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The visual and visuo-haptic exploration of geometrical shapes increases their recognition in preschoolers

Solène Kalenine[1], Leatitia Pinet[1] and Edouard Gentaz[1]

Abstract

This study assessed the benefit of a multisensory intervention on the recognition of geometrical shapes in kindergarten children. Two interventions were proposed, both conducted by the teachers and involving exercises focused on the properties of the shapes but differing in the sensory modalities used to explore them. In the "VH" intervention, the visual and haptic modalities were used to explore the raised shapes while only the visual modality was involved in the "V" (Visual) intervention. We compared the effect of the two interventions on the acquisition of conceptual knowledge about squares, rectangles and triangles in 72 preschoolers. Results showed that children progressed more importantly following VH than V intervention for rectangles and triangles. The addition of the haptic modality in intervention provides beneficial effects by allowing children to better understand what is included in a shape category. Results are discussed in relation to the multimodal coding (in line with embodied theories) and the analytic perception generated by the haptic modality.

Keywords

category, hand, learning, shape, space, touch

This study assesses the effects of multisensory intervention on the recognition of geometrical shapes in kindergarten children. Geometrical shapes can be considered as categories including an infinite number of shape exemplars that share common properties. The abstract knowledge of the properties that define these categories allows humans to organize their geometrical knowledge and to successfully process any new shape exemplar (Neisser, 1976). The correct recognition of geometrical shapes in preschoolers is an important prerequisite of positive adaptation to elementary mathematics, and plays a crucial role in the development of spatial orientation (Lee & Spelke, 2008; Shusterman, Ah Lee, & Spelke, 2008). For instance, preschoolers use the geometrical information in simple two-dimensional maps to orient themselves in a three-dimensional environment (Shusterman et al., 2008). However, educational psychological studies carried out in different countries and for different age groups revealed that geometrical shape recognition is not trivial and depends on the shape exemplar used (Clements & Battista, 1992; Clements, Swaminathan, Hannibal, & Sarama, 1999; Kouba et al., 1988; Usiskin, 1987). Younger children seem to progress from an early phase, when they categorize shapes according to their resemblance to a prototype, to the adult-level of knowledge when they use abstract rules for categorization (Satlow & Newcombe, 1998). Before elementary school, young children correctly recognize typical exemplars (i.e., exemplars with frequently occurring features) but are not able to overcome atypical appearances to classify shape exemplars depending on their defining properties. For example, 5-year-olds consider a shape built by cutting out the vertex of an isosceles triangle makes a good exemplar of a "triangle", although they refuse to include irregular, asymmetrical triangles in this category. More recently, Pinet and Gentaz (2007, 2008) conducted a shape recognition study in 5-year-olds that included square, rectangle and triangle exemplars with a wide range of length ratios, orientations, and contour discontinuities. They showed that at the age of 5, the best recognition of squares, rectangles or triangles among distractors is obtained for some particular exemplars in each category, such as (a) the square aligned on the horizontal axis, (b) horizontal and vertical rectangles with a ratio of 1.5 between the small and large sides, (c) equilateral triangles with a horizontal base and (d) vertical isosceles triangle with a ratio of about 1.5 between the longest sides and the shorter base. These shape exemplars may constitute prototypes of each category (Rosch, 1973; Rosch & Mervis, 1975). Thus, the challenge for the present study was to develop and compare different modes of interventions to improve preschoolers' recognition performance of geometrical shapes while carefully taking into account the prototypicality factor.

Very few studies had previously examined how different types of interventions could help the acquisition of geometrical knowledge in children. Prigge (1978) showed a positive effect of the introduction of manipulation experience in 5-year-olds' learning of geometrical concepts (e.g., the concepts of line, of angle, of rectangle, of triangle). Three interventions were compared. Each intervention involved 10 exercises (one per day) but different materials. The "Written" intervention consisted of classic paper-and-pencil exercises that included explanations of each concept followed by

[1]Université Pierre Mendès-France, France

Corresponding author:
Edouard Gentaz, CNRS-LPNC, Laboratoire de Psychologie & NeuroCognition, BP 47 Domaine Universitaire Université Pierre Mendès France, Grenoble 38040 Cedex 9, France
Email: Edouard.Gentaz@upmf-grenoble.fr

questions to be answered about the particular concept. In the "Two-dimensional manipulative intervention", the exercises were associated with 2D manipulative aids: geoboard, georuler, and paper-folding. In the "Three-dimensional manipulative intervention", the exercises involved the demonstration and manipulation of geometric solids: cube, tetrahedron, clay for forming solids, parallelepiped, and a box of assorted solids. Results showed a greater improvement of childrens' performance after the third intervention involving 3D manipulation than after the first and second interventions, especially in children with a low level of geometrical knowledge. Although this study suffers from severe methodological limitations (the activities in each intervention are not detailed, the equivalence of the interventions is not controlled, the post-test is different from the pre-test, etc.), these findings tend to suggest that the development of conceptual knowledge about geometrical shapes, like the formation of concrete object concepts, would be closely linked to sensory-motor experience.

