

A developmental difference in shape processing and word–shape associations between 4 and 6.5 year olds

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Abstract. In distinguishing individual shapes (defined by their contours), older children (6.5 years of age on average) performed better than younger children (4 years of age on average), and, although the task did not involve any categorization or generalization, the error pattern was qualitatively affected by shape differences that are generally common distinctions between objects belonging to different categories. The influence of these shape differences was also observed for unfamiliar shapes, demonstrating that the influence of categorization experience was not modulated by the retrieval of shape features from known categories but rather related to a different perception of shape by age. The results suggest a direct influence of categorization experience on more abstract shape processing. When children were distinguishing shapes, new words were paired with the target shapes, and in 2 additional tasks, the acquired name–shape associations were tested. The younger age group was able to remember more words correctly.

Keywords: categorization, generalization, shape perception, naming, development, plasticity.

1 Introduction

Shape of natural kinds is not arbitrary but depends on universal laws of organic growth (e.g., the golden ratio, Zeising, 1854) and on the biological evolution into different kinds (e.g., D'Arcy Thompson, 1917/1942). In this respect, shape reflects something about the developmental and evolutionary history of kinds. For artificial kinds, shape is often a necessary condition to fulfil a particular need, and small shape differences frequently reflect functional optimization. Therefore, children's reliance on shape in the formation of new natural and artificial categories is probably an essential predisposition. Indeed, many developmental studies have demonstrated its importance in an early stage of life (e.g., Gershkoff-Stowe & Smith, 2004; Landau, Smith, & Jones, 1988). Another indication of the importance of shape in categorization is the so-called shape bias, where it has been demonstrated that names are generalized to new objects that preserve the shape properties of a category (Landau & Leyton, 1999; Landau et al., 1988; Landau, Smith, & Jones, 1998; Smith, 2003). For instance, in the work of Landau et al. (1988), a new word (e.g., “dax”) was used to refer to a reference object. Participants relied on shape to generalize new words to new instances. However, when reference objects were not labelled but participants were instructed to select new objects that go together with the reference objects, participants seemed to rely less on shape, although still more on shape than on non-shape cues such as texture or size. In sum, participants rely more on shape when words are associated with them and it probably indicates that human experience with visual shape perception and category naming leads to the expectation that names are referring to objects that have similar shapes (see also Rosch & Mervis, 1975).

1.1 Different kinds of shape similarity

In vision research, it is sometimes crucial to control for the influence of category representations when a perceptual task involves familiar objects. For instance, manmade objects have more straight

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contour segments in their boundaries than natural kinds. We could hypothesize that it takes longer to distinguish a pair of manmade objects from each other than a manmade object from a natural object because the manmade objects share more similar boundary segments. However, manmade categories and natural kinds are also forming two separate cognitive categories, and cognitive factors could influence reaction times too. To exclude a potential influence from prior experience from known categories, one could try to create unfamiliar (nonexisting) objects for which no category representations exist but that have similar shape characteristics such as, for instance, contours composed of straight and curved boundary segments. However, it is difficult to define a set of similar shape characteristics between familiar and unfamiliar objects, and assumptions about the relevant shape characteristics are necessary. Therefore, many developmental studies of shape perception relied on one or another specific theoretical framework of object recognition such as, for instance, Biederman's (1987) "Recognition By Components" or RBC theory (e.g., Abecassis, Sera, Yonas, & Schwade, 2001; Haaf et al., 2003; Mash 2006). In RBC theory, object representations consist of structural spatial relations between volumetric parts called geons. Geons are considered to form the shape primitives of the visual system, and they consist of quasiregular volumetric shapes such as for instance cylinders and cuboids. New unfamiliar objects are then created by any arbitrary assemble of geons.

Here, we introduce changes to category-relevant and -irrelevant shape properties using a planar interpolation algorithm developed in the computer vision literature: thin plate splines or TPS (Bookstein, 1989; see also Ons & Wagemans, 2011, and the references therein). This tool allows us to make specific types of shape changes, which can be applied equally well on familiar and unfamiliar shapes, without having to make assumptions about shape primitives or without selecting manually salient contour points in a morphing algorithm (De Winter & Wagemans, 2008; Newell & Bühlhoff, 2002). More specifically, the TPS algorithm is able to extract a deformation scheme between a pair of two familiar contours, for instance, two contours from a different category. The deformation can be considered as a technical implementation of coordinate transformations in object recognition (Graf, 2006). Once the deformation scheme is determined between a pair of contours, it is possible to use the same deformation scheme on a new unfamiliar one, resulting into a second unfamiliar contour. When the initial transformation scheme is extracted from two contours from different basic-level categories, then the unfamiliar contours can be assumed to inherit similar category-relevant shape differences as they involve the same deformation scheme. Similarly, when the two original contours are members of the same basic-level category, then the derived unfamiliar contours from the same scheme can be assumed to inherit shape differences that do not imply any category change.

In Figure 1, some examples of this procedure are provided. These stimuli are also used in our experiment. In the upper half of Figure 1, there are pairs of contours related to the same and to different basic-level categories. The gridlines behind each donkey, dog, bowl, bottle, car, and hat demonstrate the planar transformations causing the deformation of the upper-left contour (including the rectangular grid in the background) into any other contour of the same cluster. Within each cluster, the horizontal contour pairs are members of the same basic-level class, while the vertical pairs are members of different classes. In the lower half of Figure 1, the same transformations are executed on unfamiliar contours (note that the curve paths of the grid lines do not fully correspond because they are initially located at slightly different positions in the image plane). Although the lower contours are not related to any familiar category, they can be assumed to inherit some within and between basic-level shape differences from the original contour pairs because they underwent the same planar transformations. For more technical details about this procedure, we refer to the Appendix.

