Late development of metric part-relational processing in object recognition

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Abstract

Four experiments with unfamiliar objects examined the remarkably late consolidation of part-relational relative to part-based object recognition (Jüttner, Wakui, Petters, Kaur, & Davidoff, 2013). Our results indicate a particularly protracted developmental trajectory for the processing of metric part relations. School children aged 7–14 and adults were tested in 3-AFC tasks to judge the correct appearance of upright and inverted newly learned multi-part objects that had been manipulated in terms of individual parts or part relations. Experiment 1 showed that even the youngest tested children were close to adult levels of performance for recognizing categorical changes of individual parts and relative part position. By contrast, Experiment 2 demonstrated that performance for detecting metric changes of relative part position was distinctly reduced in young children compared to recognizing metric changes of individual parts, and did not approach the latter until 11–12 years. A similar developmental dissociation was observed in Experiment 3, which contrasted the detection of metric relative size changes and metric part changes. Experiment 4 showed that manipulations of metric size that were perceived as part (rather than part-relational) changes eliminated this dissociation. Implications for theories of object recognition and similarities to the development of face perception are discussed.

Keywords: development, object recognition, face recognition, configural, relational, part, geon, metric, categorical

Introduction

There is increasing evidence that it takes surprisingly long for object recognition skills in children to become fully adult-like. In the past, similar claims have been made more frequently for face perception. In that domain it has been demonstrated that despite indications of remarkable face recognition skills in young infants (Pellicano & Rhodes, 2003; McKone & Boyer, 2006; de Heering, Houthuys, & Rossion, 2007) such skills continue to improve deep into the second decade of life (e.g., Ellis, 1975; Carey & Diamond, 1977; Carey, Diamond, & Woods, 1980; Mondloch, Le Grand, & Maurer, 2002). Much of the late developing skills for face recognition have been attributed to the processing of spatial relations between facial features, and there is some evidence that similarly protracted skills to process relations between object parts might also affect the recognition of non-face objects in children (Davidoff & Roberson, 2002; Jüttner, Müller, & Rentschler, 2006; Jüttner, Wakui, Petters, Kaur, & Davidoff, 2013).

For example, Davidoff and Roberson (2002) examined the recognition of familiar animals by children aged 6 to 16 years. In each trial participants were shown three variations of the same animal, the (correct) original depiction and two (incorrect) distracters. The incorrect alternatives could either involve part changes, derived by replacing one part of an animal with that from another, or a part-relational change, here defined by an alteration of the animal's proportions, i.e. the relative size of its parts. Manipulations of parts and part relations were calibrated in such a way that adults found them equally difficult to detect. The results showed that it was not until 11 years that children were at adult levels for the correct recognition of a part change and not until 15–16 years for the recognition of a part-relational change. Control experiments demonstrated that these differences could not be attributed to a reduced ability in young children to perceptually discriminate part-relational image changes. Rather they indicate dissociating trajectories for part-specific and part-relational processing in object recognition, and motivate an analysis of developmental mechanisms in terms of theoretical approaches that explicitly involve structural object representations.

Several recent studies on object processing by children and infants have been based on Biederman's Recognition-by-components (RBC) model (Biederman, 1987; 2000). It proposes that complex objects are encoded as spatial arrangements, or configurations, of basic parts that come from a restricted reservoir of certain elementary shapes, the so-called geons. Geons are defined by categorical contour properties (like "parallel" vs. "nonparallel" or "straight" vs. "curved"). These properties are non-accidental in the sense that they are largely invariant to changes in viewpoint. Similarly, the spatial configuration of geons is encoded in terms of certain categorical relations between geons (like "on top of" or "larger"). Furthermore, Biederman contrasts shape differences in terms of categorical, non-accidental properties with those arising from continuous, or metric, variations of part and part-relations (for example, the degree of non-parallelism within the contours of a given object part, or the precise distance between two parts). Metric properties tend to be viewpoint dependent and may require processing mechanisms that differ from those involved in non-accidental comparisons (Biederman, 2000).

Within the RBC framework, developmental differences for detecting part-specific and part-relational changes could indicate different trajectories for part and part-relational processing, both of which may further dissociate into different pathways for dealing with non-accidental and metric attributes. Most previous developmental work considering the role of structural object descriptions has focussed on the status of individual parts. There is substantial evidence that parts receive particular attention in the analysis and detection of shape similarity (e.g., Tversky & Hemenway, 1984; Schyns & Murphy, 1994; Saiki & Hummel, 1996; Rakison & Cohen, 1999), and that this preference emerges very early in life. Toddlers and even infants have been shown to attend selectively to parts when categorizing or matching objects (Madole & Cohen, 1995; Smith, Jones, & Landau, 1996; Rakison & Butterworth, 1998) even though it has been more contentious whether the early primacy of parts in visual processing reflects a peculiar status of geons (Abecassis, Sera, Yonas, & Schwade, 2001; but see: Haaf, Fulkerson, Jablonski, Hupp, Shull, & Pescara-Kovach, 2003).

Unlike for parts, until recently relatively few studies explicitly considered the processing of object part relations within the RBC framework. Mash (2006) examined similarity judgements of novel object images differing by a metric part and a part-relational property in children aged 5 years and 8 years, as well as in adults. Young children were found to have a strong bias for classifying objects on the basis of part specific information only. With increasing age participants came to select both part-specific and part-relational information in their classification judgements. Control experiments showed that the bias in young children against the use of part-relational properties could not be explained by a reduced discrimination ability. Rather it suggests a retarded processing of part-relational relative to part-specific processing. However, in Mash's study it remained unclear whether the observed developmental differences are confined to tasks involving a perceptual online classification (i.e., of simultaneously available objects) as opposed to those of recognition proper (i.e., the matching of a sensory percept to a stored object representation). Evidence for the latter was provided in a comprehensive study by Jüttner, Wakui, Petters, Kaur and Davidoff (2013).

Jüttner et al. asked children aged 7 to 16 years and adults to judge the correct appearance of familiar animals, artifacts and newly learned multi-part objects that had been manipulated either in terms of individual parts or part relations (here: relative size). For animals and artifacts, even the youngest children were close to adult levels for the correct recognition of an individual part change. By contrast, it was not until 11 – 12 years that they achieved similar levels of performance with regard to altered metric part relations. The distinctly protracted development of part-relational relative to part-specific processing was the same for both types of stimuli thus generalising Davidoff and Roberson's (2002) earlier observations made for animal recognition. To further constrain the origin of children's difficulties with relational information, Jüttner et al. then introduced a set of novel objects that - unlike depictions of natural objects - permitted a more precisely controlled manipulation of parts and part relations at either non-accidental or metric level, as defined within the RBC framework. For metric manipulations of the spatial proportions of these objects, recognition accuracy showed a similarly protracted development as in case of animals and artefacts, thus demonstrating the ecological validity of those stimuli (see also Petters et al., 2014). By contrast, no such retardation was observed in case of categorical relative-size changes of the object parts.

Jüttner et al.'s results provide the first evidence that late developing object recognition skills might be the consequence of a generic difficulty to process metric spatial relations in early adolescence. However, this evidence can still be seen as limited in the sense that only a single part-relational attribute - namely relative size - was being tested, and that the critical experiment contrasting metric part and metric relative size changes employed a single group of children aged 7 – 8 years thus providing only a coarse indication of the developmental trajectories concerned. The present paper reports four experiments that, based on Jüttner et al.´s paradigm, aimed to systematically test and extend the generality of their findings: First, by tracing the development of part-relational object processing in children aged 7 to 14 for the attribute *relative position* – a key attribute used to describe part relations in the original RBC model (e.g., Biederman, 1987) and all later variants (e.g., Hummel & Stankiewicz, 1996; Hummel, 2001). Manipulations of this attribute were compared with those for individual parts both at categorical (Experiment 1) and metric level (Experiment 2). Furthermore, a similar assessment was performed for metric relative size changes (Experiment 3) thus permitting a comparison of the developmental trajectories for the two core part-relational attributes size and position within the RBC framework. Finally, manipulations of relative size were considered within a perceptual context where they were perceived as part (rather than part-relational) changes (Experiment 4), as a further test of the hypothesis of a distinctly protracted development for part-relational relative to part-specific object processing in adolescence.

A generic protracted development of metric part-relational processing would have implications for current theories of object recognition in adults. Here there has been a long-standing debate between proponents of structural approaches (e.g., Marr, 1977; Biederman 1987, 2000) on the one hand and those of so-called image-based approaches (e.g., Ullman, 1989; Poggio & Edelman, 1990; Tarr & Bülthoff, 1995; Riesenhuber & Poggio, 1999) on the other. Image-based models have been proposed in various forms (e.g., Ullman, 1989; Poggio & Edelman, 1990; Tarr & Bülthoff, 1995; Riesenhuber & Poggio, 1999) but their common denominator is the idea of a view-like, non-analytic representation where object features are stored in terms of their literal position within a pictorial, two-dimensional coordinate system. Recent evidence from behavioural (e.g., Hummel, 2001; Forster & Gilson, 2002; Hayward, 2003; Thoma et al. 2004) and neuroimaging (e.g Vuilleumier et al., 2002; Thoma & Henson, 2011) studies suggests that structural and image-based representations might even co-exist in the visual system, but their relative contribution to object recognition remains unclear. With regard to our change detection paradigm, image-based models predict a different developmental trajectory as degraded object views in children would necessarily favour the detection of part-relational manipulations over those involving specific parts due to the lower spatial correlation between target and distracter features - in contrast to the above predictions of the RBC model. Thus, by explicitly testing the latter our study offers a novel perspective to implicitly assess the primacy of structural and view-based object recognition during the transition from adolescence to adulthood.