Indeed, growing evidence support embodied views of concepts (Barsalou, 2008; Borghi, 2005; Gallese, & Lakoff, 2005). Several studies have demonstrated that participants run multi-modal simulations of objects when processing concepts (Barsalou, Pecher, Zeelenberg, Simmons, & Hamann, 2005). Perceptual but also motor simulations would play a key role in conceptual processing. Motor information about how objects have been manipulated is automatically reactivated when concrete objects are presented (Chao & Martin, 2000; Creem-Regehr & Lee, 2005; Grafton, Fadiga, Arbib, & Rizzolatti, 1997; Grezes & Decety, 2002). The reactivation of some aspects of motor experience can in turn facilitate conceptual processing of such objects (Borghi et al., 2007; Kalénine, Bonthoux, & Borghi, 2009; Mounoud, Duscherer, Moy, & Perraudin, 2007) and may help conceptual development. Arguments in favor of this assumption come from research on multimodal perception. Three-dimensional shape recognition is improved when adult participants can explore an object in the haptic modality in comparison to visual-only exploration (Craddock & Lawson, 2008; Wijntjes, Volcic, Pont, Koenderink, & Kappers, 2009). The benefit of multimodal exploration has recently been extended to raised letters: several studies indicate a positive effect of visuo-haptic exploration of cursive raised letters in the learning reading acquisition in preschoolers (Bara, Gentaz, & Colé, 2007; Bara, Gentaz, Sprenger-Charolles, & Colé, 2004; Gentaz, Colé, & Bara, 2003; Hillairet de Boisferon, Gentaz, & Colé, 2007). Taken as a whole, these findings indicate that the facilitation induced by multimodal processing of objects, especially visuo-haptic exploration, can be generalized to various domains and to different age groups, i.e., young children and adults (Fredembach, Hillairet de Boisferon, & Gentaz, 2009; Gentaz, 2009).

The main objective of the present study was to compare two different ways to acquire experience about geometrical shapes. In comparison to visual experience alone, we assumed that increasing multi-modal experience during school interventions by focusing on both visual and haptic modalities may facilitate the recognition of geometric shapes in kindergarten children. Moreover, we hypothesized that interventions would particularly help the recognition of shapes and exemplars for which preschoolers have the most identification difficulties. Shape category and typicality of exemplars have not been taken into account in the previous studies. Regarding shape categories, the recognition of circles among distractors usually appears far more successful (the recognition of circles was almost perfect in 5–6-year-olds; Pinet & Gentaz, 2007, 2008) than the recognition of squares, rectangles or triangles. Thus, we focused interventions on the shape categories which are not already acquired by preschoolers, namely squares, rectangles and triangles. In addition, since the prototypicality of exemplars appears to influence performance, we carefully introduced both prototypical and non-prototypical exemplars in the assessment of each shape category. Finally, a crucial goal of the present study was to test the "ecological validity" of interventions. Such interventions would have strong educational implications only if they could further be integrated in classes in a systematic way. Thus, our interventions were conducted by the classroom teachers. The few studies on reading acquisition in which training was led by the teachers showed that they were effective in teaching phonemic awareness. However, the effect on reading was smaller than for the interventions led by researchers (Ehri et al., 2001). Nevertheless, it seems that intervention efficiency results from the training attended by teachers. Previous studies (Bara et al., 2007; Blachman, Tangel, Wynne-Ball, Black, & McGraw, 1999) have shown that after giving teachers specific training on the goals and the procedure of the intervention, no difference remained between teachers and researchers. Consequently, in our study, teachers received specific training equivalent to the training given to researchers in our previous research.

Overall, we expected that preschoolers' performance would increase after both interventions but that greater improvement should be observed following the multisensory intervention (VH) than following the classic intervention (V). Moreover, the effect of interventions, and particularly the multisensory intervention, should be more important for shape categories which are hardly recognized by preschoolers. As we introduced prototypical and non-prototypical exemplars, we considered that interventions may further improve the recognition of non-prototypical shape exemplars.

Method

Participants

Seventy-two 5-year-old children (39 boys and 33 girls) selected from a sample of 106 children, with a mean age of 5 years 5 months (5–6 years), took part in this study. Since our learning experiment involves a pre-test, several intervention sessions and a post-test, in the study we only included the children who could attend the two test sessions and most of the intervention sessions. Therefore, the data from 34 children of the initial sample who missed one of the test session or more than one intervention session (due to sickness or unpredicted school absence) were removed from the analysis.

Children were attending preschool in five different classes. In each classroom, children in the two intervention groups were strictly matched on each of the following criteria: age and performances at the pre-test (mean scores of correct response—max. 6—and errors—max 14—for square, rectangle and triangle), presented in Table 1. In total, there were 36 children from the five different classes in each intervention group. The present study was conducted in accordance with the Declaration of Helsinki.

Material and procedure

The three categories of plane geometrical shapes studied (square, rectangle and triangle) were chosen with regard to the contents of the instructions of the Department of Education of French Ministry. The instructions specify that children must master these basic geometric concepts before entering elementary school. Because young

Table 1. Mean numbers (Standard Deviations) of correct responses (maximum 6) and errors (maximum 14) as function of shape, period and interventions.