The advantage of the latter approach is that we do not need to define relevant and irrelevant shape features explicitly, and therefore, we can relax the assumptions on the specific features and shape primitives involved in category representation, and thus, reduce the dependency of the study on a particular theory of object recognition.

1.2 The present study

The shape bias has mainly been investigated in the context of a name generalization task (e.g., Imai, Gentner, & Uchida, 1994; Landau et al., 1988; Smith, 2003; Smith Jones, & Landau, 1996) and demonstrates the influence of visual shape on category naming. Here, we intended to study whether human experience with categories and names also leads to biases in shape perception. Therefore, we focused on two kinds of shape differences: the first kind comprises shape differences that are irrelevant for determining the basic level of category ownership (therefore, in the current study, this con-

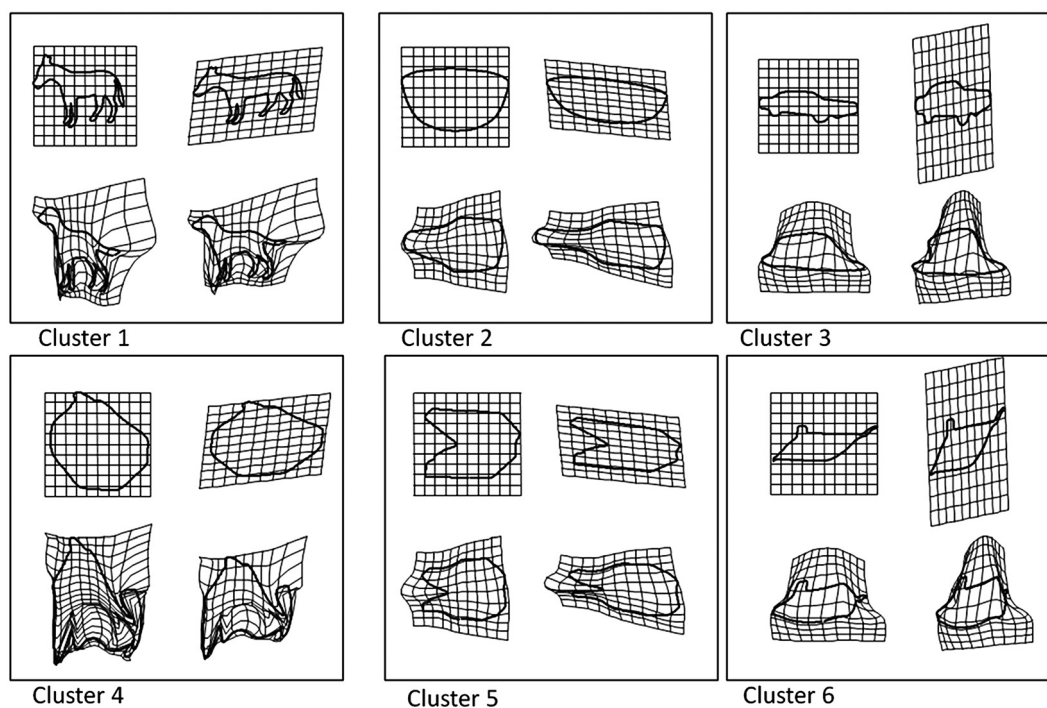


Figure 1. Category-relevant and -irrelevant shape differences, illustrated with the stimuli from the experiment (see text for an explanation).

dition is labelled “*Irrelevant*”), while the second kind comprises shape differences that are generally relevant for categorization (labelled “*Relevant*”). We investigated the influence of these two kinds of shape differences on children’s ability to distinguish individual shapes, and we examined children’s pattern of confusion between shapes. Older children are more experienced in abstracting and generalizing relevant information (Son, Smith, & Goldstone, 2008), therefore, we hypothesized that older children make proportionally more errors for objects differing in irrelevant properties compared with relevant properties (Ons & Wagemans, 2011). Such an influence of category-dependent shape differences would be a nontrivial outcome because our task does not require any categorical abstractions or generalizations. Each shape was paired with only one individual nonsense name.

To introduce a clear difference in the level of prior experience and developmental phase, we included two distinct age groups: one group consisted of children between 3.1 and 5 years of age (4 years on average) and the other group consisted of children between 6 and 7.1 years of age (6.5 years on average). Children in this age range are very well able to participate in a computerized experiment, which allows us to gather data in a well-controlled setting, and their vocabulary is still growing considerably, reflecting probably a great deal of developmental changes in their acquired category representations.

In the experiment, the contour shape (the target) and its corresponding new name (e.g., “knaai”) were first provided by the computer. Subsequently, the same contour and three other contours (the distracters) were displayed on the monitor screen. The distracters were varying on category-relevant and -irrelevant shape properties. The computer asked the children to indicate the target contour (called “knaai”) between the alternatives on a touch screen. We referred to this task as “*perceptual identification*.” The predicted outcome that older children make proportionally more errors for objects differing in irrelevant properties would suggest that shape perception is influenced by category-relevant processing.

