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Area Judgment from Width and Height Information: The Case of the Rectangle

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We assessed the effect on performance of shifting from a perceptual area judgment situation, in which the physical quantity to be judged (the area) is present in the stimulus, to a situation in which it is not present in the stimulus. Adults, 9-year-olds, and 5-year-olds were shown combinations of horizontal and vertical lines of various sizes, presented on the same wall or on different walls, and asked to estimate the corresponding area. The following main results were obtained (a) When width and height information items were completely separated, 5- and 9-year-old children gave the same weight to both dimensions in their estimations; (b) when width and height information items were on two different walls, adults gave a greater weight to the larger dimension; (c) when width and height were joined, 9-year-old children gave a greater weight to the larger dimension but when they were separated, they did not.

Our objective was to study how the performance of participants of various ages (children aged 5 and 9, and adults) placed in an area judgment situation would be affected by shifting from a situation in which the physical quantity to be judged (the area) was present in the stimulus to a situation in which it was not. Only information relating to the dimensions on which the judgment had to be based (height and width) was provided.

Since Anderson and Weiss (1971), many studies conducted in the framework of information integration theory (Anderson, 1981) have been dedicated to the judgment of rectangular areas. Several judgment rules have been proposed, including, obviously, the normatively correct rule

$$J(\text{area}) = f(\text{Height} \times \text{Width}). \quad (1)$$

Taken literally, this rule implies that subjects (a) acquire information concerning the height of the area to be judged, (b) acquire information concerning its width,

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TABLE 1
Study Results Compatible with Equation 1: *J*(Surface) = *f*(Height × Width)

Study	Context	Participants	Ratios
Anderson & Weiss (1971)	Perception of rectangle	American adults	4.60
Anderson & Cuneo (1978)	Perception of rectangles	American 11-year-olds	1.95
Wilkening (1979)	Perception of rectangle (reduction of area into units, and mental alignment of units)	German adults	2.33, 3.36
	(16 cm height excluded)	German 11-year-olds	2.75
Leon (1982)	Perception of rectangle	American adults	2.00
Algom, Wolf, & Bergman (1985)	Perception of rectangle	Israeli adults	6.80
	Memorization of rectangle	Israeli adults	6.50
Wolf & Algom (1987)	Perception of rectangle	Israeli 10-year-olds	2.94
	Memorization of rectangle	Israeli 10-year-olds	2.04
Gigerenzer & Richter (1990)	Perception of rectangle (reduction of area into units, and mental alignment of units)	German adults	3.14
Avons & Thomas (1990)	Perception of rectangles (by surface matching, PEST technique)	English adults	3.42
	Perception of rectangles (by surface matching, PEST technique)	English 10 and 11-year-olds	2.82, 2.88
Wolf (1995)	Perception of rectangles (after playing with stimuli)	Israeli 5 to 7-year-olds	2.33, 2.23, 2.61, 1.71, 4.00
	Perception of right triangles (after playing with stimuli)	Israeli 5 to 6-year-olds	8.00

and (c) integrate these two items by applying a multiplicative operation. It is more likely that at least some subjects judge area directly, without using the intermediate step of acquiring information about height and width. Under such circumstances Eq. (1) could appropriately be replaced by

$$J(\text{area}) = f(\text{Area}). \tag{2}$$

The multiplicative rule has been proposed on many occasions, not only regarding perception of rectangular stimuli but also their memorization. The main studies are listed in Table 1. Most of these studies have plotted the results as a graph, with the judged surface on the y-axis, the width on the x-axis, and the height as the curve parameter (or vice versa). When the multiplicative rule is applied by subjects, the curves are clearly divergent, forming the typical fan-shaped graph (Anderson, 1981). From the figures in each study it is possible to compute ratios by dividing the height effect observed when the width is maximal, by the width effect observed when the length is minimal. These ratios are obviously only rough indications but they are sufficient to show that in all of the studies listed in Table 1, there is a large degree of divergence in the curves (all ratios are greater than 1.00).

It can be concluded that the multiplicative rule can be used to account for the predominant pattern of results seen in adults, and the modal pattern of results seen in children over 10. When familiarization with the stimulus is provided, even 5- and 6-year-olds exhibit the use of a multiplicative rule, but how persistent the familiarization effect is, is still not well established (Wolf, 1995).

THE ADDITIVE RULE

Whereas the multiplicative rule appears to be the most natural rule in this type of situation, it is nevertheless not the only rule to have been inferred. In particular, the study by Anderson and Cuneo (1978a) provided evidence in young children (age 5) of results indicating the use of a totally unexpected rule, the additive rule

$$J(\text{area}) = f(\text{Height} + \text{Width}). \tag{3}$$

These authors presented young subjects with rectangles whose dimensions corresponded to all possible combinations of three lengths (7, 9, and 11 cm) and asked them to estimate the area of the rectangles in terms of degree of satisfaction (in a situation where larger areas were more satisfying) along a graduated scale. The surprising thing about these results, at the time, was that the three curves plotting the mean results did not diverge to the right as required by the multiplicative rule or the direct area judgment rule, but instead showed no divergence (three parallel lines, with the nine values covering a substantial part of the response scale and preventing the detection of any floor or ceiling effect). An analysis of variance on the raw data revealed clear effects of the height and width factors, but no interaction effect. This led the authors to interpret their results as reflecting the application of the rule described by Eq. (3).

Taken literally, this rule implies that the subject (a) acquires information concerning the height of the area to be judged, (b) acquires information concerning its width, and (c) integrates these two items by applying an additive operation. It may also be that participants judge perimeter directly, but such a strategy was not found by Mullet and Miroux (1996) in a gestural strategy study on children born blind.

Anderson and Cuneo's (1978a) results and interpretation were criticized by Lohaus and Trautner (1989), Gigerenzer (1987), and Gigerenzer and Richter (1990). One of the chief arguments of these authors, already put forward by Bogartz (1978), is that the analyses of variance performed by Anderson and Cuneo lacked power for the detection of an interaction effect, chiefly in young children, whose responses on the rating scale showed considerable intraindividual variation (Gigerenzer & Richter, 1990). Their argument would be much more convincing if the raw data led to the suspicion of a bilinear interaction effect, reflected by divergence to the right of the three curves. In Anderson and Cuneo's Fig. 3 (p. 344), the ratio was exactly 1.00. In other words, the magnitude of the width factor effect was strictly identical whether the higher or the lower length level was considered. It would be difficult under such circumstances, even by multiplying the number of subjects by 10, or by reducing the degree of error through greater care in the recording of data, to demonstrate the existence of a bilinear interaction (see also Anderson and Cuneo's reply to Bogartz' comment, 1978b).

In Anderson and Cuneo's Fig. 4 (p. 348, a precise replication of Experiment 1, the ratio was 0.80. In their Fig. 5 (p. 349, replication of Experiment 1 with variation of the distance of the subject from the stimuli), the ratio was 0.92 in the 65-cm condition. In their Fig. 8 (p. 352, a precise replication of Experiment 1), the ratio was 0.84. Thus the curves converged rather than diverged.

A second criticism made by Gigerenzer and Richter (1990) is related to the fact that a pattern of three rising parallel lines is not an adequate basis for inferring an additive process. An alternative to this interpretation would be that area judgment does indeed obey a multiplicative rule but that when the response is stated on the scale, it is distorted via a logarithmic conversion. However, a special feature of the resultant curves argues against the idea of a logarithmic conversion. In the figures shown by Anderson and Cuneo (analyzed above) the 9-cm curve was always equidistant (or almost) from the 11-cm and 7-cm curves. If a logarithmic conversion of the responses did indeed occur, the 9-cm curve would have been much closer to the 11-cm curve than to the 7-cm curve (see for example the graphs in Verge & Bogartz, 1978, where a logarithmic transformation was applied to the data). This never happened. (Additional comments about Gigerenzer's criticisms can be found in Anderson, 1996, Note 5, p. 276.)