	Correct responses (max. 6)			
Period	Pre-test		Post-test	
Interventions	V group	V-H group	V group	V-H group
Square				
M	4.36*	4.89	4.69	5.25
SD	(1.59)	(1.39)	(1.49)	(1.40)
Rectangle				
M	3.42 ns	3.14 ns	4.33	5.50
SD	(1.83)	(2.17)	(1.72)	(0.85)
Triangle				
M	4.25 *	3.50 *	5.25	5.44
SD	(1.52)	(2.02)	(1.52)	(1.03)
General Mean				
M	4.01ns	3.84 ns	4.82	5.39
SD	(1.64)	(1.86)	(1.57)	(0.76)
	Errors (max. 14)			
Period	Pre-test		Post-Test	
Interventions	V group	V-H group	Correct answers	Errors
Square				
M	2.36 ns	2.67	0.83	1.08
SD	(2.51)	(2.01)	(0.01)	(1.20)
Rectangle				
M	1.61 ns	1.78	0.50	0.56
SD	(1.69)	(2.07)	(0.81)	(0.97)
Triangle				
M	3.64 ns	4.22	0.58	0.53
SD	(3.74)	(3.68)	(0.63)	(1.34)
General Mean				
M	2.53 ns	2.89 ns	0.63	0.53
SD	(2.64)	(2.58)	(0.98)	(1.17)

Note. * indicates significant differences and ns indicates no significant differences among Visual and Visuo-Haptic groups concerning correct responses and errors in pre-test period.

children easily recognized circles, we thus decided not to include this shape in the present interventions.

Pre-tests and post-tests. The geometrical knowledge was measured by three pencil-and-paper tasks: one for each shape category (Figure 1). The presentation order of the three tests was randomized. The children were assessed approximately 15 days before (pre-test) and after the interventions (post-test). Each test contained 20 geometrical shapes, represented by their outline (0.03 inch in thickness) on a sheet of paper (in size A4, landscape). For each exemplar of shape, we checked the size (side of 4.5 inch length for the biggest to 0.2 inch length for the smallest), the orientation, and the ratio between the biggest and the smallest side. Each test presented six target shapes (i.e., six exemplars of the studied shape) and 14 distractors (i.e., 14 exemplars of non-studied shapes). Protypical and nonprotypical target shapes were empirically derived from children's performance before intervention (see the analysis on the pretest scores in the Results Section below). The 14 distractors of a test included eight categories of geometrical shapes that are perceptively closed to the studied shape. For example, the square-test contained six square exemplars and 14 other shape exemplars (rectangle, parallelogram, rhombus . . .) varying in size and orientation.

Three control children studies. Three control studies were conducted in additional classes on different children of the same age before starting the intervention study. The objective was to test the potential influence of the administration mode, the context of presentation and the representation of the shapes on shape recognition. In each control study, the same children performed two different versions of the recognition task with a two-week interval between the two versions. The order of the sessions was counterbalanced. In the first study (17 children), the shapes to identify were presented either all together on the same sheet, or one per page in a notebook. In the second study (24 children), the two versions of the recognition task corresponded to two different spatial arrangement of the shapes on the recognition sheet. The third study (20 children) compared two modes of representation of the shapes: outline only, or outline and colored surface. The results of the three control studies did not show any significant effect of the administration mode, the context of presentation or the representation of the shapes (all $p > .25$).

