm in length. The ends of the cylinders were cut perpendicular to the long central axis of the cylinder. Black linear stripes, 14 mm wide, were alternated with light-colored stripes. This image was created on a computer, printed with a laser printer on colored paper (blue or green), and was wrapped around the cylinders. The cylinders were presented at opposing 30° angles. Thus, these cylinders were actually slanted at the angle that generated the same curvature contour as the frontal view of the experimental cylinders. In other words, the frontal views of the control and experimental cylinders were geometrically matched.[1] The rods that supported the cylinders were inserted into the white background and the bell sounded when a cylinder was moved.

3.1.3 *Procedure.* In experiment 2, infants viewed the displays binocularly and the cylinders were actually slanted in depth. Otherwise the procedure was the same as that used in experiment 1.

Scoring of reaching was modified to deal with the fact that, owing to the slant of the cylinders, the closer end of each cylinder was easier for the infant to contact by chance than the far end was. To make scoring of the slanted cylinders similar to that used in experiment 1, a reach was scored when the infant's hand crossed a line that

[1] Twelve adults judged the apparent distance in the surface contour display on two trials. That is, they judged the distance between the two ends on the right and the left sides of the display. The mean difference in depth reported was 3.02 cm (sd = 1.01).

connected the corners of the cylinders closest to the infant. This line represented the location of the non-slanted cylinders. Only the first time an infant's hand crossed the line on each trial was recorded. The scoring line was divided into three 6.9-cm-long regions:[2] the near, middle, and far regions. The cylinders were moved into and out of reach until at least 5 reaches had been completed. The position of the cylinders was then reversed, and the procedure was repeated until at least 5 more reaches were completed. Because only one condition (binocular) was necessary for experiment 2, it was possible to ask for more reaches from the infants. It was decided that the total number of reaches should be flexible to maximize the amount of data gained from each infant.

Two video cameras were used to record reaching behavior. One camera was positioned at the side (at the height of the cylinders), and the second was positioned directly above the display. The side camera allowed the scorers to know which of the cylinders the infant's hand was approaching. The presence or absence of the eye patch on the infant was not visible on the recording to reduce the possibility that experimenter bias influenced scoring.

3.2 *Results*

The 5-month-old infants tested in the actual slant study demonstrated a clear ability to reach for the closer ends of the actually slanted cylinders. The infants reached to the closer, middle, and far regions of the cylinders on 75.49% (sd = 15.96%), 11.80% (sd = 10.02%), and 12.71% (sd = 11.19%) of the trials, respectively. The percentage of reaches to the closer ends is higher than would be expected if the infants were unable to control their reaching behavior. If the likelihood of contacting each third of the scoring line was assumed to be equal, reaching to the actually closer side on three quarters of the trials is very unlikely ($t_{19} = 11.81$, $p < 0.001$).

3.3 *Discussion*

Experiment 2 demonstrated that 5-month-old infants have the motor ability and motivation to direct their reaches consistently to the closer end of a tilted cylinder when binocular information is available to specify which end is closer.

4 General discussion

As hypothesized, the 7-month-old infants reached more often to the apparently closer ends of the cylinders in the monocular condition than they did in the binocular condition. This suggests that, like adults, infants of this age perceive the apparently closer ends as closer to them. They are able to use the surface contour constraint to interpret the spatial layout of their environment. The lack of preferential reaching by 5-month-old and $5\frac{1}{2}$-month-old infants suggests that these younger infants may not be sensitive to depth information provided by surface contour information. When stereo and other cues specify depth, as in experiment 2, 5-month-old infants demonstrate the ability to reach to the closer end of the cylinder. Thus the failure to reach to the apparently closer ends of the cylinders was not caused by an inability to direct reaching to the 'closer' side of the display. It is possible that infants younger than 6 months have not yet begun to use the surface contour constraint. However, we cannot conclude the null hypothesis. It should be noted that the children in experiment 2 reached to the closer ends of the cylinders at a higher rate than any of the groups of children in experiment 1. This may indicate that the depth perceived in the actual slant display was more clear than the depth in the surface contour display. This is not surprising, because there are more cues indicating depth in the actual slant display than in the surface contour display. Still, the finding that 7-month-old infants reach more often

[2] Because the cylinders were presented at an angle, the line connecting the two ends was shorter than the 24-cm length of the cylinders.