Experiment 1

Visual representations necessarily require the encoding of positional information of image features and therefore have an intrinsic spatial quality (Marr, 1982). In the context of the RBC model spatial relationships are expressed in terms of the relative location of adjacent object parts. Biederman (1987) refers to this particular spatial property as *verticality*. Verticality is assumed to be a categorical attribute that attains one of three values: for any two parts P1 and P2, P1 can either be "above", "below" or "to the side of" P2. In this paper we will refer to this coarse attribute characterizing spatial relationships as "categorical" relative position, in order to differentiate it from its continuous counterpart, "metric" relative position (cf. Experiment 2). Categorical relative position is a nonaccidental relational property in the sense that that it is invariant to most changes in viewpoint. In addition to verticality (or categorical relative position), Biederman (1987) also considers other potential relational non-accidental properties (NAPs). However, as with NAPs characterizing individual parts, the catalogue of part-relational NAPs has shown certain variability over time. Slightly different lists of NAPs have been proposed for later part-based models that were inspired by the RBC approach (cf. Hummel & Biederman, 1992; Hummel & Stankiewicz, 1996; Hummel, 2001). Nonetheless, all of these variants share two *core* part-relational NAPs: *relative size* and *relative position*.

Categorical relative size coarsely describes the proportions between two adjacent parts as being "much smaller", "approximately equal" or "much larger" (cf. Biederman, 1987).

Jüttner et al. (2013, Exp. 2) found that children´s ability to detect changes of this relational NAP develops early and follows a trajectory that does not significantly differ from that for detecting NAP changes of individual parts. In Experiment 1 we tested the generality of this finding by contrasting positional changes at categorical level with NAP manipulations of individual object parts.

Following the paradigm introduced by Jüttner et al. we employed a set of six novel objects for which manipulations of parts and part relations could be carefully controlled. We first trained the participants to associate each object with a label (here given by the object number). Subsequently, we assessed their object knowledge in a one-in-three (3-AFC) selection task, where they had to choose the correct depiction among the original and two distracters, both of which had been derived by introducing either a part-relational change or a part-specific changes.

As an additional manipulation, half of the stimuli in the recognition task were presented upside down. Impairment of performance by inversion has frequently been used as one indicator for part-relational (configural) processing, in particular in the context of face recognition (Carey & Diamond, 1977). While such a disruption is more pronounced for objects that have – like faces – an internal part structure (Yin, 1969) it has been also been demonstrated for many other types of stimuli including those without internal features (e.g., de Gelder et al., 1998; Bruyer & Crispeels, 1992; McLaren, 1997). Thus, in the context of the present experiments, we used an inverted presentation to validate our two types of stimulus manipulation, predicting a stronger impact of inversion on the detection of part-relational changes than on part-specific ones.

Method

Participants

Four age groups took part in the experiment, each consisting of 32 participants: The groups were adult volunteers (17 females and 15 males; mean age 19 years 11 months), 7- to 8-year-olds (17 females and 15 males; mean age 8 years 0 months), 9- to 10-year-olds (16 females and 16 males; mean age 9 years 10 months), and 13- to 14-year-olds (15 females and 17 males; mean age 13 years 11 months). The children were drawn from state schools in Birmingham, UK. The adults were recruited among undergraduate Psychology students at Aston University. They received course credit for participation.

Materials

The experiment employed a set of six compound objects adopted from Jüttner et al. (2013). Each object consisted of three parts (Figure 1). The parts were taken from a reservoir of three-dimensional shape primitives (geons) with unique combinations of non-accidental contour properties. We constrained these properties to a subset of the attributes suggested by Biederman (1987) and Hummel (2001), characterizing the type of cross section (straight vs. curved), the shape of the main axis (straight vs. curved), and the surface along the main axis (parallel vs. expanding vs. convex vs. concave). For example, the NAP signature of a cube would be a straight cross-section, a straight axis and parallel surfaces; the signature of a cone would be a curved cross section, a straight axis and expanding surfaces.

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Insert Figure 1 about here

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Within each object, parts were uniquely arranged in configurations that could be characterized by the relational NAP properties *relative position* “above” vs. “below” vs. “beside”) and *relative size* (“larger” vs. “equal” vs. “smaller”). For example, object 3 could be described as consisting of a curved cylinder beside a smaller truncated cone, with the latter sitting above an equally-sized cube.

Within the learning set, objects 1 and 2 and objects 3 - 6 formed two subsets, referred to as *facilitator* objects and *probe* objects, respectively. Objects 3 - 6 consisted of the same three parts (either two bigger and a smaller one, or two smaller and a bigger one), employed the same spatial structure (involving one “beside” plus one “above” or “below” relation). Thus, these objects could not be identified on the basis of a single (diagnostic) part but required consideration of their overall shape, i.e., the spatial configuration formed by all three geon components. By contrast, objects 1 and 2 consisted of a different set of geons arranged in a distinctive horizontal or vertical configuration. During the learning phase of the experiment (cf. section *procedure*), the inclusion of the (relatively easily discriminable) facilitator objects served the purpose of maintaining motivation in children during the supervised learning procedure. During the recognition test (cf. *procedure*), facilitator objects were used in practice trials, whereas experimental trials only included the four probe objects.

For each object in the learning set, two manipulated distracter versions were created. The manipulations either involved a part change or a part-relational change at categorical level (Figure 2). Part changes consisted in the substitution of the original part with that taken from another object. More specifically, in case of probe objects, part substitutions involved geons from the facilitator objects to ensure that altered parts had no novelty advantage and had received a similar amount of exposure during the acquisition phase of the experiment. Part-relational changes were confined to systematic manipulations of the position of object parts relative to each other. For each part-relational distracter, a given spatial relation was altered into one of the two remaining alternative values (for example, the relation “above” between two parts in the original object would become “below” in one distracter and “besides” in the second). Using the procedure of Jüttner et al. (2013), part and part-relational manipulations were calibrated across the set of probe objects for equal difficulty [$t(31) = -.16$, $p = .87$; paired t-test] in adult observers.

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Insert Figure 2 about here

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Objects and distracters were designed as virtual 3D models using a graphics design software package (POV-Ray version 3.63, Persistence of Vision Raytracer Pty. Ltd.). For each object the rendered 3D model was converted into a grey-level image (resolution 300 x 300 dpi), using a fixed light source and a perspective preserving the visibility of all object components. The object images were shown to the participants at a mean size (height x width) of 15.6 x 10.8 deg of visual angle during the familiarization and learning phase of the experiment. During the recognition test, in each trial the three images (the original and the two distracters) were presented horizontally, each image appearing at a mean size of 10.3 x 7.1 deg of visual angle and spaced at a centre-to-centre distance of 11.5 deg. Viewing distance was 50 cm throughout the experiment. Stimulus presentation and response collection were controlled by an Eprime 1.1 (Psychology Software Tools, Inc.) script running on a laptop computer.

Procedure

The experiment consisted of three parts: familiarization, learning and recognition test. Given the novelty of the objects the first two parts served to train participants to associate each object with a label (represented by the object number) before their object knowledge was assessed in the final part. The three parts were introduced to children as a series of computer games of increasing difficulty to maintain their interest and motivation.

Familiarization. Participants were first introduced to the objects in a so-called “Add-Me-Up” task to motivate the children. Here in each trial the observer was shown two objects on the computer screen, separated by the symbol “+”. The task was to respond by typing in the sum of the numbers used to label the objects. The two objects remained on the screen until a response had been made. No memorization was required as this stage, as subjects were encouraged to use a printed handout showing all six objects and their labels. Feedback was given on each trial about the correctness of the answer.

Learning. Here participants were systematically trained to associate each object with its label, employing a modified version of a supervised-learning paradigm (Rentschler *et al.*, 2004; Jüttner *et al.*, 2006). The training procedure was partitioned into learning cycles, each consisting of a learning phase and a test phase. During the learning phase each object of the current learning set was presented once for 250 msec and in random order, followed by the corresponding object label displayed for 1s. During the test phase, each object of the set was presented twice and assigned to its label by the observer. Upon completion of the test phase, participants received feedback concerning their percent correct value of their responses. The series of learning cycles continued until the observer had reached a criterion of 90% in the recognition test. For the current study, this standard paradigm was modified by using an expanding learning set. The learning started with a set of (randomly chosen) two objects. Once these objects had been learned the learning set was expanded by a third object (randomly chosen from the remaining four) and the subject re-trained to criterion. In this way, the learning set was gradually expanded until all six objects had been included and successfully learned to criterion. The gradual expansion of the learning set from 2 to 6 implied a minimum number of five learning cycles to be performed by each participant.

Recognition test. In the final part of the experiment participants were tested on the previously learned objects using the one-in-three selection task (Davidoff & Roberson, 2002). In each trial, three images labelled A, B, C were presented on the screen, one original and two distracter stimuli (both involving either a part or a part-relational change). The observer had to choose the “correct” depiction of the object by pressing the appropriately marked button (A, B, C) on the keyboard. The stimulus remained on the screen until the participant had responded. Response time and accuracy were measured as dependent variables. The recognition test was divided into blocks involving either a part or a part-relational change, and either an upright or an inverted stimulus presentation. Each block was preceded by two practice trials involving the facilitator objects (objects 1 and 2, cf. section *materials*), whereas experimental trials only involved the probe objects (objects 3 - 6) from the learning set. Each object was shown once in each block. The order of the four presentation conditions (“part change – upright”, “part change – inverted”, “part-relational change – upright”, “part-relational change – inverted”) was counterbalanced across subjects. Participants were instructed not to attempt to rotate their head to see the rotated pictures.