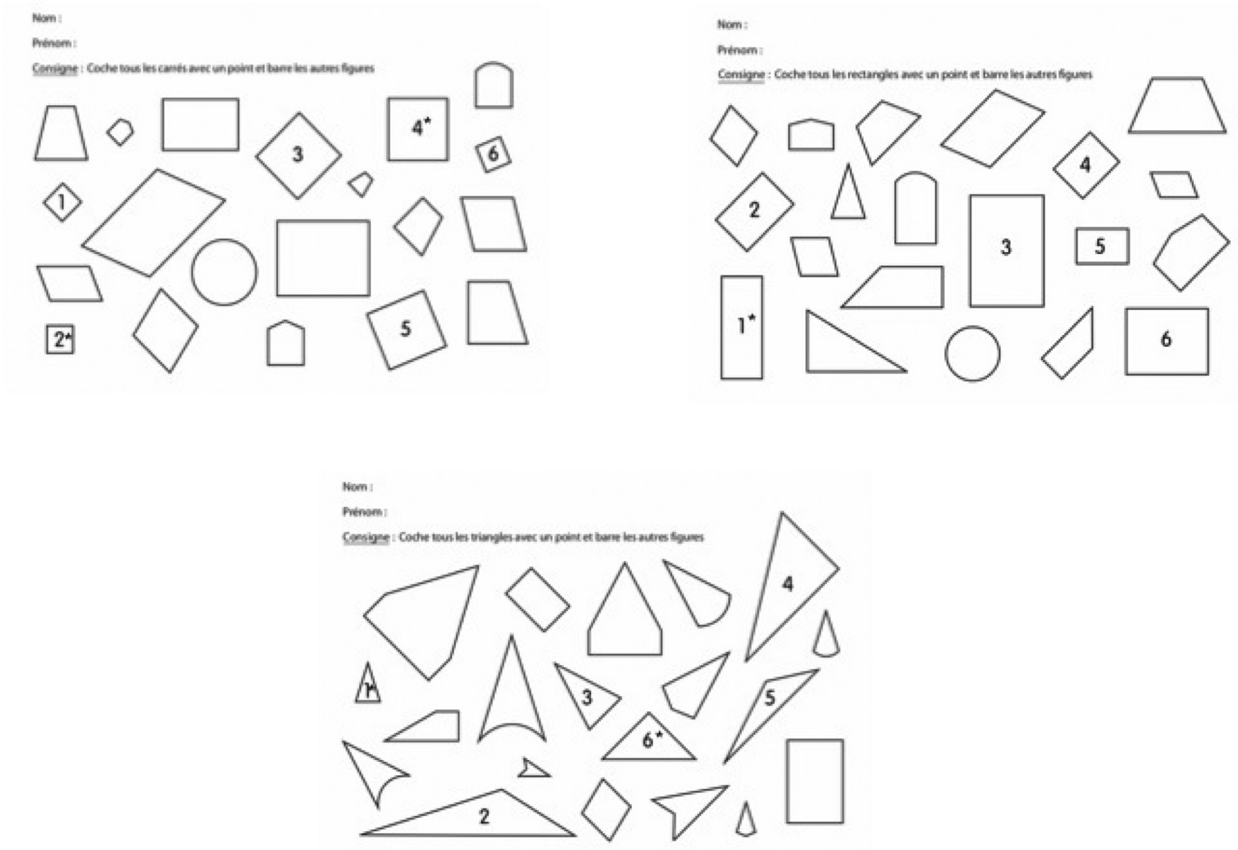

Figure 1. The three pen-and-paper tests proposed to the children. Target shapes are numbered from 1 to 6. The stars (*) indicated the prototypes of each shape category.
Note. The numbers (from 1 to 6) displayed inside the target shapes are not shown to children during the tests.

One control adult study. Beyond the precautions taken in the choice of the accurate target shapes and distractor shapes, we estimated the similarity between the target shapes on the one hand and the distractor shapes on the other hand for the three tests (square, rectangle and triangle). This control study was conducted to evaluate to what extent the effect of shape category would be related to differences in the visual similarity between targets and distractors within each category. For each test, we systematically associated each target shape with each distractor shape, resulting in 84 associations for the square, 84 for the rectangle and 84 for the triangle. The 252 associations were randomly distributed in four subsets. Each subset was estimated by eight different adults with no timing instructions (32 adults in total). They had to rate, on a 10-point scale, the similarity of all possible pairs of target and distractor shapes (from 1 = "looking a little like", to 10 = "looking very much like"). The instructions specified to judge on visual appearance only, considering the physical characteristics of the shapes. The distribution and the response mode are represented by a graph for each shape category in Figure 2. The results showed that the median is situated at 5 for the square and at 4 for the rectangle and triangle. These results revealed that similarity is judged higher between the square and its distractors than between the rectangle and its distractors, and between the triangle and its distractors.

Experimental procedure. The pre-tests and post-tests were carried out individually. The instructions were a) for the *square recognition test*: "Mark all the *squares* with a dot, and cross out the other shapes"; b) for the *rectangle recognition test*: "Mark all the *rectangles* with a dot, and cross out the other shapes"; c) for the *triangle recognition test*: "Mark all the *triangles* with a dot, and cross out the other shapes". No time requirement and no feedback were given to the child.

In each class, children were divided into the two intervention groups. Groups were equivalent to their performance at the pre-test, both on correct responses and errors. Other individual criteria (e.g., gender, general intelligence) were not considered so that individual factors were randomly distributed across groups. Each group was given a type of intervention: visual "V" or visuo-haptic "VH". There were 15 girls and 21 boys in the visual group, and 18 girls and 18 boys in the visuo-haptic group.

Using different materials, the objective of the interventions was to help children discover and use shape properties to identify geometrical shape exemplars. The interventions were proposed weekly to subgroups of no more than six children. Each intervention session was centered on the study of a geometrical shape category and its properties. There were two sessions per shape. The training sessions focused on the modal exploration of the shapes but also involved the justification of children's identification choices and the feedback from the group. The interventions took place during the school year, from March to April. The last session was a revision of the properties of the three shape categories. In total, there were seven sessions (3 shapes $\times$ 2 and 1 revision session). The intervention sessions always took place in the same way (the same