In addition to being proposed in the above experiment, the additive rule has been used very often as an explanation, once again, not only regarding perceived rectangular stimuli, but also regarding memorized or mentally-divided rectangular stimuli. The main studies are listed in Table 2. The ratios are very close to 1.00, which corresponds to approximate parallelism of the curves.

It can be concluded that the additive rule accounts for the general pattern of results seen in 5- to 6-year-old children when no familiarization with stimuli is provided and accounts for the pattern of results seen episodically in older children (usually when the response scale is not graduated).

MAXIMAL EXTENT AND GRANTING GREATER WEIGHT TO THE LARGER DIMENSION

A third judgment rule was suggested by Leon (1982). The stimuli presented by Anderson and Cuneo (1978a) ranged from 49 to 121 cm^2, so they increased by

TABLE 2
Study Results Compatible with Equation 3: J(Surface) = f(Height + Width)

Study	Context	Participants	Ratios
Anderson & Cuneo (1978)	Perception of rectangles	American 5-year-olds	1.00, 0.85, 0.92, 0.84, 1.09
	Perception of isoceles and right triangles	American 5-year-olds	1.00, 1.20
Wilkening (1979)	Perception of rectangle (reduction of area into units, and mental alignment of units)	German 5-year-olds	0.92
Wolf & Algom (1987)	Perception of rectangle	Israeli 6-year-olds	0.97
	Memorization of rectangle	Israeli 6-year-olds	0.93
Lautrey, Mullet, & Paques (1989)	Perception of rectangles (non-graduated response scale)	French 8-year-olds (conserving)	0.83
Mullet, Lautrey, & Glaser (1989)	Perception of rectangle	French 6-year-olds	1.04
Gigerenzer & Richter (1990)	Perception of rectangle (reduction of area into units, and mental alignment of units)	German 5 to 6-year-olds	0.77
Mullet (1991)	Perception of rectangle	French 5-year-olds	
Mullet & Paques (1991)	Perception of rectangle (biased distribution of stimuli and graduated response scale)	French 6-year-olds	0.78, 0.86, 0.91
	Perception of rectangle (biased distribution and graduated response scale and unbiased distribution and ungraduated response scale)	French 7-year-olds	1.10, 0.71
Wolf (1995)	Perception of rectangles	Israeli 5 to 7-year-olds	1.20, 1.21, 1.04

a factor slightly greater than two. The stimuli presented by Leon ranged from 9 to 144 cm^2, i.e., a variation about six times greater. The curves produced by Leon showed very marked convergence (ratio of 0.68) and an analysis of variance provided evidence of a significant interaction, essentially concentrated on the bilinear component. The rule proposed by Leon, which he considered valid for 7-year-olds (i.e., children in a transitional phase) was

$$J(\text{area}) = f(\text{Maximal extent}). \tag{4}$$

Similar results to Leon's were reported later on. They are listed in Table 3. The ratios are always clearly lower than 1.00, which means a large degree of curve convergence. However, according to Lautrey, Mullet, and Paques (1989), these results can be interpreted as reflecting an additive process in which the weight

TABLE 3
Study Results Compatible with Equation 5: J(Surface) = f(w Larger Dimension + w' Smaller Dimension)

Study	Context	Participants	Ratios
Anderson & Cuneo (1978)	Perception of rectangles (Exp. 3, condition 20 cm distance of the subject, and Exp. 5)	American 5-year-olds	0.68, 0.70
Leon (1982)	Perception of rectangle	American 7-year-olds	0.68
Lautrey, Mullet, & Paques (1989)	Perception of rectangles (ungraduated response scale)	French 6- to 7-year-olds (non-conserving)	0.40
Mullet & Paques (1991)	Perception of rectangle (biased or unbiased distribution of stimuli and graduated or ungraduated response scale)	French 5-year-olds	0.14, 0.50, 0.41, 0.50
	Perception of rectangle (biased distribution of stimuli and ungraduated response scale)	French 6-year-olds	0.35
	Perception of rectangle (biased distribution and ungraduated response scale)	French 7-year-olds	0.50
Mullet & Miroux (1996)	Tactile perception of rectangle	French and Belgian congenitally blind 6-year-olds	0.25

attributed to one dimension depends upon the value of that dimension in relation to the value of the other dimension. When the rectangle is higher than it is wide, the child attributes more importance to height than to width and vice versa. The equation describing such a process would be

$$J(\text{area}) = f(w \text{ Larger dimension}) + w' \text{ Smaller dimension}), \qquad (5)$$

where w' is less than w. In certain extreme cases, w' can have a null value or be very close to zero as it is when there is centering on the largest of the two dimensions (e.g., the case of numerous kindergartners and second graders in Verge & Bogartz, 1978).

It should be noted that Lautrey *et al.*'s interpretation is closer to the one presented by Anderson and Cuneo (1978a) or Wilkening's (1979) than to the one proposed by Leon. Leon hypothesized the use of a single dimension, the diagonal, which other than in special circumstances, has never been given as such and must be constructed visually. He made no reference to an integration process. It should also be noted that even the results reported by Leon on the one hand, and by Lautrey *et al.* and Mullet, Lautrey, and Glaser (1989) on the other, are not in total contradiction with Anderson and Cuneo's basic results (1978a, see Fig. 3). The work by Mullet and Miroux (1996), who studied gestural strategies among congenitally blind children, support the dimensional integration rule advocated by Lautrey *et al.* (1989). In addition, Lohaus and Trautner (1989) and Gigerenzer and Richter (1990) using a paired comparison technique found a rule involving centering on the larger of the two dimensions by some 5- to 6-year-olds (see also Verge & Bogartz, 1978).

FROM A DIMENSIONAL STRATEGY TO THE DIRECT PERCEPTION OF AREA

Despite seemingly relatively marked differences, the overall picture emerging from the studies on the development of the ability to judge the size of a rectangular area is a clear one. In very young children (age 5 and under), judgment of area already involves the integration of height and width information. The integration process is most probably an additive process but the weight attributed to the dimensions varies according to their relative size. The larger dimension receives the greater weight (Eq. (5)). Hence, at age 5 or below, the structure of the data (relative length of the dimensions) plays a powerful role in the judgment process.

In 6- and 7-year-olds, these two items are obviously still integrated but the weight attributed to the two dimensions no longer varies in relation to their size (Eq. (3)). Thus at age 6, the structure of the data no longer plays a role.

In older children (age 8 or 9), the additive process is modified. Area as such starts to be considered. It is possible that the response then results from the simultaneous application of the two processes described in Eq. (2) and (3). A number of results concerning this transitional age are shown in Table 4. It can be seen that the mean value of the ratio in 8-year-old children is consistently higher than 1.00.

After the age of 10, the response patterns obtained conforms to the height $\times$ width rule (Eq. (2)). The child then automatically has access, perceptually speaking, to the area of the rectangle.

Performance at each level of development may depend in part on the conditions under which the task is accomplished. The availability of a graduated response scale, or the possibility of handling stimuli for some time before answering, are favorable factors likely to improve the area estimations, at least temporarily and locally.

This developmental progression, sketched on the sole basis of studies on the *judgment* of perceived area, is supposed to apply only to this type of situation. In other situations, e.g., ones involving *comparison* of perceived areas, the progression is not necessarily the same because the number and nature of the items to be processed may differ. In a situation where two areas are being compared, there are twice the number of items, implying many more processing requirements (Wilkening & Anderson, 1991). In addition, comparisons can be made on an interdimensional basis as well as on an intradimensional basis.