<u>Results</u>

During the learning part of the experiment, children and adults acquired the set of six objects with relative ease. Five participants (two within the age groups 7 – 8 yrs and 8 – 9 yrs, one within age group 13 – 14 yrs) did not complete the learning procedure and had to be replaced. On average, participants required 6.41 (SD 1.5) learning cycles to reach the target criterion of 90% correct responses – marginally longer than the minimum of 5 cycles implied by the expanding learning set. There was a weak trend of young children using more cycles than older ones [$F(3,124) = 2.10$, $p = .09$, $\eta_p^2 = .05$; one-way ANOVA].

Performance in the recognition test was analysed in terms of the accuracy and the latency preceding a correct response. To check whether the accuracy data had been affected by any extreme values for individual stimuli, the distributions of scores were checked for outliers. No outliers (defined by the group mean ±3 standard deviations) were observed in any of the age groups. Regarding response times, our instructions did not promote fast responses, therefore a few participants showed particularly long latencies. Three participants with latencies classified as outliers were removed from the data set prior to the statistical analysis (one participant in age group 7 – 8 yrs and two in age group 9 – 10 yrs).

Accuracy

Means and standard errors of the recognition accuracy for each age group and for each of the two manipulation conditions (Part vs. Part Relations) and orientations (Upright vs. Inverted) are shown in Figure 3A. The accuracy data were analysed in a 4 (Age: Adults vs. 13 – 14 yrs vs. 9 – 10 yrs vs. 7 – 8 yrs) x 2 (Manipulation: Part vs. Part Relation) x 2 (Orientation: Upright vs. Inverted) mixed ANOVA with Age as the between factor. The analysis yielded significant main effects for Manipulation [$F(1,121) = 8.77$, $p < .01$, $\eta_p^2 = .07$], Orientation [$F(1,121) = 35.74$, $p < .001$, $\eta_p^2 = .23$] but not for Age [$F(3,121) = 1.77$, p = .16]. The only significant interaction was between Manipulation and Orientation [$F(1,121) = 16.39$, $p < .001$, $\eta_p^2 = .12$].

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Insert Figure 3 about here

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A separate ANOVA for the Upright condition showed no significant main effects for Age [$F(3,121) = .85$, $p = .47$], Manipulation [$F(1,121) = .07$, $p = .79$], or for their interaction [$F(3,121) = .35$, $p = .79$]. A similar analysis for inverted stimuli only gave a significant effect for Manipulation [$F(1,121) = 19.07$, $p < .001$, $\eta_p^2 = .14$]. Thus, inversion negatively affected recognition significantly more in case of part-relational than for part changes.

Latency

Response times were analysed for the correct responses of each observer. Figure 3B shows means and standard errors of the latencies for each age group, manipulation condition and orientation. In analogy to the accuracies, the latencies were analysed in a 4 (Age) x 2 (Manipulation) x 2 (Orientation) mixed ANOVA with Age as between factor. The analysis yielded a significant main effect for Age [$F(3,115) = 9.39$, $p < .001$, $\eta_p^2 = .20$], with adults and older children (13 – 14 yrs) responding faster than the children in the two youngest age groups (*p*s < .05; Tukey HSD test). Orientation also proved significant [$F(1,115) = 8.53$, $p < .01$, $\eta_p^2 = .07$], with latencies to inverted stimuli being longer than to upright ones. All other main effects and interactions were non-significant.

There were no speed-accuracy trade-offs in any age group for upright presented stimuli (Pearson rs $< .24$, ps $> .20$). For inverted stimuli, adults showed a significant correlation in the part-relational change condition ($r = .55$, $p < .01$), whereas the correlations were non-significant for all other age groups and conditions (rs $< .11$, ps $> .54$).

Discussion

Experiment 1 shows that children's ability to detect manipulations involving the categorical position of object parts develops early. Even the youngest tested children spotted such changes as reliably as adults. Speeded responses were not requested of participants in our task and young children responded more slowly than older ones. Nonetheless, their performance was not the result of a speed-accuracy trade-off. Neither for accuracy nor response times were there significant interactions between Age and Manipulation for upright stimuli. This suggests that the abilities to detect categorical part-specific and categorical part-relational changes follow the same developmental trajectory.

Stimulus inversion impaired performance more severely in case of categorical part-relational changes than part-specific ones. This result both validates our experimental manipulations and follows the predictions of RBC theory. Accordingly, inversion should hinder recognition performance by affecting the categorical part relations "above" and "below" in addition to any costs incurred by an inverted presentation of individual geons.

However, its impact should be mitigated by that fact that some relations (like “besides”) are invariant to orientation changes.

Overall the results of Experiment 1 regarding the attribute *relative position* show a very similar pattern as those obtained for the attribute *relative size* in Experiment 2 of Jüttner et al. (2013). The equivalence for the two core part-relational properties in structural theories of object recognition (Biederman, 1987; Hummel & Biederman, 1992; Hummel & Stankiewicz, 1996; Hummel, 2001) suggests an early ability to process non-accidental properties regardless whether such properties are characterizing individual parts or part relations. However, an early maturation for the processing of attributes at a categorical level does not necessarily imply a similarly steep trajectory for their processing at a metric level. In Experiment 2, we considered part-relational changes that were constrained to such metric, i.e. continuous, variations of an object’s part configuration.

Experiment 2

The continuous attribute *relative position* permits to encode the precise spatial relationships between the parts of an object. In the context of the RBC model, continuous attributes are generally referred to as “metric” to distinguish them from “categorical” attributes describing non-accidental properties. Unlike the latter, metric attributes are not viewpoint independent and their computation may recruit different mechanisms. Biederman (2000) suggests that the evaluation of such attributes may rely on combining filter outputs from retinotopic representations. Similarly, later dual-route variants of the RBC model have proposed that analytic, structural object descriptions are augmented by so-called non-analytic, view-based object representations (Hummel & Stankiewicz, 1996; Hummel, 2001), which also may provide a basis for metric attribute extraction.

The fact that feature processing at the metric level might call upon different mechanisms from that extracting NAPs raises the possibility of a different developmental trajectory for detecting metric object manipulations. It also entails the possibility that the developmental paths of processing metric changes of individual parts dissociate from those dealing with metric part relations. Few studies have previously considered this possibility. With regard to the metric part-relational attribute *relative position* Mash (2006) found that when combining positional and shape information for similarity judgements of novel objects consisting of two parts, 4-year-olds and 8-year-olds, but not adults, showed a consistent tendency to base their classification judgements on part-information alone, which by implication supports the idea of a protracted development of processing part-relational (here: positional) information relative to that of individual parts. Concerning manipulations of the metric attribute *relative size*, Experiment 3 of Jüttner et al. (2013) found that 7- to 8-year-olds' ability to detect such alterations in previously learned objects was distinctly reduced compared to their ability to spot metric shape changes in individual parts. In order to test whether this result also generalised to positional changes, Experiment 2 contrasted the detection of such part-relational changes with that of manipulations in individual object parts.

Method

Participants

Four age groups took part in the experiment: The groups were forty adult volunteers (25 females and 15 males; mean age 20 years 1 month), forty-eight 7- to 8-year-olds (25 females and 23 males; mean age 7 years 11 months), forty-eight 9- to 10-year-olds (24 females and 24 males; mean age 9 years 10 months), and forty-eight 11- to 12-year-olds (23 females and 25 males; mean age 12 years 0 months). The children were drawn from state schools in Birmingham, UK. The adults were recruited among undergraduate Psychology students at Aston University. They received course credit for participation.

Materials

The same set of learning objects was used as in Experiment 1 (cf. Figure 1).

For each object in the learning set, two manipulated distracter versions were created. The manipulations either involved a metric part change or a metric part-relational change (Figure 4) of the learning objects. Metric part changes were obtained by changing the aspect ratio of the original part in the distracters. Metric part-relational changes concerned manipulations of the relative position of object parts, which – in contrast to Experiment 1 – did not alter their categorical relation. Thus, the categorical spatial relation between two parts in the original object (for example, “above” or “beside”) would continue to apply to the corresponding parts of the two distracter versions. Part and part-relational manipulations were calibrated across the set of probe objects for equal difficulty [t(23) = -.15, p = .96] in adult observers. Stimulus dimensions and presentation conditions were identical to those in Experiment 1.

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Insert Figure 4 about here

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Procedure

The experimental procedure was identical to that in Experiment 1.

Results

Similar to Experiment 1, children and adults learned the set of six objects with relative ease. Eight participants (three within the age groups 7 – 8 yrs and 8 – 9 yrs, two within age group 11 – 12 yrs) did not complete the learning procedure and had to be replaced. On average, participants required 6.85 (SD 1.7) learning cycles to reach the target criterion of 90% correct responses. There were no significant differences of learning time across age groups [F(3,180) = 1.38, p = .25; one-way ANOVA].

Performance in the recognition test was analysed in terms of the accuracy and the latency preceding a correct response. As in Experiment 1, some participants showed particularly long latencies. Four participants with latencies classified as outliers (defined by the group mean ±3 standard deviations) were removed from the data set prior to the statistical analysis (two participants in age group 9 – 10 yrs, and one in each of the age groups 11 – 12 yrs, and adults).

Accuracy

Means and standard errors of the recognition accuracy for each age group and for each of the two manipulation conditions (Part vs. Part Relations) and orientations (Upright vs. Inverted) are shown in Figure 5A. The accuracy data were analysed in a 4 (Age: Adults vs. 11 – 12 yrs vs. 9 – 10 yrs vs. 7 – 8 yrs) x 2 (Manipulation: Part vs. Part Relation) x 2 (Orientation: Upright vs. Inverted) mixed ANOVA with Age as the between factor. The analysis yielded significant main effects for Age [$F(3,176) = 13.92$, $p < .001$, $\eta_p^2 = .19$], Orientation [$F(1,176) = 36.47$, $p < .001$, $\eta_p^2 = .17$] and Manipulation [$F(1,176) = 11.55$, $p < .01$, $\eta_p^2 = .06$]. Importantly, there was a significant interaction between Age, Manipulation, and Orientation [$F(3,176) = 2.96$, $p < .05$, $\eta_p^2 = .05$].