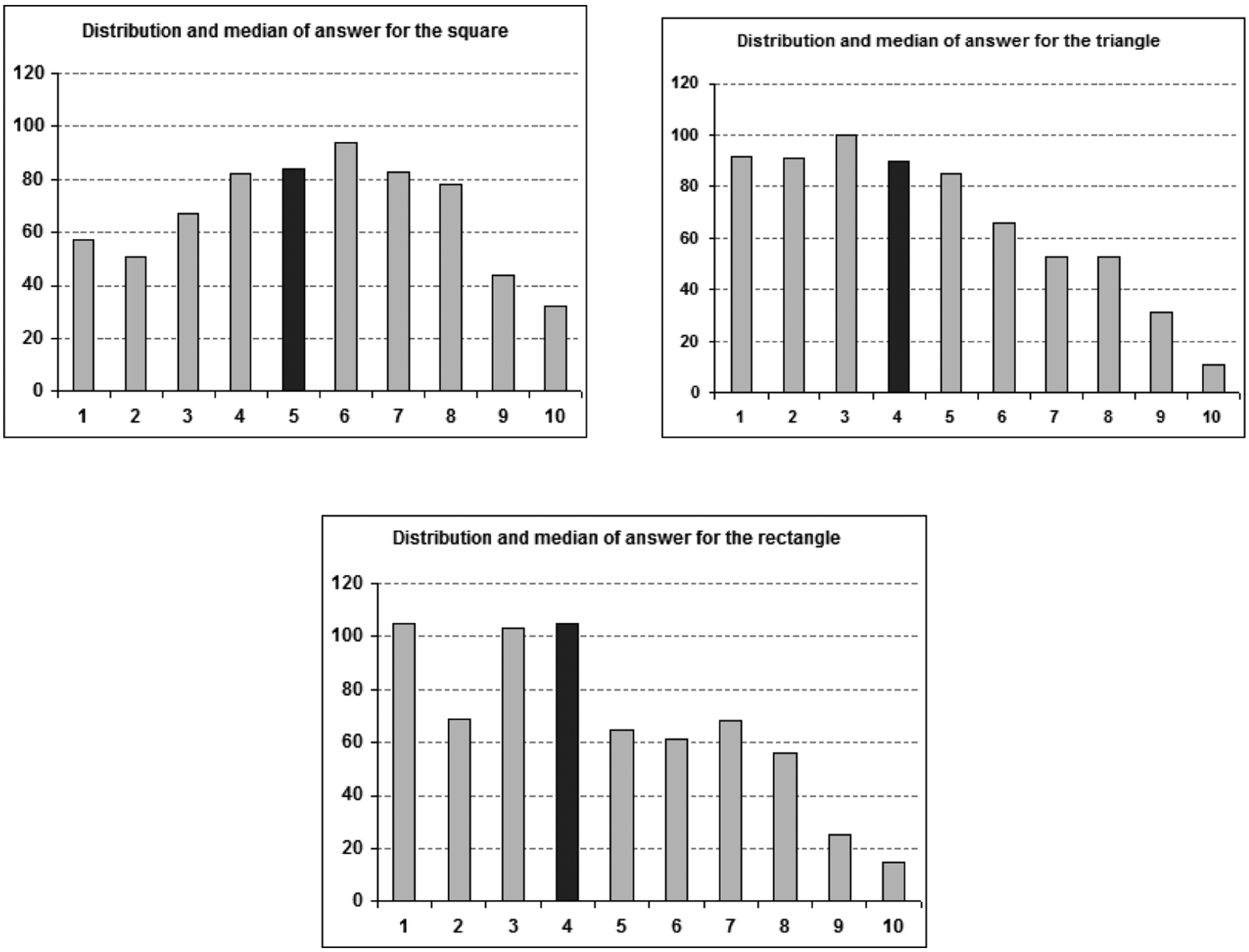

Figure 2. Frequency of each category of responses obtained in 32 adults for all 84 associations of square, rectangle and triangle. Measure of degree of perceptive similarity between the target shapes and distractors given by adults for the square, the rectangle and the triangle.
Note. Scale of 1 (looking a little like) to 10 (looking very much like); the median response is indicated in black.

exercises were carried out in the same order). Each intervention lasted approximately 25 minutes and took place in a classroom with the regular teacher. The intervention time for the sessions of the interventions "V" and "VH" was controlled and was strictly the same exercise by exercise (Table 2).

The children (groups of six maximum) sat around a table so as to ease the interactions between them. In each small group, the children participated equally and received an individual exercise. Although interactions between children were favored and feedback from the teacher was given at the end of each exercise, the children explored the shapes individually and had to give a personal response after each exploration (see Table 2). The correct response could not be inferred from the other children in the group, since the shape exemplars proposed were different for each of them.

Both interventions followed the same design. However, the "VH" intervention was carried out with shapes in relief (made of plastic foam 0.15 inch thick) while the "V" intervention was carried out with shapes printed on color paper. As in previous multisensory studies, we propose printed shapes in the "V" intervention because preliminary sessions showed that relief shapes induced children to manually explore them and, consequently, teacher to intervene ("don't touch the shapes"); the printed shapes avoided this interference. In both interventions, the shape exemplars proposed were strictly identical and were stuck on round supports in order not to favor a particular orientation. One part of the shapes was large-sized (21 shapes, 3.1 inch high, on a support 4.7 inch in diameter) and the other part was of smaller size (16 shapes, 1.6 inch high, on a support 2.7 inch in diameter). The shapes exemplars used during the interventions differed from those presented in the three assessment tests.