This progression from an additive to a multiplicative rule may seem relatively fast compared to other judgment tasks, with a structure appearing at first to be

TABLE 4
Study Results Compatible with the Idea of a Transition Between Additive and Multiplicative Processing

Study	Context	Participants	Ratios
Anderson & Cuneo (1978)	Perception of rectangles	American 8-year-olds	1.42
Wilkening (1979)	Perception of rectangle (reduction of area into units, and mental alignment of units)	German 8-year-olds	1.78
Wolf & Algom (1987)	Perception of rectangle	Israeli 8-year-olds	1.67
	Memorization of rectangle	Israeli 8-year-olds	1.69
Mullet, Lautrey, & Glaser (1989)	Perception of rectangle (precutting of the surface)	French 6-year-olds	1.78
Gigerenzer & Richter (1990)	Perception of rectangle (reduction of area into units, and mental alignment of units)	German 7- to 9-year-olds	1.82
Mullet & Paques (1991)	Perception of rectangle (unbiased distribution of stimuli and graduated response scale)	French 7-year-olds	1.50

similar to that of the studies reported in Tables 1–4. In a study involving the balancing of the arms of a pair of scales, Surber and Gzesh (1984) showed that until the age of 14, children estimating the distance from the center where a fixed weight had to be placed in order to balance another weight of variable mass located at a variable distance from the same center, applied an additive rule (weight + distance) instead of the correct multiplicative rule. In a study on the judgment of mass based on volume and density information, Leoni and Mullet (1993) showed that only a small number of their 18- to 20-year-old subjects were capable of applying a multiplicative rule. At the age of 8 or 9, the majority of subjects applied an additive rule and one third appeared to use only density information, neglecting volume. For a task less directly related to the judgment of physical quantities, Demerval and Mullet (1993) found that at least until the age of 10, children used an additive rule to estimate how many items might be remembered by a student shown a varying number of items and having made a variable amount of effort to learn them. One third of the 10-year-olds used the effort information and ignored the information about the number of items.

AREA JUDGMENT FROM HEIGHT AND WIDTH INFORMATION ONLY

What seems to characterize these tasks in relation to area judgment tasks is the fact that the dimension to be estimated (appropriate distance along scale arm, object mass, recall performance) is not present in the stimulus. Only information related to the dimension is available (weight and distance along other side of scale, volume and density, effort and total number of items). The task is not only a perception task, but also an integration task, in the most comprehensive sense of the term.

Our objective here is to study the effect on performance of shifting from an area judgment situation in which the quantity to be estimated is present in the stimulus to an area judgment situation in which it is not. There have been few studies on the effect of shifting from direct perception to estimation from parameter values, and authors have generally paid little attention to this distinction. However, we might mention a study by Algom and Cohen-Raz (1987) regarding the perception of velocity in adults. In this study, 36 different stimuli (all combinations of six distances and six durations) were shown to the subject under perception conditions. Each stimulus consisted of an object moving at a variable speed governed by duration and distance. In conditions of estimation from parameter values, only duration and distance information was provided, with velocity never being directly perceived. The response patterns of the two conditions were very different, with the curves fanning out to the right (multiplicative) in the perception condition and parallel (additive) in the other condition. It is therefore quite likely that a perception condition will lead to higher performance than an estimation-from-parameters condition.

Why shift from the study of the perceptual judgment of area to the study of the estimation of area from height and width information? The essential reason is that this shift will probably modify the way in which the area is judged by adults and children. The nature of this modification is predictable on the basis of what is known about the processes used in the perceptual judgment of area. Hypotheses can therefore be proposed and tested.

By way of illustration, let us imagine a situation in which height information and width information are shown on two opposite walls of a room, in such a way that both are never visible in a single glance. In adults or adolescents, the fact of having to make a greater effort to grasp the information should not be a major handicap. By contrast, the fact of not being provided with information on area itself could be far more disturbing. If adults usually judge by applying Eq. (2), which appears likely in a perception condition, the differences should be considerable. A complete change in strategy is forced upon them in the parameter-based estimation situation. The prediction would thus be that performance would drop, although the extent of the drop cannot be foreseen for the time being. It is possible that at least some adults return to an additive rule, as observed by Algom and Cohen-Raz (1987).

In 5-year-old children, the fact of having to make an extra effort to grasp the two items of information could be a handicap from the onset. A pilot study in this type of situation showed that 5-year-olds only looked once or twice at height and width information before deciding whether the area was large or small. Furthermore, the order in which the information was considered was relatively stable:

The children usually looked to the right then to the left. It is therefore reasonable to expect effects of the same type as those usually found (greater weight to one of the dimensions). The difference will be that instead of choosing the larger dimension as the first information to be integrated (Eq. (5)), 5-year-olds will probably always choose the same dimension, the one located on the right. Turning now to the actual integration rule of 5-year-olds, this rule is unlikely to be greatly modified in this situation. The additive rule is not made more difficult in a situation in which the two dimensions appear on two opposite walls. One can thus expect to find evidence in 5-year-olds of attribution of greater weight to one of the two dimensions, irrespective of its length.

In 9-year-olds, typically halfway between adults and 5-year-olds, the two rules, additive (Eq. (3)) and multiplicative (Eq. (2)), probably coexist (Table 4). It is therefore probable that these children will have no particular difficulty integrating the two information items by application of the still available additive rule. In contrast, it is likely that the attribution-of-greater-weight effect will not be as strong in the younger children.

Studying subjects in an area judgment situation where only height and width information are present should thus provide answers to a number of questions regarding area judgment rules, the most important of which we believe to be (a) the extent to which 5-year-olds attribute greater weight to information processed first and (b) whether adults in that situation apply a rule compatible with Eq. (1) or Eq. (2).

EXPERIMENT 1

Experiment 1 was aimed at answering the questions raised above. Two conditions were used in this experiment: a standard area perception condition for comparative purposes, and an area estimation from height and width information (EHWI) condition. In the EHWI condition, special precautions were taken to ensure that participants never had the two information items in the same visual field, which would have enabled them to make a simple mental representation of the area.

Method

Participants. Sixty participants living in the Pas-de-Calais area (France) took part in the experiment. They were selected on the basis of age and gender. The three groups had mean ages (and age ranges) of 5;0 (4;9 to 5;3), 9;0 (8;9 to 9;3), and 25;7 (22;0 to 44;1). Each group included the same number of males and females with middle- or lower-class backgrounds.

Material. The material was composed of 11 sheets of white 150 $\times$ 150 cm paper. One rectangle was drawn in black pencil on each sheet. Nine of the 11 rectangles corresponded to a full factorial design, i.e., height $\times$ width (3 $\times$ 3). The height and width were 70, 90, and 110 cm (the same progression as in Anderson & Cuneo, 1978a). The other two stimuli were the extremes used as anchors (50 × 50 cm, and 130 × 130 cm). The material was also composed of 10 sheets of white 150 × 150 cm paper. One line, horizontal or vertical, was drawn on each sheet. The lengths of the lines were 50, 70, 90, 110, and 130 cm.

A series of booklets containing 15-cm-long response scales were also prepared. Faces served as anchors at each end of the scale, a sad face at the left end and a smiling face at the right. The response scale had 19 small circles placed along it, as in Anderson and Cuneo.

Procedure. Participants in each of the three age groups were randomly assigned to one of the two conditions defined by the type of task. In the perception condition, all 11 rectangles were used. The two extreme rectangles were presented first. The participant was asked to imagine that each rectangle was a window that a child could have in his/her bedroom. When the window was very small (50 × 50 cm), the child would not be very happy (left-hand anchor). When the window was very big (130 × 130 cm), the child would be very happy (right-hand anchor). After the two extreme stimuli had been associated with the two response scale anchors, the nine test rectangles were presented and the subject was asked to rate the degree of happiness of a child having a window of that size in his/her bedroom. Each sheet was presented at a distance of 150 cm in front of the participant.