To follow up the three-way interaction separate ANOVAs for the Upright and Inverted condition were conducted. For upright stimuli, the effects of Age [$F(3,176) = 9.59$, $p < .001$, $\eta_p^2 = .14$] and Manipulation [$F(1,176) = 9.01$, $p < .01$, $\eta_p^2 = .05$] were both significant, as was their interaction [$F(3,176) = 2.74$, $p < .05$, $\eta_p^2 = .05$]. Posthoc comparisons revealed that the interaction was the consequence of children in the age groups 7 – 8 yrs and 9 – 10 yrs scoring significantly lower in the Part-Relational change than in the Part Change condition (ps < 0.05; paired t-test). For inverted stimuli, Age

[F(3,176) = 10.23, $p < .001$, $\eta_p^2 = .15$] and Manipulation [F(1,176) = 6.83, $p < .01$, $\eta_p^2 = .04$] were both significant whereas their interaction was not [F(3,176) = .81, p = .49].

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Insert Figure 5 about here

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Latency

Response times were analysed for the correct responses of each observer. Figure 5B summarises means and standard errors of the latencies for each age group, manipulation condition and orientation. The latencies were analysed in a 4 (Age) x 2 (Manipulation) x 2 (Orientation) mixed ANOVA with Age as between factor. The analysis yielded significant main effects for Age [F(3,157) = 3.94, $p < .05$, $\eta_p^2 = .07$] and Orientation [F(1,157) = 5.16, $p < .05$, $\eta_p^2 = .03$] but not for Manipulation [F(1,157) = .90, p = .34]. Children aged 11 - 12 yrs responded faster than children in the two youngest age groups (ps < .05; Tukey HSD test) but not relative to adults. The interaction Manipulation x Orientation was approaching significance [F(1,157) = 3.51, p = .06, $\eta_p^2 = .02$] indicating a trend towards higher inversion costs for metric part-relational than metric part changes. All other interactions were non-significant. There were no significant speed-accuracy trade-offs in any age group or condition (Pearson *r*s < .25, *p*s > .10).

Discussion

The remarkable finding of Experiment 2 is that children's ability to detect manipulations involving metric position follows a distinctly protracted trajectory relative to that of detecting metric changes to individual parts. It was only in 11- to 12-year-olds that performance levels in the two conditions became statistically equivalent. Again, these performance differences cannot be explained in terms of speed-accuracy trade-offs, which remained non-significant. Indeed, younger children required distinctly more time to respond than older ones, thus the differences in the accuracy data are conservative estimates.

The late development of children's ability to detect changes of metric part position also contrasts with the comparatively early maturation they show for the detection of categorical changes in part locations. These differences cannot be attributed to overall differences in task difficulty as both types of part-relational manipulations had been calibrated to a similar target accuracy in adults. Thus, the observed developmental dissociation indicates a pronounced difficulty in young children to process metric positional information. Such a finding is consistent with Mash's (2006) observation that young children tend to base similarity judgements of objects on the shape of individual parts rather than the positional relationships between those parts. However, it also transcends this finding by establishing such a dominance of parts over part-relations in a context involving recognition proper rather than perceptual classification, and in a task that requires the evaluation of a single, either part-specific or part-relational, manipulation.

The results of Experiment 2 are in principle also compatible with those of Experiment 3 of Jüttner et al. (2013), who performed a similar comparison for the attribute metric relative size. Jüttner et al. observed a distinct reduced performance in 7- to 8-year-old children relative to adults with regard to the detection of relative-size changes. However, the use of only two age groups in that study precludes a more detailed comparison with the data in Experiment 2. To assess the generality of our findings, Experiment 3 therefore re-examined the trajectory of the processing of part-relational information regarding the attribute *relative size*.

Experiment 3

Within the context of the RBC model, *relative size* constitutes the second core part-relational attribute and has been implemented in all versions of that approach (cf. Biederman, 1987; Hummel & Biederman, 1992; Hummel & Stankiewicz, 1996; Hummel, 2001). Similar to the attribute *relative position*, *relative size* can take on a categorical form, specifying the coarse proportions of an object's components (such as "larger"), as well as a metric form, which permits a precise specification of size ratios on a continuous scale. Concerning categorical relative size judgements, Jüttner et al. (2013, Exp. 2) observed that children´s ability to detect changes of this relational NAP develops early and follows a trajectory that does not significantly differ from that for detecting

NAP changes of individual parts – a result that mirrored the results of Experiment 1 regarding the attribute categorical position.

The question arises whether a similar equivalence holds between the developmental trajectories for processing metric variations of relative size and relative position. Preliminary evidence for such an equivalence was provided in Experiment 3 of Jüttner et al (2013), in which a distinctly reduced performance was observed with regard to the detection of relative-size changes in 7- to 8-year olds relative to adults. The aim of Experiment 3 was to replicate and extend these results in a study that employed the same age sampling as in Experiment 2, to permit a more comprehensive comparison of the developmental trajectories for the processing of the attributes *relative size* and *relative position*.

Method

Participants

Four age groups took part in the experiment: The groups were forty adult volunteers (23 females and 17 males; mean age 19 years 11 months), forty-eight 7- to 8-year-olds (24 females and 24 males; mean age 7 years 9 months), forty-eight 9- to 10-year-olds (23 females and 25 males; mean age 9 years 11 months), and forty-eight 11- to 12-year-olds (23 females and 25 males; mean age 11 years 11 months). The children were drawn from state schools in Birmingham, UK. The adults were recruited among undergraduate Psychology students at Aston University. They received course credit for participation.

Materials

The same set of learning objects was used as in Experiment 1 (cf. Figure 1). The distracter stimuli, adopted from Experiment 3 of Jüttner et al. (2013), were manipulated versions of the original stimuli, with the manipulation either involving a metric part change or a metric part-relational change of the learning objects. For each type of manipulation, two distracter versions were created for each object in the original learning set. Metric part changes were obtained by changing the aspect ratio of the original part in the distracters (Figure 6 left). Metric part-relational changes were confined to systematic manipulations of the relative size between object parts, which did not alter their categorical relation. As illustrated in Figure 6 (right), the relation between two parts in the original object (for example, “smaller”) would continue to apply to the corresponding size-changed parts of the distracter versions. The distracter stimuli had already been calibrated for equal difficulty of metric part change and metric part-relational change condition in adult observers by Jüttner et al. (2013). Stimulus dimensions and presentation conditions were identical to those in Experiment 1.

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Insert Figure 6 about here

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Procedure

The experimental procedure was identical to that in Experiment 1.

Results

As in the previous experiments, children and adults learned the set of six objects relatively quickly. Eight participants (four within the age groups 7 – 8 yrs, three in age group 8 – 9 yrs, and one within age group 11 – 12 yrs) did not complete the learning procedure and had to be replaced. On average, participants required 6.54 (SD 1.4) learning cycles to reach the target criterion of 90% correct responses. There was a weak trend of young children using more cycles than older ones [$F(3,180) = 2.22$, $p = .09$, $\eta_p^2 = .04$; one-way ANOVA].

Performance in the recognition test was analysed in terms of the accuracy and the latency preceding a correct response. Six participants with latencies classified as outliers (defined by the group mean ±3 standard deviations) were removed from the data set prior to the statistical analysis (three in the age group 7 – 8 yrs, and one in each of the age groups 9 – 10 yrs, 11 – 12 yrs, and adults).

Accuracy

Means and standard errors of the recognition accuracy for each age group and for each of the two manipulation conditions (Part vs. Part Relations) and orientations (Upright vs.

Inverted) are shown in Figure 7A. The accuracy data were analysed in a 4 (Age: Adults vs. 11 – 12 yrs vs. 9 – 10 yrs vs. 7 – 8 yrs) x 2 (Manipulation: Part vs. Part Relation) x 2 (Orientation: Upright vs. Inverted) mixed ANOVA with Age as the between factor. The analysis yielded significant main effects for Age [$F(3,174) = 12.42$, $p < .001$, $\eta_p^2 = .18$], Orientation [$F(1,174) = 21.03$, $p < .001$, $\eta_p^2 = .11$] and Manipulation [$F(1,174) = 7.77$, $p < .01$, $\eta_p^2 = .04$]. There was also a significant interaction between Age, Manipulation, and Orientation [$F(3,174) = 2.99$, $p < .05$, $\eta_p^2 = .05$].

To consider the three-way interaction in more detail separate ANOVAs for the Upright and Inverted condition were conducted. For upright stimuli, the effects of Age [$F(3,174) = 9.82$, $p<.001$, $\eta_p^2 = .15$] and Manipulation [$F(1,174) = 5.19$, $p < .05$, $\eta_p^2 = .03$] were both significant, as was their interaction [$F(3,174) = 2.98$, $p < .05$, $\eta_p^2 = .05$]. Posthoc comparisons revealed that the interaction was the consequence of children in the age groups 7 – 8 yrs and 9 - 10 yrs performing significantly lower in the metric Part-Relational change than in the metric Part Change condition (ps < 0.05; paired t-test). For inverted stimuli, Age [$F(3,174) = 9.15$, $p < .001$, $\eta_p^2 = .14$] and Manipulation [$F(1,174) = 6.58$, $p < .05$, $\eta_p^2 = .04$] were both significant whereas their interaction was not [$F(3,174) = .54$, $p = .66$].