to the 'near' ends of the cylinders in the surface contour display than they do to the 'far' ends suggests that these infants do perceive depth in this display. It is possible that the younger infants also perceived depth in the surface contour display, but that this perceived depth was not enough to influence their reaching. Additionally, having their eyes patched could have affected their reaching. However, children in this age range have demonstrated the ability to reach accurately in similar monocular conditions (Yonas et al 1978; Yonas and Owsley 1987).[3]

These findings and others suggest that by 7 months of age infants use highly consistent properties of the environment to interpret the layout of their surroundings. Both adults and 7-month-old infants act as if they assume that contours on a surface follow that surface's lines of curvature and take the shortest possible path (ie they are geodesic). By 7 months of age, infants respond to a wide variety of static-monocular depth cues.

Multiple assumptions, such as the following, are required for all of these static-monocular cues to be effective. The optic array is viewed from a generic viewpoint. Multiple linear contours that converge to a point are parallel (linear perspective). Objects are roughly equal in size (relative retinal size). This study, in conjunction with previous research on static-monocular depth cues in infants suggests that 5-month-old infants are unresponsive to all of these depth cues and seemingly employ none of the constraints that 7-month-old infants do. The question remains, what happens between 5 and 7 months of age that accounts for this change?

One explanation is that all static-monocular depth cues and their constraints are innate, and development is independent of the infant's experience. Such a strong nativist theory posits that these constraints are acquired over evolutionary history and that the mechanisms underlying the effectiveness of each cue simply reach maturity at 6 months. The common age of onset of sensitivity to many different static-monocular depth cues points to this possibility. Alternatively, the human infant is a superb learning machine and at least some of these constraints may depend on a constructed environment that was not present over our evolutionary history. This would suggest that these constraints must be learned. However, if the constraints are acquired through experience, it seems rather unlikely that all would be learned simultaneously. Experience with the variety of environmental regularities that could form the basis for the acquisition of these constraints would probably be distributed over time.

It is also possible that development of sensitivity of one set of cues is limited by the development of a second set of cues. It may be the case that binocular information for layout must be available before static-monocular cues can develop. Infants must have some way of knowing about the external environment before they can acquire knowledge of regularities in the structure of that environment. By investigating the development of sensitivity to static-monocular cues in infants who lack binocular vision this hypothesis could be explored. However, adults who have never experienced depth from binocular information are sensitive to the set of static-monocular cues. Thus, while binocular vision may be important for the early onset of sensitivity, it is not absolutely necessary.

A model for the development of sensitivity to static-monocular cues, proposed by Yonas (1995), involves both maturation and experiential factors. According to this view, information about distal regularities, which makes sensitivity to static-monocular cues possible, is slowly acquired and stored in some form of implicit memory beyond the visual processing areas. For example, for familiar size to function as a depth cue, the familiar object must be recognized by mechanisms in the temporal lobe. Once recognized, information about the visual angle of the particular object is used to retrieve its distance from memory. It is hypothesized that information for distance is only

[3] Our thanks to the anonymous reviewer for this suggestion.

able to influence perception and direct action when descending neural fibers from the temporal lobe reach extrastriate visual areas such as V3. The model asserts that ascending fibers from visual projection areas to the temporal lobe mature before descending fibers and it is at 6 months that the descending pathway becomes effective in the human infant.

The finding that 7-week-old pigtailed macaque monkeys show evidence of sensitivity to linear perspective and relative size, whereas 5-week olds do not, is consistent with the maturational account, since several perceptual capacities have been found to develop four times faster in monkey than in human infants (Gunderson et al 1993). Perhaps descending pathways reach the needed level of functioning at 6 weeks in monkeys. Whether pictorial depth cues are acquired by associative learning or not, some account is needed to explain for the common onset of their ability to direct action.

Although the dispute between nativists and empiricists on the development of static-monocular depth perception has been going on for centuries, neither the maturation-based nor the learning-based explanation for acquisition can be ruled out at this time.

Acknowledgements. This research was supported by a grant to the Center for Research in Learning, Perception, & Cognition from the National Institute of Child Health and Human Development (HD-07151). We wish to thank Kathleen Bittinger for her assistance in data collection. Portions of this article were presented at the Society for Research in Child Development, New Orleans, LA, March 1993, and the International Conference on Event Perception and Action, Vancouver, BC, August 1993.

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