In the EHWI condition the 10 sheets containing vertical or horizontal lines were used. The procedure was the same except that the sheets containing vertical lines were presented to the left of the participant and the sheets containing horizontal lines were presented to the right. The presentation order was always vertical line then horizontal line, and the participant was seated on a swivel chair. Here also, the 50–50 cm pair was presented first, then the 130–130 cm pair. After these two extreme stimulus pairs had been associated with the two anchors, the nine combinations corresponding to the nine rectangles shown in the perception condition (70–70 cm to 110–110 cm) were presented.

There were three trials in all. The first trial familiarized the participant with the material. On trials 2 and 3 the stimulus presentation order was randomized except that the extreme stimuli were always presented first.

Results

The means for each of the six subgroups are shown in Fig. 1. Inspection of the response patterns showed that they differed considerably in terms of convergence/divergence. In the perception condition, the pattern for 5-year-olds was converging. The 9-year-old curves were nearly parallel. Finally, the adult pattern was clearly diverging.

In the EHWI condition, the 5-year-olds' curves were almost parallel. The three curves rose slightly (a height effect) but were clearly separate (a width effect). The 9-year-old pattern was highly similar in shape, although the rise was steeper and the curves were not as far apart. By contrast, the pattern for the adults was converging.

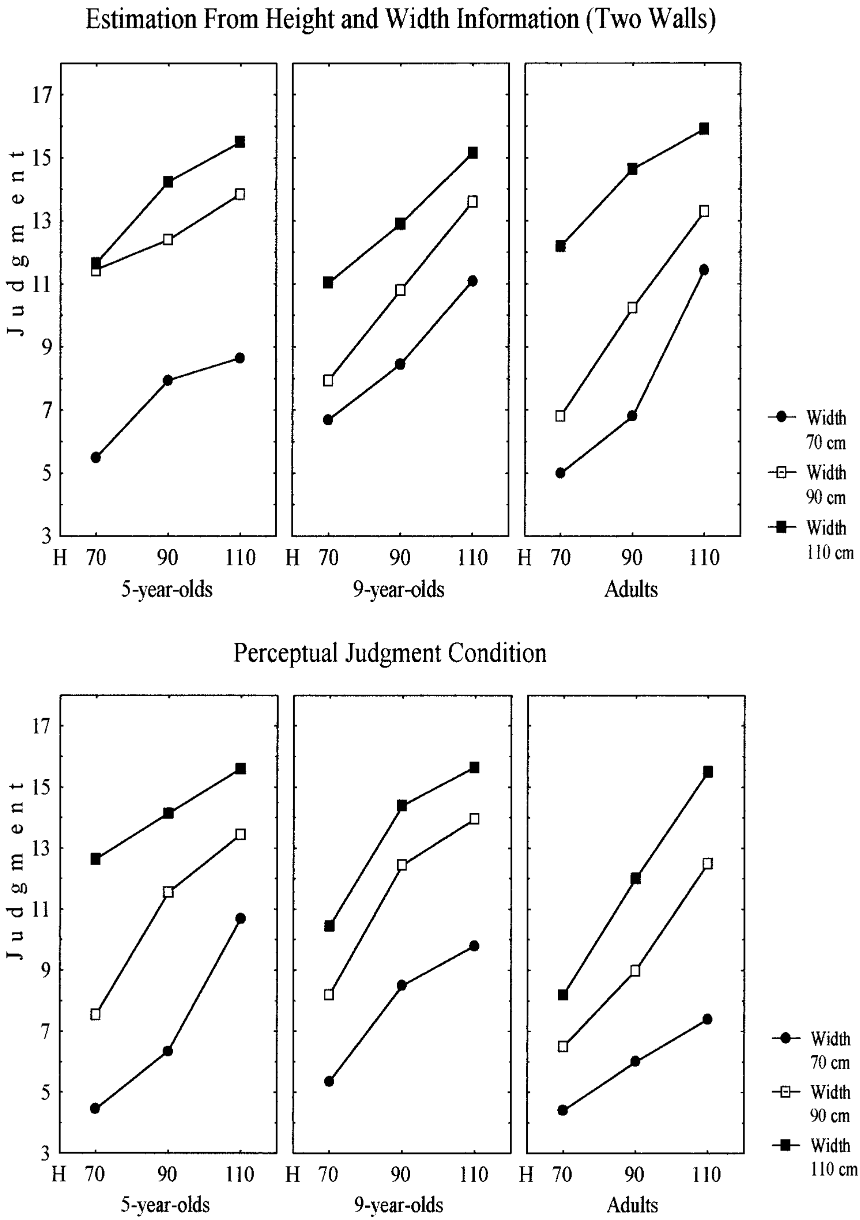

FIG. 1. Mean area judgments as a function of height and width in the estimation from height and width information condition (two walls) and the perception condition for the three age groups (Experiment 1).

TABLE 5
Results of Individual Analyses, Experiments 1–3

	Experiment 1												
	Inference			Perception			Experiment 2			Experiment 3			
Age group	5	9	Ad.	5	9	Ad.	5	9	Ad.	5	9	Ad.	Total
Converging	2	2	8	6	3	0	4	4	3	7	9	0	48
Parallelism	6	7	2	4	2	2	3	4	6	3	0	8	47
Diverging	2	1	0	0	5	8	2	2	1	0	1	2	24
Unclassified	0	0	0	0	0	0	1	0	0	0	0	0	1
Total	10	10	10	10	10	10	10	10	10	10	10	10	120

Note. (5 = 5-year-olds, 9 = 9-year-olds, Ad. = Adults)

An analysis of variance was conducted on the entire set of data with an age × condition × height × width (3 × 2 × 3 × 3) design (the gender effect and all interactions involving gender were nonsignificant). The main effects of height and width were significant. The most interesting result concerns the age × condition × height × width interaction. The interaction was significant and mainly concentrated on the quadrilinear component, $F(1,54) = 30.39$, $p < 0.000001$. Six complementary analyses of variance with a height × width design were performed, one for each subgroup. In each case, the main effects of height and width were significant. In the 5-year-olds, the width effect was more than four times as great as the height effect. The height × width interaction was significant only in adults (both conditions) and in 5-year-olds (perception condition). In these three cases, the interaction effect was mainly concentrated on the bilinear component. (Detailed ANOVA results are available from the second author.)

Individual analyses. The overall results were supplemented by an analysis at the individual level. The mean pattern (trials 2 + 3) of each subject was classified as clearly convergent to the right, clearly divergent to the right (resembling the multiplicative pattern), or intermediate (neither convergent nor divergent). A pattern was called convergent when both the width effect and the height effect were greater than 1.5 points, and the spread to the left was at least 1.5 times the spread to the right. A pattern was called divergent when both the width effect and the height effect were greater than 1.5, and the spread to the right was at least 1.5 times the spread to the left. When a pattern was neither convergent nor divergent, it was classified as intermediate. These cut-off points were used because they divided the patterns into three clearly distinct categories, each containing a substantial number of subjects. Fifty-nine subjects were classified; the remaining subjects exhibited a width effect only. The results are given in Table 5.

The individual results are in line with the overall results. For 5-year-olds and 9-year-olds in the EHWI condition, the patterns were predominantly parallel. For 5-year-olds in the perception condition and adults in the EHWI condition, the patterns were predominantly convergent. For adults in the perception condition, the patterns were predominantly divergent. The individual results do not reflect the overall results in one subgroup only; for 9-year-olds in the perception condition there was no predominant type of pattern.