A second aim of the experiment was to investigate the influence of age on individual name–shape associations. We therefore included two additional tasks in the experiment to test the formed word–shape associations (referred to as the “*word comprehension task*” and the “*word production task*”). In the word comprehension task, the name of a shape was provided and the child had to indicate the correct shape between the alternatives on a touch screen. Conversely, in the word production task, a shape was presented and the child had to recall the correct nonsense name. Although many

theories advocate the predisposition of young children to make word–shape associations (e.g., the “critical period of language acquisition,” see Lenneberg, 1967; or the “vocabulary burst”, for an overview, see Goldfield & Reznick, 1990), we expected older children to perform better because they have more general cognitive skills to cope with a computerized experiment. The two additional tasks provided remarkable results. Despite an average age difference of 2.5 years and a minimum age difference of 1 year for each individual from both age groups, we found that both age groups performed equally well in the word comprehension task and that the younger age group even outperformed the older one in the word production task.

2 Methods

2.1 Participants

There were two age groups (variable age): The younger age group consisted of 18 children between 3.1 and 5 years of age ($M = 4$, $SD = .5$) and the older age group consisted of 18 children between 6 and 7.1 years of age ($M = 6.5$, $SD = .3$). Children were recruited from the Mater Dei School in Genk, Belgium. Participation was voluntary, and written informed consent was obtained from the parents. Each child did all the tasks two times: once for a cluster of familiar objects and once for a cluster of unfamiliar objects.

2.2 Apparatus

The experiments were conducted on a Microtouch 3M Inc. 15-inch touch screen and a Pentium IV 3.2 GHz computer. The experiment was programmed in Eprime 1.3, and the stimuli were created in MATLAB R2007b.

2.3 Stimuli

Three stimulus pairs were selected from our set of outlines (Wagemans et al., 2008) derived from the Snodgrass and Vanderwart set (1980): donkey and dog, bowl and bottle, car, and hat (see Figure 1, upper half). In addition, there were three unfamiliar contours created by the addition of multiple line fragments randomly selected from contours of the Snodgrass and Vanderwart set (1980; see Figure 1, lower half). Three deformation schemes were obtained, one for each set of three pairs of objects, which was then also applied for a matched pair of unfamiliar shapes (see Introduction for an explanation and the Appendix for more detail).

Three unfamiliar contours (see the upper left contours in the lower clusters of Figure 1) were placed one by one in each transformation scheme, creating nine clusters of unfamiliar contours (3 unfamiliar objects \times 3 deformation schemes) that inherited the basic-level shape differences from the existing contours, as explained above. Three examples are depicted in the lower half of Figure 1. The variable that distinguishes between these two kinds of contours (familiar vs. unfamiliar) was labelled “FAMILIARITY.” In the experiment, the contours were presented without the grids depicted in Figure 1. Within each cluster, shapes on the same row are different in category-irrelevant properties and shapes on different rows are different in category-relevant properties.

In each session, the four stimuli of a cluster were paired with four word-like non-words (resembling normal Dutch nouns). The non-words were randomly selected from a pool of 16 non-words in the beginning of the experiment: “baak, drun, knaai, fauf, guig, huut, lool, krips, meen, pieg, roeid, prans, shoes, stel, weir, zeuj.” The four selected non-words were consistently related to the same four stimuli in the perceptual identification task. The new words were spoken in a sentence in the native Dutch mother tongue, recorded digitally and reproduced on-line by the computer.

2.4 Procedure

Two sessions were administered to each participant: one session consisted of a set of four shapes derived from a pair of familiar objects and one session consisted of a matched set of four shapes of unfamiliar objects (in the sense that the same transformation scheme was involved). A non-word administered to one participant in the first session was never repeated in the second session. Each set was used equally often within each age group, and the order of the two sessions (familiar and unfamiliar) was counterbalanced within each age group. So, the three clusters of familiar objects were each used six times in total by the 18 participants of each age group, and the nine clusters of unfamiliar objects were each used two times in total by the 18 participants of each age group. The clusters were randomly assigned without replacement to the participants.

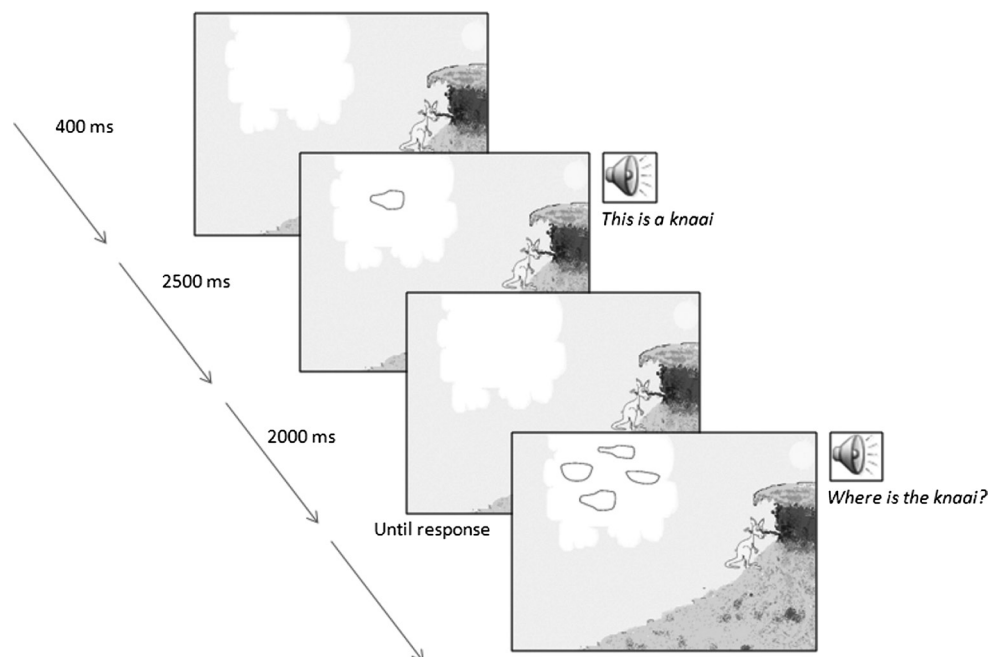


Figure 2. A trial from the perceptual identification task 1.