Results

The correct responses and the errors for the three shape categories before and after both interventions are presented in Table 1. Both correct responses and errors were of interest since poor performance on recognition tasks can result from not identifying all the present targets (omissions) and identifying distractors as targets (false alarms) independently.

Analysis on pre-test scores

We first analyzed correct responses and errors in shape recognition during the pre-test. A first $2 \times 3 \times 6$ analysis of variance (ANOVA) with intervention group (V and VH) as between-subject factor and

Table 2. Detailed description of a session focused on triangle shape category.

	Description of exercise
N°1	Each child discovers and investigates a wide triangle, randomly oriented, the objective being to validate its name (category) and its characteristics (properties) with the teacher. The proposed exemplars are varied. In the "V" group intervention, the children are invited to look accurately at the shape whereas in the "VH" group intervention, they first have to look at and touch the shape globally, and then follow its outline several times with their forefinger.
N°2	Once the exploratory movements are well mastered by the children, the teacher proposes the second activity. Each child has a wide hidden-faced shape. Moreover, a wide triangle is placed in the middle of the table, used as a referent during this exercise. One after the other, each child turns and discovers his/her shape. The children of the group are presented with different exemplars. After a moment of consideration, they decide if it is a triangle or not. The child also tries to justify their choice, and then the teacher validates the answer. The shapes belong to a set of 22 cards including 6 different triangles and 15 distractors
N°3	Then, every child discovers and investigates a small triangle, randomly oriented, and confirms again its name and its properties with the teacher. Next the teacher introduces the wide triangles and validates within the group the triangle concept by reminding some properties, this in spite of changes of size (small or wide), of ratio of sides (isosceles, rectangle . . .), of color and of orientation that can occur.
N°4	Afterwards, the teacher proposes a game of draw from the stock, with all the wide and small shapes, spread on the table, with their faces visible. One after the other, each child has to find an exemplar of triangle among distractors (12 exemplars of triangles among 25 other shapes). The child makes his/her choice, justifies it, validates it or possibly corrects it with the teacher. If the answer is correct, he/she keeps the triangle, if not, the shape is put back on the table.
N°5	When all the exemplars of triangles have been found, and all the children agree, the teacher proposes a classification activity of the remaining distractive shapes. A child selects one distractor, then describes it to the other pupils so that they can give him/her all the exemplars of this shape, to arrange them. The teacher validates all the answers. This development was the same for all five categories of distractors. The aim is to categorize the distractive shapes according to their properties but without naming them. During this exercise the difficulty is increased because there are more shapes, and with half of them being smaller, it requires a sharp discrimination.

shape category (square, rectangle, and triangle) and exemplars (1–6) as within-subject factors was conducted on the mean score of correct responses. A second 2 x 3 ANOVA with intervention group (V and VH) as between-subject factor and shape category (square, rectangle, and triangle) as within-subject factor was also carried out on the mean number of errors. In both analyses, no main effect of group was observed, confirming that both groups were equivalent before interventions [$F < 1$].

Results of the first analysis on correct responses also showed a main effect of shape category: squares were better recognized than both rectangles and triangles [$F(1,70) = 19.47$; MSe = 0.45; $p < .001$] and triangles were better recognized than rectangles [$F(1,70) = 4.41$; MSe = 0.48; $p < .05$]. In addition, planned comparisons were performed to test the existence of prototypical exemplars for each shape category (see exemplars on Figure 1). Dunnett's test adapted for the comparison of several means to one standard mean was used. As predicted from a previous study (Pinet & Gentaz, 2008), performance for the exemplars of squares n°2 (91 %) and n°4 (94 %) was equivalent, and was higher than for squares n°1 (56 %), n°3 (74 %), n°5 (79 %), and n°6 (68 %) [$p < .05$]. Independent of their size, these two squares with a horizontal side were better identified than the other exemplars of squares.

Regarding the rectangle category, exemplar n°1 with the small side aligned on the horizontal axis with a 2.5 relationship between length and width was supposed to be the prototype of rectangles. Rectangle n°1 (71 %) was better recognized than rectangle n°3 with the same orientation but with a lower ratio (1.25) between sides (62 %), than rectangle n°4 (30 %), rectangle n°5 (57 %) and rectangle n°6 (46%) [$p < .05$]. However, performance for rectangle n°1 (71 %) and rectangle n°2 (61 %), which was 45° oriented with a ratio of 1.6, did not differ significantly.

Regarding the triangle category, both isosceles triangles n°1 (87 %) and n°6 (83 %) were expected to be the prototypes of triangles and were indeed both easily identified. Triangle n° 1 was better recognized than triangles n°2 (50 %), n°3 (74%), n°4 (51 %) and n°5 (42%) [$p < .05$]. Triangle n°6 was better identified than triangles n°2, n°4 and n°5, but not triangle n°3, which was 45°-oriented with the same ratio as triangle n°1 [$p < .05$].