Discussion

In the perception condition, the main results found in earlier studies were confirmed. The pattern for adults as a group, as well as 8 out of 10 individual patterns, were compatible with Eq. (1) and (2) presented in the introduction. The pattern for 5-year-olds as a group, as well as 6 out of 10 individual patterns, were compatible with Eq. (5) (the others were compatible with Eq. (3)). The pattern for 9-year-olds children was halfway between that of the adults and 5-year-olds. The effect of width was considerably greater than that of height in 5-year-olds (almost twice in terms of the share of variance explained). Thus the 5-year-olds tended to attribute greater importance to width than height.

In the EHWI condition, the results were markedly different. They supported our hypotheses for children, but far less so for adults. In 5-year-olds, the mean pattern and 6 out of 10 of the individual patterns were compatible with Eq. (3). It was as if a majority of children were unaffected by the tendency to attribute greater weight to the larger of the two dimensions, despite the fact that they often fell prey to this tendency in the perception condition. However, their response patterns indicated that they systematically attributed greater weight to width (regardless of how large the width was). Although the two variables had identical objective sizes, the share of variance explained by the width factor was four to five times greater than that explained by the height factor. Observation of the children's behavior as they took the test provided information that was consistent with the phenomenon of greater weight attribution to width. Unlike the adults, the children were relatively passive, merely registering information in a constant order, width first (the dimension for which they already showed a marked preference in the perception condition), then height.

The performance of the 9-year-olds differed little from that of the younger children, except that the height dimension was taken into account to a greater extent. This may be due to the fact that they have learned how to read, and hence have automated the left-to-right reading order (used in western countries). More children may therefore have considered the height dimension first. With regard to the integration rule, the 9-year-olds simply returned to the additive rule. This rule was applied almost perfectly, the absence of area information preventing competition effects from the area rule (Eq. (2)).

For the adults, the mean pattern and eight individual patterns out of ten were basically compatible with Eq. (5). This was quite unexpected. It was as if the adults, like the very young children in the perception situation, fell prey to the greater-weight-to-larger-dimension bias. Observation of the behavior of the adults as they took the test might contribute to explaining this finding. Through-out the test, the adults approached the problem in an active way, systematically turning their heads from right to left. This activity was probably aimed at determining which of the two dimensions was the larger. Once that dimension had been identified, the adults, being unable to apply the rule described by Eq. (2), probably proceeded sequentially, processing the dimension with the larger size first, then the other dimension. An attention decrement (Anderson, 1981) can thus be evoked to account for the difference in weighting.

Taken as a whole, the results supported (a) the use of a direct area judgment rule by adults in a perception condition (as well as other equivalent rules), (b) the combined use of an area judgment rule and a dimensional rule with an additive structure by 9-year-old children in a perception condition, and (c) the use of a sequential rule with an additive structure, such that the item considered first (varying across situations) is attributed the greater weight by 5-year-old children in a perception condition. The last rule is also the one apparently used by the adults and 9-year-olds in the EHWI condition.

The hypotheses stated above could be tested by facilitating the visual scanning of the two stimuli by placing them in the same direction relative to the subject, but still in such a way that the area could not be directly perceived. This test was the basis of Experiment 2.

EXPERIMENT 2

In this experiment, two stimuli were placed in front of the subject. Although the stimuli were far enough apart to require a head movement to be seen, this arrangement was expected to facilitate information pick-up. Young children, who could now move visually from one stimulus to the other more easily than in Experiment 1, were expected to attribute a greater weight to the larger dimension, as mentioned above. In contrast, adults, now better able to represent the figures mentally, were expected to have a response pattern corresponding to Eq. (2). Finally, 9-year-olds were expected to show a parallel pattern. It seemed unlikely that 9-year-olds would be able to apply the strategy consisting of mentally representing an area on the basis of vertical and horizontal line information, even when the lines were located in the same field. (Note, however, that Wilkening, 1982, showed that 5-year-old children were capable of imagining the distance covered by an animal traveling at different speeds and moving for different periods of time, provided they were visually exposed to the animal's path).

Method

Participants. Thirty participants living in the same area as in Experiment 1 took part in the experiment. The group mean ages (and age ranges) were also the same (mean adult age: 26;2). Each group included the same number of males and females with middle- or lower-class backgrounds.

Material and procedure. The material was composed of the 10 sheets of white paper used in the EHWI condition of Experiment 1. The response scale was the same.

The procedure was also the same as in the EHWI condition of Experiment 1, except that the sheets containing vertical lines and horizontal lines were presented in front of the subject, on the left for the vertical lines, and on the right for the horizontal lines.

Results

The results for each of the six subgroups are given in the upper panel of Fig. 2 (width and height separated). Inspection of the response patterns showed that they differed slightly in terms of convergence/divergence. The 5-year-olds' curves were almost parallel. The three curves were rising and clearly separated. The pattern for the 9-year-olds was convergent. The adult pattern was also converging, but to a lesser extent.

An analysis of variance was conducted on the entire set of data with an age $\times$ width $\times$ height ($3 \times 3 \times 3$) design. The main effects of width and height were significant. Neither the width $\times$ height interaction nor the age $\times$ width $\times$ height interaction was significant.

Two complementary analyses of variance were conducted. The first, with an age $\times$ condition (Experiment 2 vs. Experiment 1, EHWI condition) $\times$ width $\times$ height ($3 \times 2 \times 3 \times 3$) design, showed that the overall results obtained in Experiment 2 were not significantly different as to convergence/divergence from the overall results obtained in the EHWI condition of Experiment 1, $F(8,216) = 1.88$, n.s., for the higher level interaction. The second analysis, with an age $\times$ condition (Experiment 2 vs. Experiment 1, perception) $\times$ width $\times$ height design, showed that the overall results of Experiment 2 were significantly different as to convergence/divergence from the overall results of the perception condition in Experiment 1, $F(8,216) = 4.33$, $p < .001$, for the higher level interaction, and $F(1,27) = 13.10$, $p < .001$, for its trilinear component.

Individual results. The individual results are presented Table 5 (central panel). These results are in line with the overall results for the adults. Among 5-year-olds and 9-year-olds, there was no truly predominant pattern type. In all groups, however, divergent patterns were rare.

Discussion

With regard to the 5-year-olds, the hypothesized greater frequency of response patterns described by Eq. (5) was not observed, even though the number of children whose pattern converged doubled (going from 2 to 4). In fact, the very young children did not turn out to be notably more active in this experiment than in the first.

Compared to Experiment 1, few changes were found for adults and 9-year-olds. The response pattern was slightly convergent in 9-year-olds but less convergent (and thus more consistent with Eq. (3)) in adults. However, the overall differences between the results of the two experiments (EHWI condition of Experiment 1, and Experiment 2) were small and nonsignificant.