Each session consisted of four tasks. Two perceptual tasks (perceptual identifications 1 and 2) allowed us to investigate shape perception at different ages and two small tasks (word comprehension and word production) allowed us to investigate the word–shape associations at different ages. In perceptual identification task 1, participants carried out a delayed match-to-sample task with four alternatives (see [Figure 2](#)). During the target presentation, the selected non-word was spoken by the computer as indicated in [Figure 2](#). The participants had to indicate the target among four alternatives on a touch screen. The four alternatives consisted of the four stimuli in one cluster (see [Figure 1](#)). All four contours served an equal number of times as target and as distracter. For each target contour, there was always one distracter differing in category-irrelevant shape properties and two distracters differing in category-relevant shape properties. To motivate the children, a kangaroo jumped upwards on a hill for each correct answer. In the perceptual identification task 2, the same four stimuli served as target. However, to make the perceptual identification task more difficult, four in-between morphs were added and participants had to choose between eight alternatives instead of four. Except for the number of alternatives, perceptual identification 2 was identical to perceptual identification 1. One of the purposes of the subtle variation between tasks was to create a computer game with different levels of difficulty to motivate the children.

In the word comprehension task, the target stimulus presentation was omitted (second and third display in [Figure 2](#)) and only the four alternatives were shown (first and fourth display in [Figure 2](#)) simultaneously with the spoken question by the computer. To choose correctly between the four presented contour shapes, children had to remember the correct shape alternative to which the name was referring in the preceding perceptual identification blocks. In the word production task, only the target contour was presented (display 1 and display 2, now until response) simultaneously with the spoken question translated to English “How was this called?” and the children’s answers were registered by the experimenter. The experimenter chose one of the word alternatives depending on what the children uttered. In case of doubt, she mentioned the four alternatives and asked the child to choose.

Each session consisted of six consecutive blocks: the first, the third, and the fifth block constituted the perceptual identification task 1 and the second block constituted the perceptual identification task 2. The fourth block constituted the word comprehension task and the sixth block constituted the word production task. The reason behind the block order is to alternate between an easy task (perceptual identification 1) and the more difficult tasks in order to prevent fear of failure.

Because participants were young children, we could administer only a limited number of trials (to prevent fatigue and boredom). The six blocks contained 8, 12, 8, 12, 8, and 12 trials, respectively.

In all blocks, all contours from one set of four served an equal number of times as target and all contours served also an equal number of times as distracter with relevant shape properties or irrelevant shape properties in respect to the target. Each name–shape pair was administered seven times in total in all the blocks of the perceptual identification task before the onset of the word comprehension task and nine times in total before the onset of the word production task. Each contour–name association was tested three times in the word comprehension task and three times in the word production task. In the word comprehension task, the word production task and the perceptual identification task 2, the kangaroo made a pleasant squeezing sound for each correct and incorrect answer given. Thus, contrary to the perceptual identification task 1, there was no feedback on the accuracy of the answers in the other three tasks.

2.5 Instructions

The experimenter guided the children individually from the classroom to a separate room where the computer-animated experiment was conducted. The experimenter tried to motivate the children but accepted a passive role in the collection of the children's responses. Children were instructed to do what the computer asked for (see [Figure 2](#)). Children were not informed about the different computer tasks. For instance, children were not informed that the computer was going to ask them to produce the words at the end of the game (experiment). There was no instruction asking explicitly to memorize the words for the shapes presented in the perceptual identification tasks. When children responded with the conventional nouns for the existing objects in the word production task, they were instructed to use one of the four spoken words in the experiment.

3 Results

We used logistic regression in SAS (i.e., the LOGISTIC procedure). The categorical variables AGE (4 vs. 6.5 years), FAMILIARITY (familiar vs. unfamiliar objects), and AGE \times FAMILIARITY were entered as explanatory variables in all models predicting the log-ratio of two counts (e.g., the number of correct vs. incorrect answers). The logarithm is used as a link function between the ratio of counts and the categorical variables to establish a generalized linear model. This is a necessary step to incorporate probabilities (e.g., accuracy) into a linear model. Because the low numbers of trials lead to low counts, we aggregated the data for all blocks of the perceptual identification task 1.

3.1 Perceptual identification

First, we compared the level of accuracy in the perceptual identification tasks between different age groups. We aggregated the number of correct target selections for the three blocks of the perceptual identification task 1. We found a small but significant difference in accuracy for the variable AGE ($\chi^2_1 = 4.55, p < .05$). The younger age group selected the target correctly in 66.2% of the trials (68.5% for the familiar shapes and 63.9% for the unfamiliar shapes) and the older age group selected the target correctly in 74.1% of the trials (77.5% for the familiar shapes and 70.6% for the unfamiliar shapes). We found a similar trend for the more difficult perceptual identification task 2 but the difference was not significant anymore, probably because of the lower number of trials ($\chi^2_1 = 0.35, p = .55$). The odds for a correct target selection for the older age group against the younger age group were 1.12 for the perceptual identification task 1 and 1.07 for the perceptual identification task 2. We did not find any significant effect for the variable FAMILIARITY and the variable AGE \times FAMILIARITY.