Analysis of children's performance improvement following interventions

Similar ANOVAs were conducted on the difference between post-intervention and pre-intervention scores. Again, a first $2 \times 3 \times 6$ analysis of variance (ANOVA) with intervention group (V and VH) as between-subject factor and shape category (square, rectangle, and triangle) and exemplars (1–6) as within-subject factors was conducted on the mean difference of correct responses. A second 2×3 ANOVA with intervention group (V and VH) as between-subject factor and shape category (square, rectangle, and triangle) as within-subject factor was also carried out on the mean difference of errors. While both groups significantly progressed following interventions (mean difference of correct responses and errors different from 0; $p < .05$), results revealed that children's performance increased more importantly after VH than after V intervention [$F(1,70) = 5.82$; MSe = 0.98; $p < .05$].

Moreover, we expected that children would improve more in the categories and exemplars that were less well identified during pre-test, namely a) rectangles and triangles and b) non-prototypical exemplars, particularly after VH intervention (see exemplars on Figure 1). Indeed, the advantage of VH over V intervention was greater for rectangles and triangles than for squares [$F(1,70) = 20.23$; MSe = 0.57; $p < .001$] for which performance did not improve overall (improvement for squares not different from 0, $p < .05$), see Figure 3. No difference was observed between rectangles and triangles on correct responses [$F < 1$] but errors decreased more strongly for triangles than for rectangles after interventions [$F(1,70) = 25.26$; MSe = 6.95; $p < .001$].

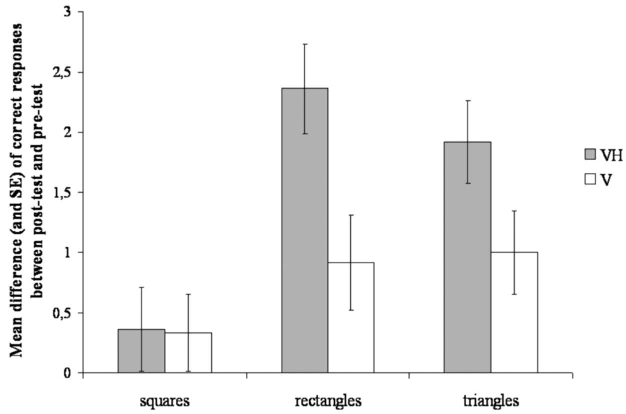

Figure 3. Mean difference and standard errors of correctly recognized target shapes between post-test and pre-test as a function of shape category (square, rectangle, triangle) and intervention group (VH, V).

Regarding the square category, analysis on pre-test scores showed that exemplars n°2 and 4 could be considered prototypes of squares. However, children's identification performance did not improve significantly more for the non-prototypical squares than for the prototypical ones and performance improvement for squares did not interact with the intervention group [$F < 1$].

Concerning the rectangle category, children made more progress for the non-prototypical rectangles than for prototypical rectangle n°1 [$F(1,70) = 4.67$; MSe = 0.16; $p < .05$]. Nevertheless, the advantage for non-prototypical rectangles over prototypical ones did not differ between intervention groups [$F(1,70) = 1.41$; MSe = 0.15; $p = .24$].

Finally, children's performance improvement was greater for non-prototypical triangles than for prototypical triangles n°1 and n°6 [$F(1,70) = 30.08$; MSe = 0.19; $p < .001$]. In addition, the reduced improvement of performance for prototypical triangles in comparison to non-prototypical ones was surprisingly more stressed following V than VH intervention, as indicated by the interaction between the type of triangle exemplars and the intervention group [$F(1,70) = 5.22$; MSe = 0.19; $p < .001$].

Discussion

In this study, we assessed the effect of specific school interventions on preschoolers' acquisition of geometrical knowledge while carefully taking into account the shape categories and exemplars used. The interventions were designed to increase children's experience with the geometrical shapes using either unimodal (visual) or multi-modal (visuo-haptic) exercises.

Before interventions, we found that a) 5–6-year-olds better recognized squares than rectangles and triangles, and b) performance was better for prototypical than non-prototypical exemplars in each shape category. More importantly, after interventions, the overall improvement of children's recognition performance was greater in the visuo-haptic (VH) than in the visual only (V) intervention group. In addition, the effect of interventions, and especially of VH intervention, was higher for the rectangle and triangle categories, which are hardly identified by preschoolers. Finally, results showed that for rectangle and triangle categories, interventions were even more decisive for the recognition of non-prototypical exemplars.

The effect of interventions depends both on the kind of intervention and the type of shape category. We did not find the expected increase of correct recognitions for squares following interventions, even for non-prototypical squares. Since children's proportion of correct responses approached ceiling at the pre-test for this particular category (4.65/6), we may not have been able to detect an improvement in square recognition following interventions with our task. This is surprising considering that the visual similarity between the target squares and their distractors was judged higher than for the other categories in the adult control study. Articulated with the absence of the effects of prototype and intervention for this particular category, this suggests that children did not rely on visual salience to categorize squares. One can speculate that 5-year-old children have reached a developmental level in which they are able to overcome appearances for this category and classify square exemplars depending on their defining properties (Satlow & Newcombe, 1998). On the contrary, interventions were crucial to help preschoolers to identify rectangles and triangles. For these categories not already acquired, the effect of VH intervention was consistently higher than in the V intervention.