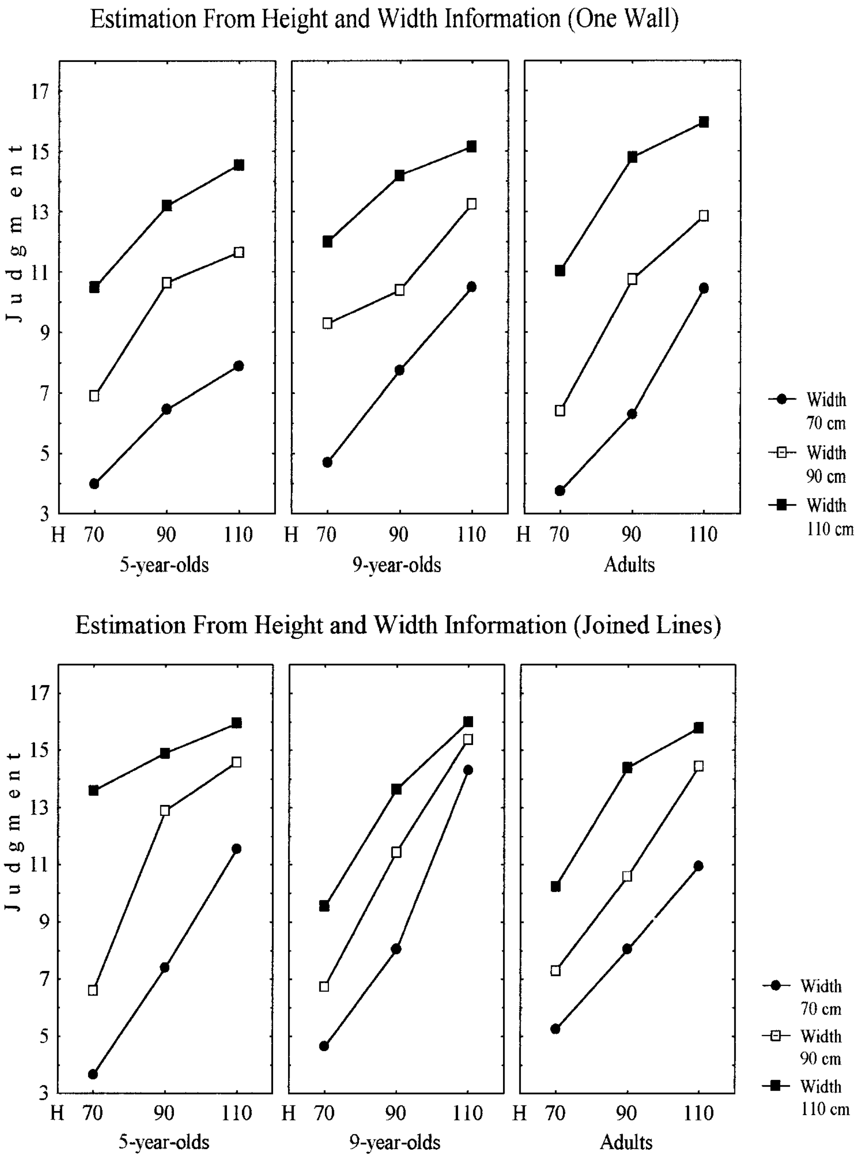

FIG. 2. Mean area judgments as a function of height and width in the one-wall condition and the joined-lines conditions for the three age groups (Experiments 2 and 3).

It is likely that the changes made for Experiment 2 were not sufficient to substantially influence the functioning of the participants. Greater changes were therefore introduced in Experiment 3.

EXPERIMENT 3

In Experiment 3, the two stimuli were touching each other (and hence very close to each other). The figure made by the stimuli was a classical coordinate-axis system: x (horizontal) and y (vertical). The two axes varied in length. Theoretically, the two stimuli could thus be seen at the same time without changing the position of the head. This was expected to facilitate comparison of the stimuli.

As in the previous experiment, young children, now better able to go visually from one stimulus to the other than in Experiments 1 and 2, were expected to exhibit a greater tendency to attribute more weight to the larger dimension. Adults, now better able to imagine the outline of the area (window), were expected to show a response pattern that was more indicative of Eq. (2). Parallel patterns were expected in 9-year-olds.

Method

Participants. Thirty participants living in the same area as in Experiment 1 took part in the experiment. The group mean ages (and age ranges) were the also the same (mean adult age: 26;9). Each group included the same number of males and females with a middle- or lower-class background.

Material and procedure. The material consisted of 11 sheets of white paper similar to those used in the perception condition of Experiment 1 except that only the part of each rectangle below the diagonal was drawn. In other words, only one width (out of two) and one height appeared on each sheet. The response scale was also the same.

The procedure was the same as in the perception condition of Experiment 1. The sheets showing one vertical line (y-axis) connected to one horizontal line (x-axis) were presented in front of the subject.

Results

The means for each of the three subgroups are given in the lower panel of Fig. 2 (width and height joined). Inspection of the response patterns showed that they differed moderately in terms of convergence/divergence. The pattern for the 5-year-olds was clearly convergent. The 9-year-olds pattern was also convergent. The adult curves were nearly parallel.

An analysis of variance was conducted on the entire set of data with an age $\times$ width $\times$ height ($3 \times 3 \times 3$) design. The main effects of width and height were significant. Both the width $\times$ height interaction and the age $\times$ width $\times$ height interaction were significant, $F(8,72) = 4.56$, $p < .001$.

Three other analyses of variance, with a width $\times$ height design, were conducted, one for each age group. For the 5-year-olds and 9-year-olds, the width $\times$ height interaction was significant, $F(4,36) = 11.05$, $p < .001$, and 4.31, $p < .006$, as was its bilinear component, $F(1,9) = 19.98$, $p < .002$, and 8.41, $p < .017$. In the adults, the bilinear component of the interaction was not significant.

Individual results. The individual results are presented in the right panel of Table 5. They are completely in line with the overall results. In 5-year-olds and 9-year-olds, the predominant pattern was convergence. In adults it was parallelism.

Discussion

Our hypothesis for 5-year-olds was clearly supported here. The response pattern of the 5-year-olds as a group, and seven out of ten individual patterns, were compatible with Eq. (5). When the stimuli were close enough to enable easy visual shifts, the 5-year-olds used the rule expressed in Eq. (5).

The 9-year-olds' response pattern was more unexpected, although in line with earlier results. In the EHWI condition of Experiment 1, the curves were parallel. In Experiment 2, the pattern was slightly convergent. In the present experiment, the pattern was markedly more convergent. Thus, across experiments, the number of convergent patterns increased from 2 to 4 to 9. It is possible that the 9-year-olds used the same rule as the 5-year-olds in the perception condition.

In adults, the overall and individual (8 out of 10) results were consistent with Eq. (3), although they did not provide much support for our hypotheses. The EHWI situation differed substantially from the perception situation, in that the adults were unable, as in the velocity judgment study by Algom and Cohen-Raz (1987), to apply the multiplicative rule with which they were certainly familiar. We thought that they would use a strategy consisting of imagining the outline of the area, so as to be able to judge it directly, quasi-perceptually. This did not appear to be the case.

EXPERIMENT 4

The purpose of Experiment 4 was essentially to replicate the results obtained in the previous three experiments. A number of results were either new or surprising. One expected result was the absence of greater-weight attribution to the larger dimension in 5-year-old children (Experiment 1, EHWI condition). This result supported our hypothesis that the children would always use the same sequential rule in this condition: width first, then height. The findings of Experiment 3 were consistent with this hypothesis. However, the patterns shown in Fig. 2 only pertain to a small number of participants. It was therefore absolutely necessary to replicate the results with a different group of participants of similar age.

The second, surprising result was the greater weight attributed to the larger dimension by adults. This result was totally unexpected. If it were possible to replicate it, this would mean that area estimation from width and height information is actually a very difficult cognitive task. All our adult participants were clearly aware of how area, width, and height are related. Is it possible that their performance drops substantially when the width and height values are presented separately using a graphic display?

The third, unexpected result was the greater weight attributed to the larger dimension by 9-year-old children in the width and height joined condition. We have no explanation for this result, other than the one suggested to account for the same findings in 5-year-olds. The fourth, also surprising result was the parallel curves in adults (Experiment 3) in a condition (width and height joined) in which they would normally have been able to imagine the outline of the areas presented.