Second, we investigated whether older children made proportionally more errors for objects differing in irrelevant properties compared with relevant properties. In each trial, there were always two distracters differing on relevant properties and only one distracter differing on category-irrelevant shape properties (see [Figure 1](#)). Therefore, it was two times more likely to select a relevant distracter than an irrelevant one at chance level. Despite the fact that there were more relevant distracters than irrelevant ones, irrelevant distracters were chosen much more frequently in both age group. For the familiar objects, the younger age group was 2.38 ($\chi^2_1 = 31.01, p < .0001$) times more likely to choose a distracter differing on category-irrelevant shape aspects than on relevant aspects and the older age group was 3.78 ($\chi^2_1 = 53.1724, p < .0001$) times more likely to choose a distracter with irrelevant shape differences. For the unfamiliar objects, the younger age group was 1.28 ($\chi^2_1 = 7.2, p < .01$) times more likely to select a distracter differing on irrelevant shape properties against a dis-

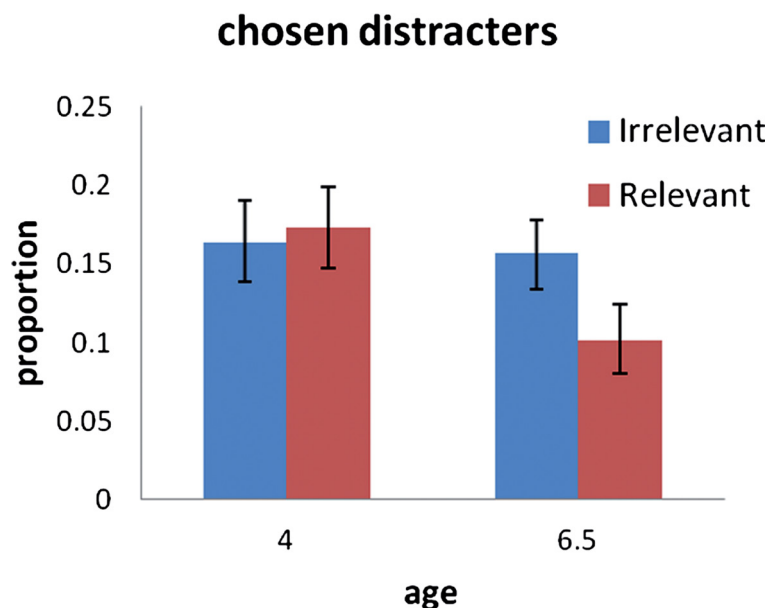


Figure 3. The proportion of irrelevant and relevant distracter selections in the perceptual identification task 1 for the two age groups. The error bars denote 95% confidence intervals.

tracter differing on relevant shape properties. The same measure for the older age group was 2.56 ($\chi^2 = 27.6, p < .0001$). Although the irrelevant distracters were chosen more frequently for the familiar objects compared with the unfamiliar objects, the trend was not significant ($\chi^2 = 2.46, p = 0.11$ for the younger age group;

$\chi^2 = 0.71, p = 0.39$ for the older age group). Thus, the effect of FAMILIARITY was not significant. To investigate the influence of age on the type of errors that were made, we compared the preference for the irrelevant distracter type against the relevant distracter type across age groups. In the perceptual identification task 1, we found developmental differences. In [Figure 3](#), the proportion of irrelevant and relevant distracter selections are plotted. The younger age group selected the irrelevant distracter in 16.4% of the cases and the relevant distracters in 17.3% of the cases, while the older age group selected the irrelevant distracter in 15.7% of the trials and the relevant distracters only in

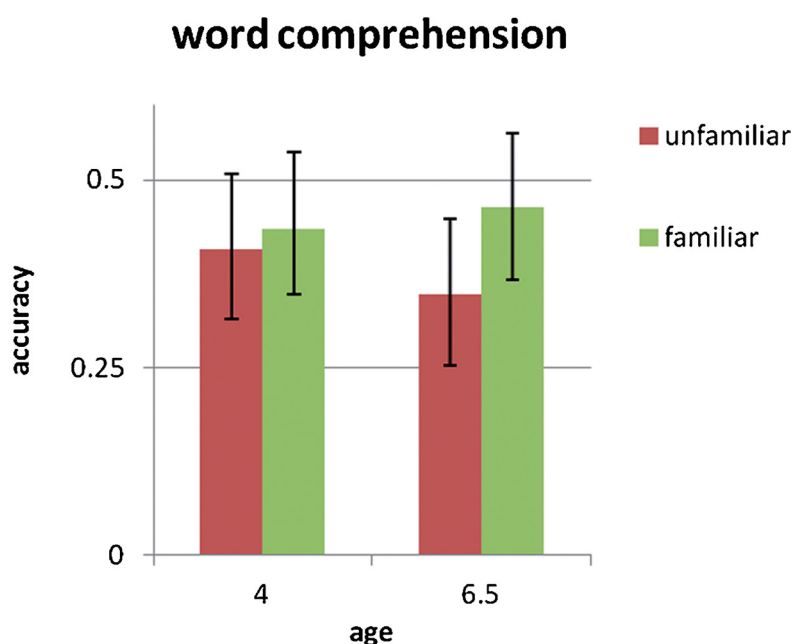


Figure 4. Accuracy for the word comprehension task for familiar and unfamiliar objects for each age group. The error bars denote 95% confidence intervals.