The addition of the haptic modality in interventions provides beneficial effects by allowing children to better understand what is included in a shape category. Two non-exclusive explanations may account for these beneficial effects. First, the use of haptic exploration in the apprehension of shapes could generate a better memorizing and recognition of their characteristics. The haptic exploration of the shapes implied an inherent multiple coding in memory, at the same time, visual, haptic and motor. This multiple coding would create a more distributed trace in memory, which may facilitate and accelerate knowledge retrieval. In our study, the haptic episode would work as an additional clue for the further recognition of shapes. Recent imaging data (Stock, Röder, Burke, Bien, Rösler, 2009) support this idea: Using fMRI, authors report a greater involvement of somatosensory and motor brain areas during the retrieval of haptically encoded stimuli, in comparison to visually encoded ones. In line with embodied theories (Barsalou, 2008; Gershkoff-Stowe & Rakison, 2005), the first explanation of the visuo-haptic effect suggests that knowledge is distributed across the multi-modal brain areas. The second hypothesis is based on the functional specificities of each sensorial modality (Gentaz, Colé, Bara, 2003; Hatwell, Streri, & Gentaz, 2003). Haptic exploration necessarily induces a sequential, analytic processing of stimuli. The visual vs. haptic processing distinction would actually refer to a global vs. analytic processing difference. Using implicit word completion and explicit cued-recall tasks, Easton, Srivinas and Greene (1997) have demonstrated that differences between visual and haptic modalities do not subsist when stimuli are presented in a sequential way in both visual and haptic conditions. Here, properties of geometrical shapes are processed more sequentially and analytically when shapes are explored through the haptic modality than through the visual modality, particularly in 5–6-year-old children (Berger & Hatwell, 1996). The analytic processing of shapes induced by the VH exploration may help young children in dissociating and processing the geometrical properties that are specific to each shape category. To test this hypothesis, further studies could assess the effect of a visual intervention in which geometrical shapes would be presented in a sequential way.

In addition, our findings underline the effect of shape category and shape exemplar on preschoolers' recognition of geometrical shapes. Results for the rectangle category drew our attention. The benefit of the VH intervention was particularly high for the rectangle category. In the case of rectangles, children need to process many dimensions of the shapes to resolve the task, i.e. to distinguish rectangles from triangles and squares. They had to focus their attention on the number of sides and tops, on the length equivalence of parallel sides and on the perpendicularity. This may explain why rectangles are hardly recognized by preschoolers and largely benefited from the VH intervention. This result is congruent with the interpretation drawn by Jovanic, Duemmler, and Schwarzer (2008) from their study in 6–8-month-old infants. In this study, infants were habituated with two objects differing in three dimensions, either in a visual or visuo-haptic condition. They were then tested with a familiar object, a switch object differing according to one dimension in comparison to one of the familiar objects, and a novel object. A novelty response as indicated by an increase in the duration of the looks at the switch object was considered to reflect the ability to process objects in a configural way. Results showed that while only 8-month-olds were able to process objects configurally in the visual condition, both 6- and 8-month-olds demonstrated the ability to do so in the visuo-haptic condition. Thus, the visuo-haptic exploration would help to integrate different object properties into a whole.

Furthermore, we highlighted the typicality of specific exemplars of the three shape categories. We suggest that the prototype of a shape category can be derived from (a) the amount of common features between category members and (b) the amount of features that distinguish the exemplars of the category from the exemplars of the other categories, as put forward by Rosch (1973) and Rosch and Mervis (1975), but also from (c) the orientation and the proportion between the shape sides (Pinet & Gentaz, 2008). For these prototypical exemplars, the effect of interventions was reduced. Nevertheless, we did not find any systematic difference between VH and V on the recognition improvement of non-prototypical shapes. Moreover, the effect of protopypicality on triangle recognition was greater following V than VH intervention. One possibility may be that prototypical exemplars do not totally overlap in the visual and haptic modalities. Woods, Moore and Newell (2008) highlighted the existence of prototypes in the haptic domain. However, these canonical views differ from those classically reported for visual perception. The VH intervention might have favored different exemplars than the prototypical exemplars that were empirically identified in our visual test. Moreover, finer measures might be needed to highlight such fine-grained distinctions. In this direction, it may be interesting to integrate reaction times in recognition tests of geometrical shapes. Overall, the present results point out the necessity to take into account the shape category and the prototypically of exemplars in the domain of geometry acquisition.

Finally, this study has been conducted to assess the ecological validity of interventions. Teachers can conduct interventions successfully. Training performed by teachers and researchers (as in our past experiment) leads to similar intervention effects. Such results extended those obtained in studies on the acquisition of reading. To conclude, the present findings may have strong implications on further research on geometrical knowledge development. More importantly, they could provide crucial tools for teachers to improve geometry learning during classes. Multimodal interventions (Gentaz, 2009) may further be integrated in the classic preschool programs.

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