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Insert Figure 7 about here

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Latency

Response times were analysed for the correct responses of each observer. Figure 7B summarises means and standard errors of the latencies for each age group, manipulation condition and orientation. The latencies were analysed in a 4 (Age) x 2 (Manipulation) x 2 (Orientation) mixed ANOVA with Age as between factor. The analysis yielded significant main effects for Age [$F(3,149) = 3.99$, $p < .01$, $\eta_p^2 = .07$] but not for Orientation [$F(1,149) = .38$, $p = .54$] or Manipulation [$F(1,149) = .21$, $p = .65$]. Children aged 11 - 12 yrs responded faster than 7- to 8-year-olds ($p < .05$; Tukey HSD test) but not relative 9- to 10-year-olds or adults. There were no significant interactions. Concerning potential speed-accuracy trade-offs within the individual age groups, 11- to 12-year-olds showed a marginally significant positive correlation in the inverted part-relational change condition (Pearson $r = .29$, $p = .05$), whereas 7- to 8-year-olds displayed a trend towards such a correlation in the upright part-change condition ($r = .28$, $p = .06$). All other correlations were non significant.

Discussion

Experiment 3 shows that children’s ability to detect manipulations of relative size in object parts follows a similar developmental trajectory as that for spotting changes of relative part position. For both attributes it was not before an age of 11 to 12 years, that children attained the same level of competence in the metric part-relational change condition as they displayed for metric part-specific changes. The observed dissociation is consistent with the preliminary evidence provided by Jüttner et al. (2013, Exp. 3) that had only included two age groups, 7- to 8-year-olds and adults. It is also compatible with Jüttner et al. (2013)'s finding (in their Experiment 1) of a distinctly protracted development of part-relational relative to part-specific processing when recognizing natural objects (here: animals and artefacts). Again, the part-relational manipulation affected the proportions of object components, i.e. their relative size at a metric level. As in Experiment 3, it was not before 11–12 years that children reached similar performance levels for the detection of part- and metric part-relational changes.

Experiment 3 had employed manipulations of relative size that ensured observers engaged in part-relational processing to solve the recognition task, as indicated by the significant stronger impact of inversion in the Part-Relational Change than in the Part Change condition. In our final experiment, we considered a variant of this experiment in which the perceptual context of the recognition task was modified in such a way that successful recognition of part-relational changes could be based on part-specific processing rather than an assessment of part relations. We used this variant as a further test of our hypothesis of a protracted development of metric part-relational processing.

Experiment 4

Manipulations of the relative size of two object parts relative to each other can be performed along a continuum of possible implementations. This continuum stretches between two extremes that affect part relations either symmetrically or asymmetrically. Symmetric size changes, as employed in Experiment 3, imply that as one part is increased in size, the other is shrunk by the same proportion (cf. the example in Figure 6). Symmetric manipulations of relative size are necessarily perceived as part-relational since they cannot be attributed to a modification of a single part. The other extreme, an asymmetric size change, is obtained by altering the size of just one part while leaving the other unaltered. Even though asymmetric size changes entail an alteration of a part relation, they may also affect the distinctiveness of the part that has been modified, and thereby induce part-specific processing. The effectiveness of the latter depends on visual context.

For the more complex case of face-like stimuli, an asymmetric size change of a single cardinal facial feature (for example, by exaggerating the nose) will result in a caricature-like distortion. Caricatures can be easier to recognize than veridical face representations (e.g. Benson & Perrett, 1991; Carey, 1992; Rhodes & Tremewan, 1994; Stevenage, 1995). This so-called caricature advantage has been attributed to the deviation of caricatures from the facial norm within a multidimensional face space, using the context provided by an observer's mental representation of all stored faces of a particular race (e.g., Valentine, 1991; Rhodes, Carey, Byatt, & Proffitt, 1998). Inversion impairs recognition of caricatures distinctly less than that of veridical face representations (Rhodes & Tremewan, 1994). This suggests that the perceived distinctiveness of caricatures is less dependent on relational processing even though that relationship may be a complex one (cf. Rakover, 2002, for a review).

With regard to the structurally simpler stimuli employed in the present study, we used, in Experiment 4, caricature-like versions of our learning objects, obtained by an asymmetrical size change of a single object part, to corroborate our hypothesis of a particularly protracted development of metric part-relational processing in adolescence. Even though these asymmetric relative-size changes qualified – like those in Experiment 3 – as metric part-relational manipulations (as they did not transgress categorical boundaries), we predicted – unlike Experiment 3 – that within the perceptual context provided by our one-in-three selection task such changes would invoke part-specific processing. Detection performance for asymmetric relative size changes should therefore follow the developmental trajectory of categorical part changes. We further expected inversion effects for such asymmetric relative size changes to be markedly reduced and not differ significantly from those obtained in the Part Change condition.

Method

Participants

Five age groups took part in the experiment, each consisting of 32 participants: The groups were adult volunteers (18 females and 14 males; mean age 20 years 2 months), 7- to 8-year-olds (15 females and 17 males; mean age 7 years 11 months), 9- to 10-year-olds

(17 females and 15 males; mean age 10 years 0 months), 11- to 12-year-olds (16 females and 16 males; mean age 11 years 10 months), and 13- to 14-year-olds (17 females and 15 males; mean age 13 years 11 months). The children were drawn from state schools in Birmingham, UK. The adults were recruited among undergraduate Psychology students at Aston University. They received course credit for participation.

Materials

The same set of learning objects was used as in Experiment 1 (cf. Figure 1). For each stimulus of the original learning set, two distracter versions were created that involved a categorical part change or a metric part-relational change of the original object. Categorical part changes (cf. Figure 8 left) consisted in the substitution of the original part with that taken from another object (cf. Part Change condition of Experiment 1). Metric part-relational changes were confined to systematic manipulations of the relative size between object parts, which did not alter their categorical relationship (such as "smaller", cf. the example in Figure 8, right). In contrast to Experiment 3 (cf. Figure 6 right), however, the part sizes changes were applied asymmetrically (i.e., they affected only one part while leaving the other two unaltered). Part and part-relational manipulations were calibrated across the set of probe objects for equal difficulty [$t(31) = -.45$, $p = .65$] in adult observers. Stimulus dimensions and presentation conditions were identical to those in Experiment 1.

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Insert Figure 8 about here

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Procedure

The experimental procedure was identical to that in Experiment 1.

Results

As in the previous experiments of this study, children and adults found the learning of the six objects relatively easy. Five participants (two within the age groups 7 – 8 yrs and 8 – 9 yrs, one within age group 13 - 14 yrs) did not complete the learning procedure and had to be replaced. On average, participants required 6.12 (SD 1.8) learning cycles to reach the target criterion of 90% correct responses. There was a marginally significant effect of age on learning time [$F(4,159) = 2.50$, $p = .05$, $\eta_p^2 = .06$; one-way ANOVA], with 7- to 8-year-olds using more cycles than adults, but not relative to older children ($p=.05$, Tukey HSD test).

Performance in the recognition test was analysed in terms of the accuracy and the latency preceding a correct response. Eight participants with response latencies classified as outliers (defined by the group mean ±3 standard deviations) were removed from the data set prior to the statistical analysis (three participants each in the age groups 7 – 8 yrs and 11 – 12 yrs, one in the age group 11 – 12 yrs, and one adult).

Accuracy

Means and standard errors of the recognition accuracy for each age group and for each of the two manipulation conditions (Part vs. Part Relations) and orientations (Upright vs. Inverted) are shown in Figure 9A. The accuracy data were analysed in a 5 (Age: Adults vs. 13 – 14 yrs vs. 11 – 12 yrs vs. 9 – 10 yrs vs. 7 – 8 yrs) x 2 (Manipulation: Part vs. Part Relation) x 2 (Orientation: Upright vs. Inverted) mixed ANOVA with Age as the between factor. The analysis yielded significant main effects for Age [$F(4,147) = 6.29$, $p < .001$, $\eta_p^2 = .15$] and Orientation [$F(1,147) = 5.98$, $p < .05$, $\eta_p^2 = .04$], while Manipulation failed to reach significance [$F(1,147) = 3.04$, $p = .08$]. There were no significant interactions.

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Insert Figure 9 about here

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Latency

Response times were analysed for the correct responses of each observer. Figure 9B shows means and standard errors of the latencies for each age group, manipulation condition and orientation. In analogy to the accuracies, the latencies were analysed in a 5 (Age) x 2 (Manipulation) x 2 (Orientation) mixed ANOVA with Age as between factor. The analysis yielded a significant main effect for Age [$F(4,136) = 5.69$, $p < .001$, $\eta_p^2 = .14$], with adults and 13- to 14-year-olds responding faster than children in the three younger age groups (*p*s < .05; Tukey HSD test). Orientation also proved significant [$F(1,136) = 4.87$, $p < .05$, $\eta_p^2 = .04$], with latencies to inverted stimuli being longer than to upright ones. All other main effects and interactions were non-significant. There were no speed-accuracy trade-offs in any age group or condition (Pearson *r*s < .29, *p*s > .14).