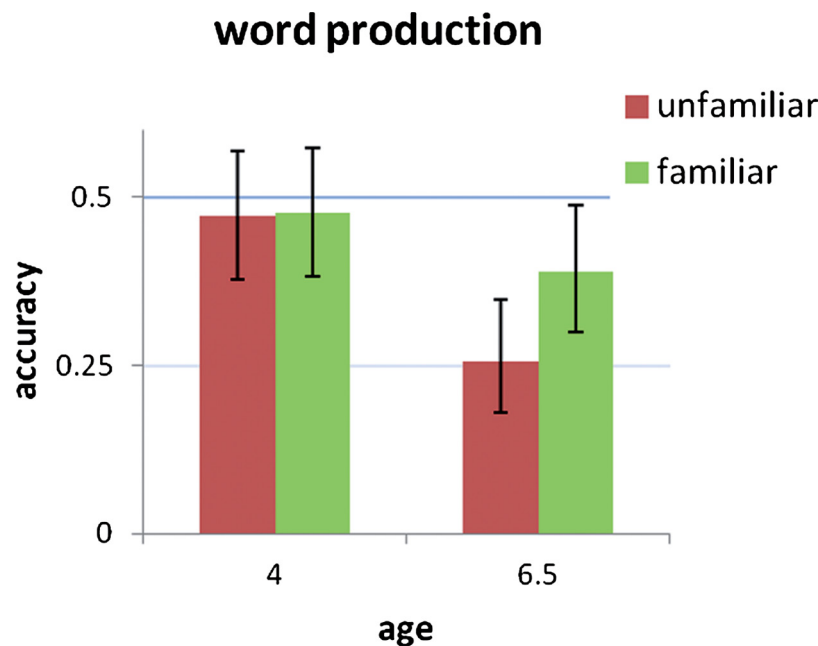


Figure 5. Accuracy for the word production task for familiar and unfamiliar objects for each age group. The error bars denote 95% confidence intervals.

10.2% of the trials. Notice that the proportion of irrelevant and relevant distracters in [Figure 3](#) and the proportion of correct responses mentioned before sum to one. Given that a distracter was chosen, the older age group was 1.25 times more likely to select the irrelevant distracter type compared with the younger age group (1.2 for the familiar objects and 1.44 for the unfamiliar objects). The variable AGE was significant

($\chi^2_1 = 4.14, p < .05$). The trends were similar in the perceptual identification task 2, but the effect of AGE was not significant anymore ($\chi^2_1 = 2.03, p = 0.15$), probably because of the lower number of trials.

3.2 Word–shape association learning

In two tasks, the word comprehension task and the word production task, the associations between words and shapes were tested. In the word comprehension task, participants had to select the shape among four alternatives that corresponded to the spoken names referring to the shape in the preceding perceptual identification task. In [Figure 4](#), the younger age group selected the correct shape for words relating to nonexisting objects in 40.7% of the cases and the correct shape for words referring to existing objects in 43.5% of the trials, while the older age group selected the correct shape for words relating to nonexisting objects in 34.7% of the trials and the correct shape for words referring to existing objects in 46.3% of the trials. The 95% confidence intervals in [Figure 4](#) demonstrate that all scores were higher than chance levels (one out of four), but there was no significant effect of AGE, FAMILIARITY, and AGE \times FAMILIARITY.

In the word production task, the participants had to name the shapes by using the same names as those used to refer to the shapes in the perceptual identification task. The word production scores were lower than the word comprehension scores for the older age group. On the one hand, the word production task should be more difficult than the word comprehension task because the participants could not choose between the four alternatives anymore and had to recall the name explicitly from memory. On the other hand, children received one extra block of perceptual identification with name–shape pairings before the onset of word production task, which might have led to better word–shape associations. The scores for the younger age group were 47.2% for the unfamiliar objects and 47.7% for the familiar objects, while the older age group scored 25.5% for the unfamiliar objects and 38.9% for the familiar objects (see [Figure 5](#)). Aggregating the data over familiar and unfamiliar objects, the variable AGE was significant ($\chi^2_1 = 9.4, p < .005$), indicating that the young children were

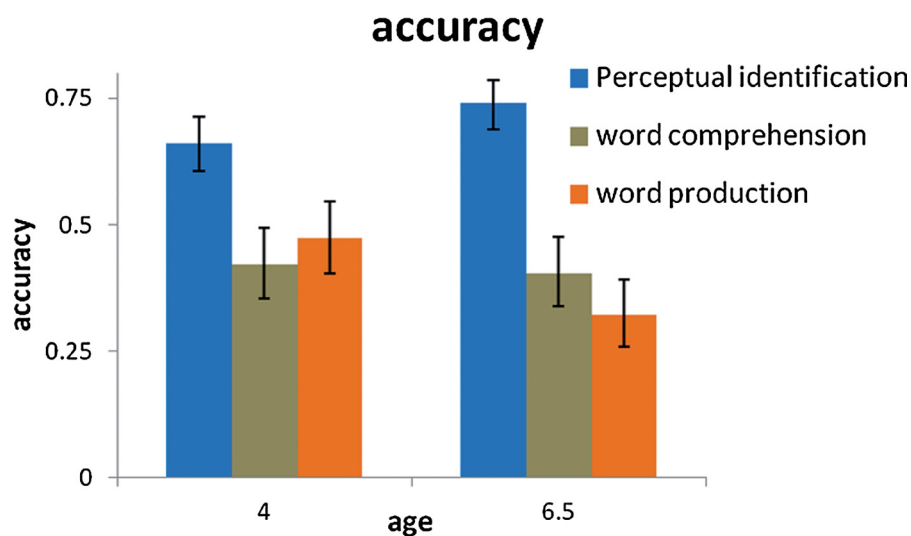


Figure 6. Comparison in overall accuracy for the three tasks for each age group. The error bars denote 95% confidence intervals.

significantly better than the older children in the word production task. The odds for a correct name production for younger against older children was 1.47. The variables FAMILIARITY and AGE \times FAMILIARITY were not significant.