Apart from the fact that the number of participants in Experiments 1 to 3 was relatively small (though of the same order as in other studies published on the subject: 9 participants in each condition in Wolf, 1995, Experiment 1), comparisons between conditions were difficult because the results were obtained with different participants each time. In the present experiment, the same participants were placed successively in the different conditions. This was designed to facilitate comparisons, although the within-participant procedure has certain disadvantages in relation to the between-participant procedure used in Experiments 1 to 3, in particular, the potential transfer of knowledge across experiments (Mullet, 1992; Reed & Evans, 1987). To minimize such learning effects, the testing order of the four conditions was arranged so that there was the smallest possible amount of transfer from one situation to the next. The order was as follows: EHWI condition of Experiment 1, EHWI condition of Experiment 2, EHWI condition of Experiment 3, perception condition of Experiment 1. Counterbalancing the order of the tests would, for example, have led certain participants to go from the perception condition to one of the EHWI conditions. Such a move would have offered transfer possibilities that we deemed to be too great (whereas in the opposite situation of moving from an EHWI condition to the perception condition, we felt that the possibilities of transfer were reduced to a minimum). These potential order effects would have hindered the comparability of the results of Experiments 1–3 and this experiment.

Thus, the expected findings for Experiment 4 were (a) no greater weight attribution to the larger dimension by children aged 5 (and 9) in the separated width and height conditions (right and left, and front); (b) greater weight attribution to width by children aged 5 (and 9) in the separated width and height conditions (right and left, and front); (c) greater weight attribution to the larger dimension by adults in the separated width and height conditions and different walls condition; (d) greater weight attribution to the larger dimension by 9-year-old children in the joined width and height condition; and (e) parallelism of curves for adults in the joined width and height condition.

Method

Participants. Thirty participants living in the same area of France took part in the experiment (15 males and 15 females with middle- or lower-class backgrounds). The group mean ages (and age ranges) were exactly the same as in the previous experiments. The adult age mean was 27;9.

Material and procedure. The material was the same as in Experiments 1 to 3. Participants in each of the three age groups were randomly assigned to all four conditions, defined by the type of task (from EHWI to perception). The condition order was always as (a) EHWI presented to the left and to the right of the participant, (b) EHWI presented in front of the participant, (c) estimation from two joined lines (as in Experiment 3), and (d) perception of rectangles. There were three trials for each condition. The time lapse between each test session was three or four days for each participant.

Results

The mean results for each of the twelve subgroups are presented in Figs. 3 and 4. Inspection of the response patterns showed that they did not differ considerably in terms of convergence/divergence from the corresponding patterns in Figs. 1 and 2. The only difference concerned the group of adults in condition 3 (estimation from two joined lines as in Experiment 3). In the present experiment the pattern was slightly divergent. In Experiment 3 it was parallel. A closer look at the two corresponding graphs obtained in Experiments 3 and 4 showed that the difference between them could be reduced to the difference in position of a single point, the 110 × 110 point. In Experiment 3, the 70- and 90-cm curves were diverging and the 70–90-cm segment of the 110-cm curve was also diverging. Only the 90–110-cm segment converged. This phenomenon may correspond to a ceiling effect.

An analysis of variance was conducted on the entire set of data with an age × condition × width × height (3 × 4 × 3 × 3) design. As in Experiment 1, the age × condition × width × height interaction was significant and was mainly concentrated on the quadrilinear component, $F(1,27) = 14.72$, $p < .0001$.

Six complementary analyses of variance, with a condition (1 vs. 2 or 3 vs. 4) × width × height were performed, two for each age group. The width × height interaction was only significant in adults (conditions 3 vs. 4) and 5-year-olds (condition 3 vs. 4). In these two cases, the interaction effect was mainly concentrated on the bilinear component. The condition (1 vs. 2 or 3 vs. 4) × width × height interaction was usually not significant. In terms of divergence/convergence, conditions 1 and 2 or 3 and 4 generally produced the same result patterns. The only difference concerned the 9-year-olds, for conditions 3 vs. 4. Two complementary analyses of variance were conducted, one for each of the two conditions. In each case the bilinear component of the width × height interaction was significant.

Discussion

The most striking result was the resemblance between the mean response patterns obtained in Experiment 4 and in Experiments 1 to 3. A response pattern of a certain type (convergent, divergent, or parallel) seen in Experiments 1 to 3 almost automatically had its replica in Experiment 4. The following results were

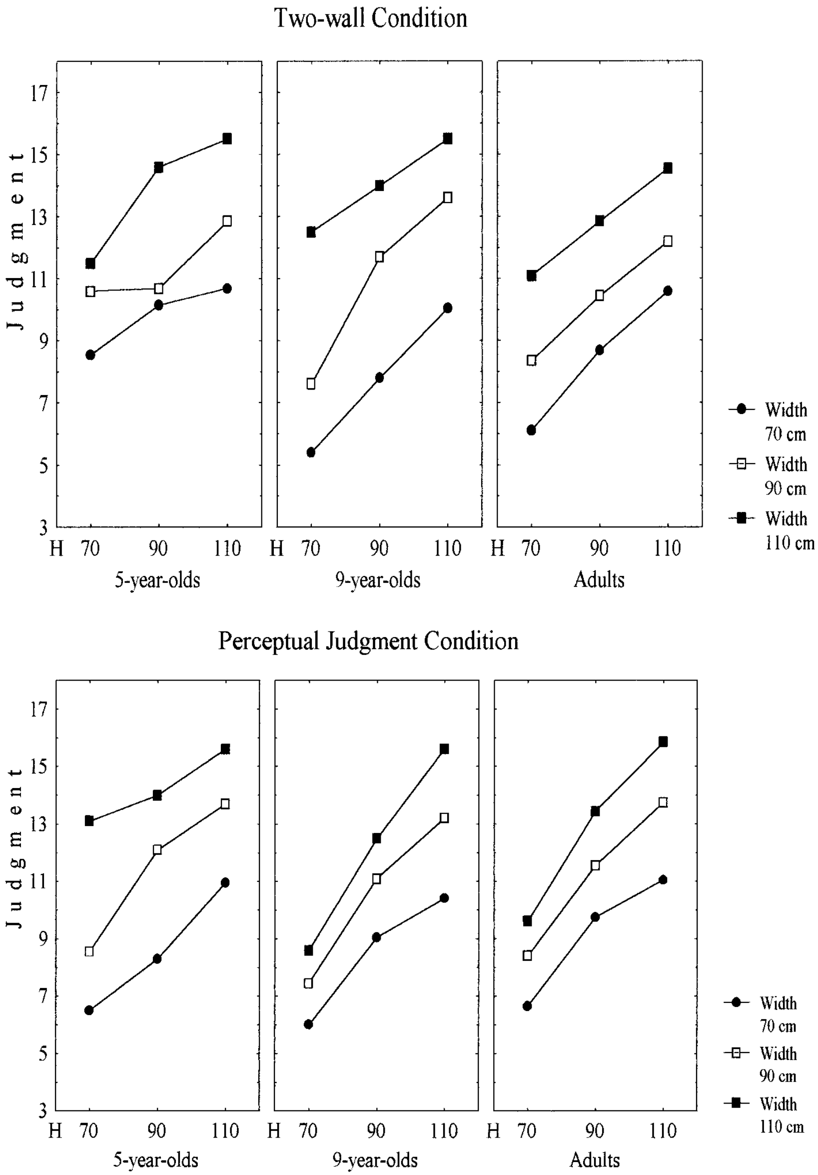

FIG. 3. Mean area judgments as a function of height and width in the estimation from height and width information condition (two walls) and the perception condition for the three age groups (Experiment 4).

seen in particular (a) no greater weight attribution to the larger dimension by 5- and 9-year-old children in conditions 1 and 2 (width and height shown separately); (b) greater weight systematically attributed to width by 5-year-old children