Comparison of Experiment 3 and Experiment 4

In order to compare the trajectories observed in Experiments 3 and 4, the accuracies were combined in a joint mixed ANOVA with Experiment (Exp. 3 vs. Exp. 4) as an additional between-subjects factor. The analysis gave significant main effects for Age [$F(4,321) = 13.93$, $p < .001$, $\eta_p^2 = .15$], Experiment [$F(1,321) = 32.65$, $p < .001$, $\eta_p^2 = .09$], and Orientation [$F(1,321) = 21.08$, $p < .001$, $\eta_p^2 = .06$]. There also was a significant interaction between Manipulation and Experiment [$F(1,321) = 9.18$, $p < .01$, $\eta_p^2 = .03$]. To consider the two-way interaction in more detail separate ANOVAs for the Part Change and Configural Change conditions were conducted. For part changes, Orientation [$F(1,321) = 11.52$, $p < .001$, $\eta_p^2 = .04$] and Age [$F(4,321) = 5.52$, $p < .001$, $\eta_p^2 = .06$] were significant, while Experiment was only approaching significance [$F(1,321) = 3.80$, $p = .05$, $\eta_p^2 = .01$]). For configural changes, Orientation [$F(1,321) = 10.52$, $p < .001$, $\eta_p^2 = .03$], Age [$F(4,321) = 8.96$, $p <. 001$, $\eta_p^2 = .10$] and Experiment [$F(1,321) = 36.24$, $p < .001$, $\eta_p^2 = .10$) were all highly significant. Thus, the critical difference between the results of the two experiments lay in the different developmental trajectories observed for the detection of configural changes, implemented by symmetric relative size changes in Experiment 3 and asymmetric relative size changes in Experiment 4[1].

[1] A similar ANOVA directly comparing the trajectories of the (identical) part-change conditions in Experiments 1 and 4 proved non-significant [$F(1,268) = .00$, $p = .95$]. Thus the different experimental context in Experiment 4 did not significantly affect performance for detecting categorical manipulations of object parts.

Discussion

Experiment 4 demonstrates that manipulations of relative size that were limited to a single part eliminated the developmental dissociation between part-specific and part-relational processing observed in Experiment 3. In contrast to the latter, now even the youngest tested children were able to detect relative size changes with the same accuracy as changes of individual parts. This pattern of results cannot be attributed to differences between Experiment 3 and 4 regarding the overall distinctiveness of the distracters resulting from the two types of size manipulations. In both experiments, the former had been calibrated against the distracter set in the Part Change condition with a similar target accuracy in adults.

We propose that it was the perceptual context provided by the asymmetric size change of our caricature-like distracters in Experiment 4 that facilitated the recruitment of part-specific mechanisms, leading effectively to a masking of the protracted development of part-relational processing and to statistically equivalent trajectories in the Part-Relational and Part Change condition. Further evidence for such a context-induced substitution of part-relational by part-specific processing is provided by the much reduced impact of inversion. In contrast to Experiments 2 and 3 there was no significant interaction between Orientation and Manipulation in Experiment 4, indicating that inversion affected the detection of part-relational (relative size) changes no more than that of part changes. Inversion effects have been traditionally seen as a hallmark of relational processing, particularly in face recognition (e.g., Yin, 1969; Carey & Diamond, 1977; for a review, see Valentine, 1988). For face caricatures inversion effects have been found to be distinctly smaller, a result that has been taken as evidence for a reduced reliance of caricature recognition on relational feature coding (Rhodes & Tremewan, 1994). An analogue conclusion regarding the relative absence of part-relational processing for the detection of asymmetric size changes can be drawn from the reduced impact of inversion in Experiment 4. We will further consider parallels of our results with those reported in the face recognition literature in the general discussion.

General Discussion

In four experiments, children aged 7 to14 years and adults were tested in 3-AFC tasks to judge the correct appearance of newly learned multi-part objects, which had been manipulated in terms of individual parts or part relations at either categorical or metric level. For the detection of categorical changes of parts and part relations, even the youngest tested children were found to perform close to adult levels. By contrast, for metric changes the data provides converging evidence for dissociating developmental trajectories of part-based and part-relational object processing, with a surprisingly late consolidation of the latter.

On the one hand, our results are compatible with a number of previous studies indicating an early maturation of object recognition skills (Golarai, Ghahremani, Whitfield-Gabrieli, Reiss, Eberhardt, Gabrieli, & Grill-Spector, 2007; Scherf, Behrmann, Humphreys, &

Luna, 2007; see also Aylward, Park, Field, Parsons, Richards, Cramer, & Meltzhoff, 2005; Gathers, Bhatt, Corbly, Farley, & Joseph, 2004). These studies typically used paradigms that did not crucially depend on part-relational processing. For example, Golarai et al. employed an old-new recognition task, which in the case of (non-face) objects used photographs of abstract sculptures that distinctly differed from one another in terms of their constituent parts. Scherf et al.'s study involved short movie vignettes, which in the "object" condition showed typical manipulations, like picking up an object from a desk. Again, the objects used could be distinguished by on the basis of individual parts. Thus, the competence observed in these studies for children as young as seven has a correspondence in the remarkable accuracy shown by children in our part-change conditions, in particular those involving non-accidental manipulations (cf. Experiment 1). On the other hand, our results go beyond that previous work by demonstrating that the ability to assess part-relations for the purpose of object recognition follows a distinctly protracted developmental trajectory, and approaches adult levels not before an age of 12. Importantly, this delay only applies to part-relations that involve the metric evaluation of attributes, but not to those that differ in categorical terms.

The distinction between categorical and metric levels of processing of parts and part relations is a fundamental principle of the Recognition-by-Components (RBC) model (Biederman, 1987, 2000) which provides the theoretical framework of the present study. According to the RBC approach objects are represented as structural descriptions that involve certain part primitives (geons) that are connected by a restricted set of categorical relations. In the past, the RBC model has inspired considerable developmental work, most of which has been concerned with the role of individual parts. Here it has been demonstrated that part information plays an important role in object categorization and matching in young children and toddlers (Madole & Cohen, 1995; Smith et al., 1996; Rakison & Butterworth, 1998, Abecassis et al., 2001; Haaf et al., 2003; Mash, 2006). Whether the early primacy of parts in visual processing reflects a peculiar status of geons, i.e., parts that differ in terms of categorical contour properties, in young infants has been more controversial (cf. Haaf et al., 2003; but Abecassis et al., 2001). However, there is agreement that by the age of 7 – the youngest children tested in our experiments – children should display a competence close to adult levels for the detection of part-specific changes, if those changes involve manipulations of non-accidental part-properties.

Unlike for parts, only very few developmental studies have addressed the processing of part relations from an RBC perspective. With regard to similarity judgements Mash (2006) observed a strong bias in children to classify objects on the basis of part specific rather than part-relational information. Mash's study involved novel objects consisting of two parts one of which was manipulated in terms of its cross-section and its relative location relative to the second. The observed reluctance of young children to take into account the latter (a metric part-relational change) and rather rely on the former (a metric part-specific change) is in principle compatible with the results of the current study, in particular those of Experiment 2. Nonetheless, the task employed by Mash did not require the involvement of long-term memory as all stimuli to be compared were presented simultaneously. Critically, control experiments showed that children's perceptual bias towards parts could not be explained by a reduced discrimination ability for part relations[2]. Mash's results therefore remain tacit as to the consequences of this bias for object learning, in particular in situations where – as in case of our four probe objects – part-specific differences are absent. By contrast, the present study in conjunction with that of Jüttner et al. (2013) indicates a critical developmental difference between metric and categorical part-relational processing in object recognition proper, i.e. a task that requires the matching of a percept to a stored memory representation. As demonstrated in Experiment 3, this difference pertains to the two core part-relational attributes in the RBC model, relative size and relative position, which suggests a generic rather than attribute-specific dissociation.

To the extent that our experiments map the transition of object recognition skills from adolescence to adulthood they also impose constraints on theories object of recognition at a more general level, beyond any particular age range. Here as an alternative to structural approaches (like RBC) so-called image-based accounts (e.g., Ullman, 1989; Poggio & Edelman, 1990; Tarr & Bülthoff, 1995; Riesenhuber & Poggio, 1999) have been suggested. They generally assume a view-like representation where object features are stored in terms of their literal position within a pictorial, two-dimensional coordinate system. Current image-based models do not directly address issues of development but object learning experiments in adult observers suggest that the acquisition of view-based object representations is predominantly driven by statistical learning (e.g., Poggio & Edelman, 1990). During such learning, distinct views emerge as a result of gradual

[2] Indeed, in these control experiments children found part-relational variations easier to discriminate than part changes (cf. also Experiment 2 of Davidoff and Roberson, 2002, for a similar observation).

familiarization with clusters of viewpoint-specific features. Given this particular representational format and assuming “degraded” object views in children, image-based models would necessarily predict a recognition advantage for part-relational relative to part-specific changes owing to the greater spatial correlation between the features of target and distracters implied by the latter - contrary to our findings in Experiments 2 and 3. They would also fail to predict a selective impairment for detecting metric (Experiment 2) as opposed to non-accidental (Experiment 1) part-relational changes if these changes are – as in our experiments – calibrated for equal difficulty in adults.

While structural and view-based representations originally have been discussed as mutually exclusive alternatives (e.g., Biederman, 1987, 2000; but Poggio & Edelman, 1990; Tarr & Bülthoff, 1995), more recent evidence from behavioural (e.g., Hummel, 2001; Forster & Gilson, 2002; Hayward, 2003; Thoma et al. 2004) and neuroimaging (Vuilleumier et al., 2002; Thoma & Henson, 2011) studies indicate that such formats might co-exist, and that the visual system might draw upon these multiple object representations in a task-dependent manner. Our results add a developmental perspective to this debate suggesting – in line with other recent evidence (Wakui et al. 2013) – a primacy of structural object recognition that leaves less room for the use of view-based representations.

Our experiments employed a set of six novel objects that were constructed as compounds of three geons, i.e. three-dimensional shape primitives with unique NAP signature (Biederman, 1987). While this construction principle permits a careful manipulation of parts and part relations as well as an easy and unambiguous recovery of the components in the context of the RBC model one might question its validity with regard to more realistic objects with a less obvious part structure. For more complex shapes RBC postulates the recovery of object components to be assisted by a parsing mechanism based on general contour properties (Hoffman & Richards, 1984) – an additional processing step that our objects do not require. Nonetheless, the compatibility of the present results with that of previous studies involving natural stimuli (animals and common objects, cf. Jüttner et al., 2013) indicates that our specific stimulus choice does not affect the generality of our conclusions concerning a critical developmental difference between metric and categorical part-relational processing in object recognition.