4 Discussion

4.1 Perceptual identification

In the perceptual identification task, we found that older children performed slightly better than the younger children. Such a difference in performance is expected when we assume that children normally develop better perceptual skills in the course of their development. Older children made fewer errors in the perceptual identification task than younger children, but when focusing on the type of errors children made, an important interaction emerged. The average number of errors was more or less constant for the irrelevant shape differences, that is, younger and older children selected equally frequently the irrelevant shape distracter (see [Figure 3](#)). However, the number of errors made by selecting the relevant shape distracters reduced substantially by age and can actually account for the whole difference in accuracy between the two age groups. Older and younger children came to the same proportion of incorrect irrelevant distracter selections but differed largely in the proportion of incorrect relevant distracter selections. In other words, older children seemed to have developed more sensitivity for shape differences when shape differences are related to typical differences between objects of different categories. When we would have observed the reduction of errors only for the familiar objects, then category representations and known labels could have been considered to account for this reduction in errors. However, the same pattern of errors was observed for the unfamiliar objects. Such a transfer of errors is only possible when experience in the mutual relation between shape and categories also transfers towards never encountered objects. The results indicate that shape perception itself is influenced by former categorization experience in the sense that relevant shape properties are perceptually stronger processed before an object is recognized (e.g., the unfamiliar objects) and that the relevance of the shape properties seems to correspond with children's former experience in distinguishing categorical relevant differences between objects (see also Folstein, Gauthier, & Palmeri, [2010](#); Gillebert, Op de Beeck, & Wagemans, [2008](#), for related behavioural evidence; and Folstein, Palmeri, & Gauthier, [2012](#); Gillebert, Op de Beeck, Panis, & Wagemans, [2009](#), for related neural evidence). The results also show that category-relevant shape processing also occur in a perceptual task that does not require any categorical abstractions.

A shape bias refers to a generalization of nouns on the basis of shape. Instead of generalizing nouns, in the perceptual identification task, shapes were matched to shapes, and therefore, the task necessarily forced responses based on shape. A shape bias is not applicable in this context. Inversely to a shape bias in the name generalization task, a category bias in matching shapes seems to occur in

the perceptual identification task. Errors in matching shapes largely depended on categorical relations. Similar to how the shape bias determines largely the generalization of nouns or categories, a category bias also seems to exist in tasks depending on perceptual processes.

4.2 Word–shape association learning

Although older children performed better than younger children in the perceptual identification tasks, they performed more poorly in the word production task (see [Figure 6](#)) and only equally well (numerically even slightly worse) in the word comprehension task. The trend is similar for familiar and unfamiliar objects. The younger children were better in remembering explicitly the associated new words when the contours were presented. The results suggest that younger children are better in the acquisition of arbitrary word–shape associations, a phenomenon that might be related to the so-called critical period of language acquisition (Lenneberg, [1967](#)). The age of the critical period in the context of our experiment should fall somewhere between the two age groups (i.e., around 5 years of age; Krashen, [1973](#)). One of the essential hallmarks of the critical period is that the pattern of decline in language acquisition should demonstrate an abrupt change at some critical age (Hakuta, Bialystok, & Wiley, [2003](#)). However, because the data only consisted of two age groups, it is impossible to determine whether the pattern declines monotonically or abruptly at a particular critical age. Nevertheless, the results clearly show a decline for word production at a very early age in childhood.

A word of caution is needed that results should be interpreted in the light of the applied instruments. For instance, in a survey study (Fenson et al., [1994](#)), a 682-word checklist was used derived from the MacArthur Communicative Development Inventories (CDI) and performed representative measurements of an infant's actually acquired vocabulary at a particular moment in their life. The word production test consisting of an inventory check list involves a completely different kind of measurement than the word production task in the present study, where only the associations between four contours and four non-words were learned and measured. Moreover, the children were not instructed to remember the spoken words and the word–shape association tests were not announced beforehand. Small details can lead to unexpected results. For instance, in Sloutsky and Fisher ([2004](#)), 5 year olds exhibited more accurate memory than adults in a new–old recognition task of previously encountered stimulus material from a preceding induction task. Before and during the induction task, the participants were not informed that a recognition task would follow. However, in a baseline group of adults and children, the same material from the induction task was presented, and the baseline participants were instructed to memorize the material to engage later on in a recognition test. Contrary to the induction groups, the baseline adults performed better than the baseline 5 year olds. Thus, the fact that the word tests were not announced might have caused the obtained effect in the current investigation. The older age group might be better in ignoring task-irrelevant aspects like the names of the objects in the perceptual identification tasks.