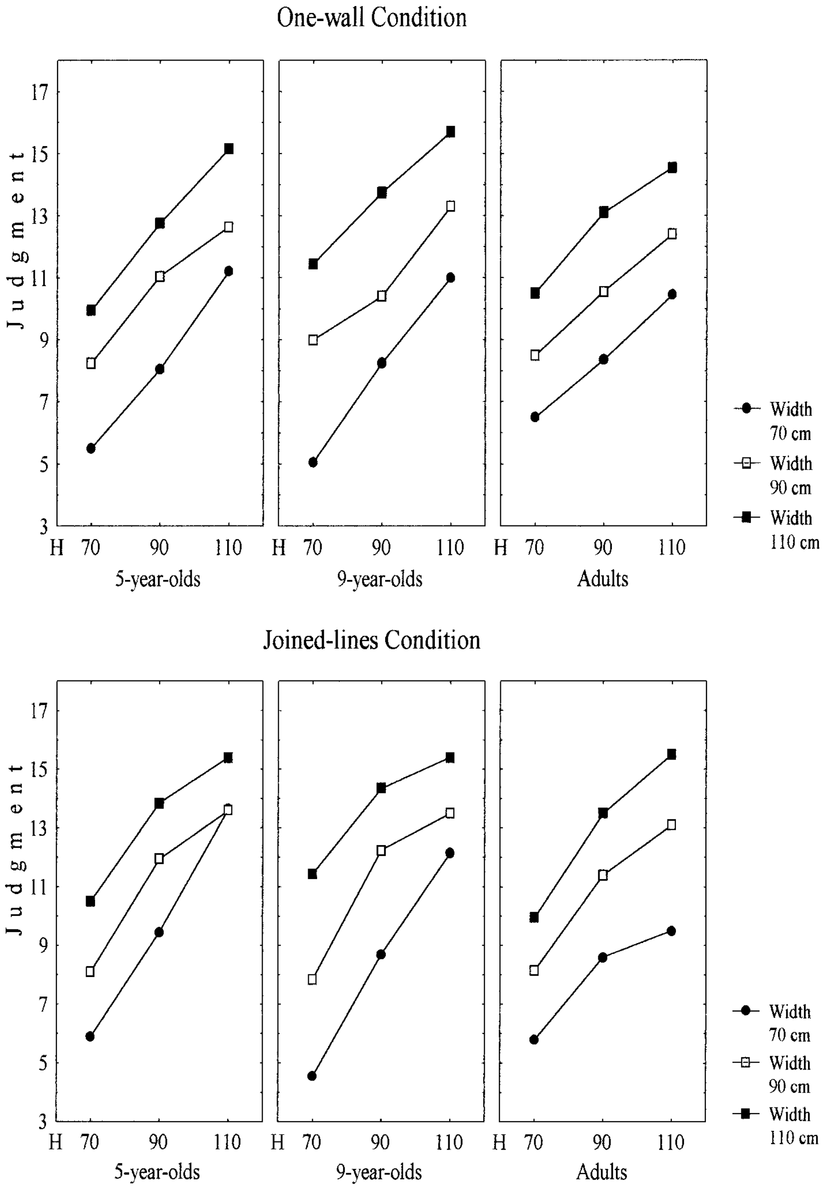

FIG. 4. Mean area judgments as a function of height and width in the one-wall condition and the joined-lines condition for the three age groups (Experiment 4).

in condition 1; (c) attribution of greater weight to the larger dimension by adults in condition 1 (width and height separated and on two different walls); (d) attribution of greater weight to the largest dimension by 9-year-old children in condition 3 (width and height joined). Overall, then, we can consider the results of Experiments 1 to 3 to have been replicated.

There was only one noteworthy difference, which concerned the adults in condition 3 (width and height joined). In this condition, adults used a multiplicative rule, and probably directly judged area by imagining it from the axes (x and y) provided. Close examination of the two patterns suggested that the difference between Experiments 3 and 4 might have been due to a ceiling effect in Experiment 3.

Another, less striking difference concerned 9-year-old children in the perception condition. The curves were notably more divergent in Experiment 4 than in Experiment 1. This might be indicative of a cumulative learning effect during the three tests preceding the perception condition.

GENERAL DISCUSSION

The shift from perception to inference had different effects for participants of different ages. The 5-year-olds' response patterns were such that one might be tempted to think that the rule they used in the EHWI condition—a rule close to that described by Eq. (3)—was more elaborate than in the perception condition—a rule close to that described in Eq. (5). The only aspect of the rule that actually appeared to change concerned its point of departure. When the width and height dimensions were shown side by side, i.e., when interdimensional comparison was facilitated, the integration process may have been preceded by a process of selection of the larger dimension. This dimension may then have been taken as the point of departure for a sequential integration process. This would lead to attribution of greater weight to the larger dimension, a phenomenon well described by Eq. (5). When the width and height dimensions were not shown side by side, the integration process may have automatically taken one of the two available dimensions as its basis, and most often the same one (width in this study). This means that there would be no preliminary interdimensional comparison process, but rather, attribution of greater weight to the first dimension integrated. Furthermore, the possible presence of area information appears to have had no effect. The algebraic structure of the integration process was invariably additive. Attribution of greater weight to one of the two dimensions brings to mind the absolute centering phenomenon seen in classical conservation tests, for which a very active intradimensional but also interdimensional comparison process is necessary most of the time, and for which the two stimuli, although generally close from the standpoint of distance, are nevertheless not joined.

The 9-year-olds' response patterns were such that it would be tempting to consider the variations to be U-shaped. When the width and height dimensions were not shown side by side and the interdimensional comparison process was made very difficult, the integration process could automatically take one of the two available dimensions as its basis, and most often the same one (height in this study). As in the younger children, there may not have been a preliminary interdimensional comparison process. When the width and height dimensions were shown in the same visual field, and even better, when they were shown side by side, the integration process may have been preceded by a process of selection of the larger dimension. This dimension may then have been taken as the point of departure for the actual integration process. When area information was provided, it was taken into account, probably concurrently with the other two items. In the 9-year-olds, the greatest contrast occurred between the perception condition and the EHWI condition with dimensions joined. The fact that an interdimensional comparison process appears to have been initiated once the stimuli were in the same field of vision can be considered in relation to the fact that most 9-year-old children are successful in simple conservation tests (quantity), which require making interdimensional comparisons.

The adult integration patterns were such that the impression given was strictly the opposite of that triggered by the 5-year-olds. When area information was provided by the stimuli or when it could easily be imagined because of their arrangement, this information was taken into account, and probably only this information. When area information was not provided and when it was difficult to imagine (when the width and height dimensions were not shown side by side), a process of comparison of the two dimensions may have taken place. This process would result in the selection of one of the two dimensions. As for the 5-year-olds in the perception condition, the chosen dimension served as a basis for the integration process, the structure of which would therefore be dimensional and additive. In adults, the greatest contrast was between the perception condition and the EHWI condition with completely separated dimensions.

Area estimation from very markedly separated width and height information appears to be a difficult task compared to other, previously studied estimation tasks. In an estimation task of the distance covered using speed and time information, Wilkening (1982) showed that while children applied a time-minus-speed rule, adults were perfectly capable of applying the correct multiplicative rule. In a study involving balancing of the arms of a pair of scales, Surber and Gzesh (1984) showed that college students estimating how far from the center a fixed weight should be placed in order to balance another weight of variable mass situated at a variable distance from the same center, applied the correct multiplicative rule.

Thus, it was clearly established in all of these studies that regardless of the value to be judged, adults were capable of applying a multiplicative rule. In these same tasks, the performance of children between the ages of 8 and 10 also appeared to be better than that seen in the present study. The reason for these differences probably lies in the level of familiarity with these situations. To infer the distance that a fast animal (a rabbit) will run in five seconds (the time it takes to load a rifle and fire) is an intellectual activity that has been entrenched in the human psyche since ancient times. The same applies to adjusting scales, since balancing one's own body is subject to the same rules.

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