Our data also offers parallels to the development of face perception. The problems observers in the two youngest age groups had with the detection of subtle positional changes of object parts in Experiment 2 is reminiscent of a similar and well-documented difficulty children have when assessing spatial relations of facial features. Here it has been shown that children's sensitivity to detect manipulations of the distances between cardinal features like the eyes, the nose and the mouth continues to improve until at least 14 years (Carey et al., 1980; Bruce et al., 2000; Mondloch et al, 2002). Such processing of spatial relations – also referred to as second-order processing – can be contrasted with the coarse assessment of the basic spatial layout of facial features – their so-called first-order relations. The sensitivity to the latter is known to develop much earlier and may already be present in newborns (e.g., Goren, Sarty, & Wu, 1975; Johnson Dziurawiec, Ellis, & Morton, 1991). It is tempting to draw a parallel between the developmental dissociation between first- and second-order relational processing of facial features on the one hand and between categorical and metric part-relational processing for non-face objects on the other. Moreover, both for faces and non-face objects are late developing processing skills for metric (second-order) part-relational manipulations particularly susceptible to inversion effects, unless such manipulations occur in perceptual contexts where they are detected as part changes, as in case of caricature-like stimuli (cf. Experiment 4).

Young children's difficulties with the evaluation of second-order relations of facial features have often been related to their limited face identification skills (Diamond & Carey, 1986; Freire, Lee, & Symons, 2000; Kemp et al., 1990; Mondloch et al., 2002). We propose that such difficulties may extend to the processing of metric part relations in general and therefore impose more fundamental limitations to object recognition in the developing mind. Unlike in face identification, these limitations may be obscured - if not effectively masked - by the fact that recognition at the so-called basic (or entry) level can often rely on the detection of changes concerning individual parts (Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976) or categorical part relations (Biederman, 1987), i.e., on processing strategies for which an early maturation is to be expected. In the context of the present study this possibility was illustrated by the successful acquisition of our object set by all observers during the learning phase of each experiment, with minimal variations across age groups. However, as demonstrated in the subsequent testing phase such successful learning does not imply an equivalence of the acquired memory representations for object shape in children and adults. Our experiments therefore add to the growing evidence (cf. Wakui et al., 2013) for a remarkably protracted development of mental representations subserving non-face object recognition, along a trajectory extending beyond childhood and well into adolescence.

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References

Abecassis, M., Sera, M. D., Yonas, A., & Schwade, J. (2001). What's in a shape? Children represent shape variability differently than adults when naming objects. *Journal of Experimental Child Psychology, 78,* 213-239. doi:10.1006/ jecp.2000. 2573

Aylward, E. H., Park, J. E., Field, K. M., Parsons, A. C., Richards, T. L., Cramer, S. C., & Meltzhoff, A. N. (2005). Brain activation during face perception: evidence of a developmental change. *Journal of Cognitive Neuroscience, 17,* 308-319. doi: 10.1162/0898929053124884

Benson, P. J., & Perrett, D. I. (1991). Extracting prototypyical facial images from exemplars. *Perception, 22,* 257-262. doi:10.1068/p220257

Biederman, I. (1987). Recognition by components: A theory of human image understanding. *Psychological Review, 94*, 115-147. doi:10.1037//0033-295X.94.2.115

Biederman, I. (2000). Recognizing depth-rotated objects: A review of recent research and theory, *Spatial Vision, 13,* 241-254. doi:10.1163/156856800741063

Bruce, B., Campbell, R. N., Doherty-Sneddon, G., Import, A., Langton, S., McAuley, S., & Wright, R. (2000) Testing face processing skills in children. *British Journal of Developmental Psychology, 18,* 319-333. doi:10.1348/026151000165715

Bruyer R., & Crispeels, G. (1992). Expertise in person recognition. *Bulletin of the Psychonomic Society, 30,* 501-504. doi:10.3758/BF03334112

Carey, S. (1992). Becoming a face expert. *Philosophical Transactions of the Royal Society of London B*, 335, 95-103. doi:10.1098/rstb.1992.0012

Carey, S., & Diamond, R. (1977). From piecemeal to configurational representation of faces. *Science, 195,* 312-314. doi:10.1126/science.831281

Carey, S., Diamond, R., & Woods, R. (1980). Development of face recognition: A maturational component. *Developmental Psychology, 16,* 257-269. doi:10.1037// 0012-1649.16.4.257

Davidoff, J., & Roberson, D. (2002). Development of animal recognition: A difference between parts and wholes. *Journal of Experimental Child Psychology, 81*, 217-234. doi:10.1006/jecp.2002.2659

de Gelder, B., Bachoud-Lévi, A.-C., & Degos, J.-D. (1998). Inversion superiority in visual agnosia may be comon to a variety of orientation polarised objects besides faces. *Vision Research, 38,* 2855-2861. doi:10.1016/S0042-6989(97)00458-6

de Heering, A., Houthuys, S., & Rossion, B. (2007). Holistic face processing is mature at 4 years of age: evidence from the composite face effect. *Journal of Experimental Child Psychology, 96,* 57-70. doi:10.1016/j.jecp.2006.07.001

Diamond, R., & Carey, S. (1986). Why faces are and are not special: an effect of expertise. *Journal of Experimental Psychology: General, 115,* 107-117. doi: 10.1037//0096-3445.115.2.107

Ellis, H. D. (1975). Recognizing faces. *British Journal of Psychology, 66,* 409-426. doi: 10.1111/j.2044-8295.1975.tb01477.x

Foster, D. H., & Gilson, S. J. (2002). Recognizing novel three-dimensional objects by summing signals from parts and views. *Proceedings of the Royal Society of London Series B - Biological Sciences, 269,* 1939-194. doi: 10.1098/rspb.2002.2119

Freire, A., Lee, K., & Symons, L. A. (2000). The face-inversion effect as a deficit in the encoding of configural information: Direct evidence. *Perception, 29,* 159-170. doi: 10.1068/p3012

Gathers, A. D., Bhatt, R., Corbly, C. R., Farley, A. B., & Joseph, J. E. (2004). Developmental shifts in cortical loci for face and object recognition. *NeuroReport, 15,* 1549-1553. doi:10.1097/01.wnr.0000133299.84901.86

Golarai, G., Ghahremani, D. G., Whitfield-Gabrieli, S., Reiss, A., Eberhardt, J. L., Gabrieli, J. D. E., & Grill-Spector, K. (2007). Differential development of high-level visual cortex correlates with category-specific recognition memory. *Nature Neuroscience, 10,* 512-522. doi:10.1038/nn1865

Goren, C. C., Sarty, M., & Wu, P. Y. K. (1975). Visual following and pattern discrimination of face-like stimuli by newborn infants. *Pediatrics, 56,* 544–549.

Haaf, R.A., Fulkerson, A. L., Jablonski, B. J., Hupp, J. M., Shull, S. S., & Pescara-Kovach, L. (2003). Object recognition and attention to object components by preschool children and 4-month-old infants. *Journal of Experimental Child Psychology, 86,* 108-123. doi:10.1016/S0022-0965(03)00108-5

Hayward, W. G. (2003). After the viewpoint debate: where next in object recognition. *Trends in Cognitive Sciences, 7,* 425-427. doi: 10.1016/j.tics.2003.08.004

Hoffman, D. D., & Richards, W. A. (1984). Parts of recognition. *Cognition,* 18, 65-96. doi: 10.1016/0010-0277(84)90022-2

Hummel, J. E. (2001). Complementary solutions to the binding problem in vision: Implications for shape perception and object recognition. *Visual Cognition,* 8, 489-517. doi:10.1080/13506280143000214

Hummel, J. E., & Biederman, I. (1992). Dynamic binding in a neural network for shape recognition. *Psychological Review, 99,* 480-517. doi:10.1037/0033-295X.99.3.480

Hummel, J. E. & Stankiewicz, B. J. (1996). An architecture for rapid, hierarchical structural description. In T. Inui & J. McClelland (Eds.), *Attention and performance XVI: Information integration in perception and communication* (pp. 93-121). Cambridge, MA: MIT Press.

Johnson, M.H., Dziurawiec, S., Ellis, H., & Morton, J. (1991). Newborns' preferential tracking of face-like stimuli and its subsequent decline. *Cognition, 90,* 1–19. doi: 10.1016/0010-0277(91)90045-6

Jüttner, M., Müller A., & Rentschler, I. (2006). A developmental dissociation of view-dependent and view-invariant object recognition in adolescence. *Behavioural Brain Research, 175,* 420-424. doi:10.1016/j.bbr.2006.09.005

Jüttner, M., Wakui, E., Petters, D., Kaur, S. & Davidoff, J. (2013). Developmental trajectories of part-based and configural object recognition in adolescence. *Developmental Psychology, 49,* 161-176. doi:10.1037/a0027707

Kemp, R., McManus, C., & Pigott, T. (1990). Sensitivity to the displacement of facial features in negative and inverted images. *Perception, 19,* 531-543. doi:10.1068/p190531

Madole, K. L., & Cohen, L. B. (1995). The role of object parts in infants' attention to form-function correlations. *Developmental Psychology, 31,* 637-648. doi:10.1037// 0012-1649.31.4.637

Marr, D. (1982). *Vision.* San Francisco: Freeman.