Furthermore, the decline in performance for the word production task could be explained by an age difference in the way attention was divided between the auditory and visual modality. The older age group might have had a tendency to attend more exclusively to the visual input, while the younger age group might have had a tendency to attend more equally to the vocally pronounced labels and the visually presented contours. Indeed, Robinson and Sloutsky ([2004](#)) found evidence that young children before the age of 4 have a preference for auditory input, while older children have a preference for visual input (see also Sloutsky & Robinson, [2008](#)). Obviously, attending both to the auditory labels and the visual contours simultaneously could lead to better word–shape associations and could explain the decline in performance for the word production task by age.

4.3 Category-relevant shape processing

Abstract shape properties present in familiar and unfamiliar shapes have to account for the category-relevance effect in perception. By abstracting very general shape properties, older children can distinguish better between relevant and irrelevant shape properties, and therefore, they might be able to focus more intensely on the relevant shape properties. This view corresponds to the view that shape recognition builds on increasingly abstract representations of object shape (Smith, [2003](#); Son et al., [2008](#)). According to Son et al. ([2008](#)), abstraction is in part simplification and it enables generalization because it requires the removal of irrelevant information.

A similar view on generalization could be offered for the word production task. Abstraction of shape properties could be helpful to narrow down the meaning of a whole set of words instead of just one. Such a process of abstraction is an efficient way to narrow down naive category representations.

Such a developmental change would predict that the older age group makes relatively more errors for objects that share basic-level shape properties and fewer errors for objects that do not share basic-level properties, a hypothesis that was confirmed in the current investigation.

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Appendix

The warping algorithm that we used to create the topological transformations of the image plane, originally formulated by Bookstein (1989), is here explained with more technical details following the textbook of Dryden and Mardia (1998). For more details and background, we recommend the textbook “Statistical Shape Analysis” of Dryden and Mardia (1998).

Consider two contours described by K equidistant points (landmarks) along their paths with $T = [t_1 t_2 \dots t_k]^T$ for the first figure and $Y = [y_1 y_2 \dots y_k]^T$ for the second one, and t and y are points consisting of the position coordinates

$$\begin{bmatrix} x_t \\ y_t \end{bmatrix}$$

and

$$\begin{bmatrix} x_y \\ y_y \end{bmatrix} = \begin{bmatrix} \varphi_1(t) \\ \varphi_2(t) \end{bmatrix},$$

then the *pair of* TPS is given by the bivariate function $(\varphi_1(t), \varphi_2(t))^T = c + At + W^T s(t)$ where $s(t) = (\sigma(t - t_1), \sigma(t - t_2), \dots, \sigma(t - t_k))^T$ and $\sigma(h) = \|h\| \ln \|h\|$ if $\|h\| > 0$ and $\sigma(h) = 0$ if $\|h\| = 0$.

A natural TPS obeys the equation

$$\begin{bmatrix} S & 1_k & T \\ 1_k^T & 0 & 0 \\ T^T & 0 & 0 \end{bmatrix} \begin{bmatrix} W \\ C^T \\ A^T \end{bmatrix} = \begin{bmatrix} Y \\ 0 \\ 0 \end{bmatrix}$$

where $S_{ij} = \sigma(t_i - t_j)$ and 1_k is column matrix of K ones. Therefore,

$$\begin{bmatrix} W \\ C^T \\ A^T \end{bmatrix} = \begin{bmatrix} S & 1_k & T \\ 1_k^T & 0 & 0 \\ T^T & 0 & 0 \end{bmatrix}^{-1} \begin{bmatrix} Y \\ 0 \\ 0 \end{bmatrix}.$$

Assume that

$$\begin{bmatrix} S & 1_k & T \\ 1_k^T & 0 & 0 \\ T^T & 0 & 0 \end{bmatrix}^{-1} = \begin{bmatrix} \Gamma^{11} & \Gamma^{12} \\ \Gamma^{21} & \Gamma^{22} \end{bmatrix}$$

where Γ^{11} constitute the first $K \times K$ elements in the upper-left part of the inverse matrix, then $W = \Gamma^{11} Y$ and

$$\begin{bmatrix} C^T \\ A^T \end{bmatrix} = \Gamma^{21} Y.$$

The solution for the nonlinear component W , the affine component A , and the translation component c completes the previous bivariate function $(\varphi_1(t), \varphi_2(t))^T$.

To compute the displacements for L points p of a nonexisting contour or the points of a grid, we can use the same bivariate function. Assume that p is a point consisting of the position coordinates

$$\begin{bmatrix} u \\ v \end{bmatrix}$$

in the image plane, then

$$s(p) = (\sigma(p - t_1), \sigma(p - t_2), \dots, \sigma(p - t_k))^T \text{ and} \\ (\varphi_1(p), \varphi_2(p))^T = c + At + W^T s(p).$$

A pair of TPS usually results in a topological transformation from a two-dimensional vector space to a two-dimensional vector space. However, if many points are recruited in T and Y , $(\varphi_1(t), \varphi_2(t))$ is not necessary a function. Some regions of the image of $(\varphi_1(t), \varphi_2(t))$ may overlap. To reduce the risk of this outcome and to circumvent unnecessary rotations, we can use the code of the shape alignment algorithm of Marques and Abrantes (1997), allowing for an optimal initial point estimation and pose estimation for the set of ordered points in T and Y . In the clusters presented in Figure 2, the first contour consists of the points T and the right lower contour consists of the points Y . The right upper contours are the points

$$(\varphi_1(p), \varphi_2(t))^T = c + At \text{ and the left lower contours are the points } (\varphi_1(p), \varphi_2(t))^T = c + W^T s(t).$$