Mash, C. (2006). Multidimensional shape similarity in the development of visual object classification. *Journal of Experimental Child Psychology, 95,* 128-152. doi:10.1016/ j.jecp.2006.04.002

McKone, E., & Boyer, B. L. (2006). Sensitivity of 4-year-olds to featural and second-order relational changes in face distinctiveness. *Journal of Experimental Child Psychology, 94,* 134-162. doi:10.1016/j.jecp.2006.01.001

McLaren, I. P. L. (1997). Categorization and perceptual learning: An effect of the face inversion effect. *Quarterly Journal of Experimental Psychology, 50A,* 257-273. doi: 10.1080/713755705

Mondloch, C. J., Le Grand, R., & Maurer, D. (2002). Configural face processing develops more slowly than featural face processing. *Perception, 31,* 553-566. doi: 10.1068/p3339

Pellicano, E., & Rhodes, G. (2003). Holistic processing of faces in preschool children and adults. *Psychological Science, 14,* 618-622. doi:10.1046/j.0956-7976.2003.psci_1474.x

Petters, D., Hummel, J., Juttner, M., Wakui, E. & Davidoff, J. (2014). Dual process models of object recognition: taking a developmental turn and beyond. *Lecture Notes in Computer Science* (in press).

Poggio, T., & Edelman, S. (1990). A network that learns to recognize three-dimensional objects. *Nature, 343,* 263-266. doi: 10.1038/343263a0

Rakison, D., & Butterworth, G. E. (1998). Infants' use of object parts in early categorization. *Developmental Psychology, 34,* 49-62. doi:10.1037//0012-1649.34.1.49

Rakison, D. H., & Cohen, L. B. (1999). Infants' use of functional parts in basic-like categorization. *Developmental Science, 2,* 423-431. doi:10.1111/1467-7687.00086

Rakover, S. S. (2002) Featural vs. configurational information in faces: A conceptual and empirical analysis. *British Journal of Psychology, 93,* 1-30. doi: 10.1348/000712602162427

Rentschler, I., Jüttner, M., Osman, E., Müller, A., & Caelli, T. (2004). Development of configural object recognition. *Behavioural and Brain Research, 104,* 107-111. doi: 10.1016/S0166-4328(03)00194-3

Rhodes, G., Carey, S., Byatt, B., & Proffitt, F. (1998). Coding spatial variations in faces and simple shapes: A test of two models. *Vision Research, 38,* 2307–2321. doi: 10.1016/S0042-6989(97)00470-7

Rhodes, G., & Tremewan, T. (1994). Understanding face recognition: Caricature effects, inversion and the homogeneity problem. *Visual Cognition, 1,* 275–311. doi: 10.1080/13506289408402303

Riesenhuber, M., & Poggio, T. (1999). Hierarchical models of object recognition in cortex. *Nature Neuroscience, 2,* 1019-1025.

Rosch, E., Mervis, C. B., Gray, W. D., Johnson, D. M., & Boyes-Braem, P. (1976). Basic objects in natural categories. *Cognitive Psychology, 8,* 382-439. doi: 10.1016/0010-0285(76)90013-X

Saiki, J., & Hummel, J. E. (1996). Attribute conjunctions and the part configuration advantage in object category learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 22,* 1002-1019. doi:10.1037//0278-7393.22.4.1002

Scherf, K. S., Behrmann, M., Humphreys, K., & Luna, B. (2007). Visual category-selectivity for faces, places and objects emerges along different developmental trajectories. *Developmental Science, 10,* F15-F30. doi:10.1111/j.1467-7687.2007.00595.x

Schyns, P. G., & Murphy, G. L. (1994). The ontogeny of part representations in object concepts. In D. L. Medin (Ed.), *The psychology of learning and motivation* (Vol. 31, pp. 305-349). San Diego: Academic Press.

Smith, L. B., Jones, S.S., & Landau, B. (1996). Naming in children: a dumb attentional mechanism? *Cognition, 60,* 143-171. doi:10.1016/0010-0277(96)00709-3

Stevenage, S. V. (1995). Can caricatures really produce distinctiveness effects? *British Journal of Psychology, 86,* 127–146. doi:10.1111/j.2044-8295.1995.tb02550.x

Tarr M. J., & Bülthoff, H. H. (1995). Is human object recognition better described by geon structural descriptions or by multiple views? Comment on Biederman and Gerhardstein (1993). *Journal of Experimental Psychology: Human Perception and Performance, 21,* 1494-1505. doi: 10.1037//0096-1523.21.6.1494

Thoma, V., & Henson, R. N. (2011). Object representations in ventral and dorsal visual streams: fMRI repetition effects depend on attention and part-whole configuration. *Neuroimage, 57*, 513-525. doi: 10.1016/j.neuroimage.2011.04.035

Thoma, V., Hummel J. E. , & Davidoff, J. (2004). Evidence for holistic representations of ignored images and analytic representations of attended images. *Journal of Experimental Psychology: Human Perception and Performance, 30,* 257-267. doi: 10.1037/0096-1523.30.2.257

Tversky, B., & Hemenway, K. (1984). Objects, parts, and categories. *Journal of Experimental Psychology: General, 113,* 169-193. doi:10.1037//0096-3445.113.2.169

Ullman, S. (1989). Aligning pictorial descriptions: an approach to object recognition. *Cognition, 32,* 193–254. doi: 10.1016/0010-0277(89)90036-X

Valentine, T. (1988). Upside-down faces: A review of the effect of inversion on face recognition. *British Journal of Psychology, 79,* 471–491. doi:10.1111/j.2044-8295.1988.tb02747.x

Valentine, T. (1991). A unified account of the effects of distinctiveness, inversion and race in face recognition. *Quarterly Journal of Experimental Psychology, 43A*, 161–204. doi:10.1080/14640749108400966

Vuilleumier, P., Henson, R. N., Driver, J., & Dolan, R. J. (2002). Multiple levels of visual object constancy revealed by event-related fMRI of repition priming. *Nature Neuroscience, 5,* 491-499. doi: 10.1038/nn839

Yin, R. K. (1969). Looking at upside-down faces. *Journal of Experimental Psychology, 81,* 141-145. doi:10.1037/h0027474

Wakui, E., Jüttner, M., Petters, D., Kaur, S., Hummel, J.E. & Davidoff, J. (2013). Earlier development of analytical than holistic object recognition in adolescence. *PLoS ONE 8(4):* e61041. doi:10.1371/journal.pone.0061041

Figure captions

Figure 1. Set of six Geon objects used in Experiments 1 to 4. Note that objects 3 to 6 (probe objects) consisted of the same parts (geons) and only differed in terms of the categorical relational properties *relative size* and *relative position*. By contrast, objects 1 and 2 (facilitator objects) consisted of a different set of geons arranged in a distinctive horizontal or vertical configuration. During the learning phase of the experiment, participants were trained to associate each of the six objects with its label (number). During the recognition test, facilitator objects were used during practice trials, whereas experimental trials only included the four probe objects. See main text for further details.

Figure 2. Examples of geon stimuli used in the recognition test of Experiment 1. Each object of the learning set was shown with two distracters. They either involved a categorical part change (left) or a categorical, part-relational change of relative position (right). Participants had to choose the correct depiction of the previously learnt object (here: the middle left and the top right stimulus).

Figure 3. Mean accuracies and latencies in Experiment 1, contrasting categorical part changes and categorical, part-relational changes of relative position. **(A)** Mean rate of correct identifications within each age group for part- and part-relationally manipulated geon stimuli in upright and inverted orientation. The dashed line at .33 indicates chance level. **(B)** Mean latencies of correct responses, corresponding to the age groups and conditions shown in (A). Error bars are standard errors.

Figure 4. Examples of geon stimuli used in the recognition test Experiment 2. Each object of the learning set was shown with two distracters, which in this experiment either involved a metric part change (left) or a metric, part-relational change in relative position (right). Participants had to choose the correct depiction of the previously learnt object (here: the bottom left and the top right stimulus).

Figure 5. Mean accuracies and latencies in Experiment 2, contrasting metric part changes and metric, part-relational changes of relative position. **(A)** Mean rate of correct identifications within each age group for part- and part-relationally manipulated geon stimuli in upright and inverted orientation. The dashed line at .33 indicates chance level. **(B)** Mean latencies of correct responses, corresponding to the age groups and conditions shown in (A). Error bars are standard errors.

Figure 6. Examples of geon stimuli used in the recognition test Experiment 3. Each object of the learning set was shown with two distracters, which in this experiment either involved a metric part change (left) or a metric, part-relational change in relative size (right). Participants had to choose the correct depiction of the previously learnt object (here: the bottom left and the top right stimulus).

Figure 7. Mean accuracies and latencies in Experiment 3, contrasting metric part changes and metric, part-relational changes of relative size. **(A)** Mean rate of correct identifications within each age group for part- and part-relationally manipulated geon

stimuli in upright and inverted orientation. The dashed line at .33 indicates chance level. **(B)** Mean latencies of correct responses, corresponding to the age groups and conditions shown in (A). Error bars are standard errors.

Figure 8. Examples of geon stimuli used in the recognition test Experiment 4. Each object of the learning set was shown with two distracters, which in this experiment either involved a categorical part change (left) or a metric, part-relational change in relative size (right). Note that in contrast to Experiment 3 (cf. Figure 6) the relative size change was asymmetric, i.e. affecting only a single part. Participants had to choose the correct depiction of the previously learnt object (here: the middle left and the top right stimulus).

Figure 9. Mean accuracies and latencies in Experiment 4, contrasting categorical part changes and metric, asymmetric part-relational changes of relative size. **(A)** Mean rate of correct identifications within each age group for part- and part-relationally manipulated geon stimuli in upright and inverted orientation. The dashed line at .33 indicates chance level. **(B)** Mean latencies of correct responses, corresponding to the age groups and conditions shown in (A). Error bars are standard errors.

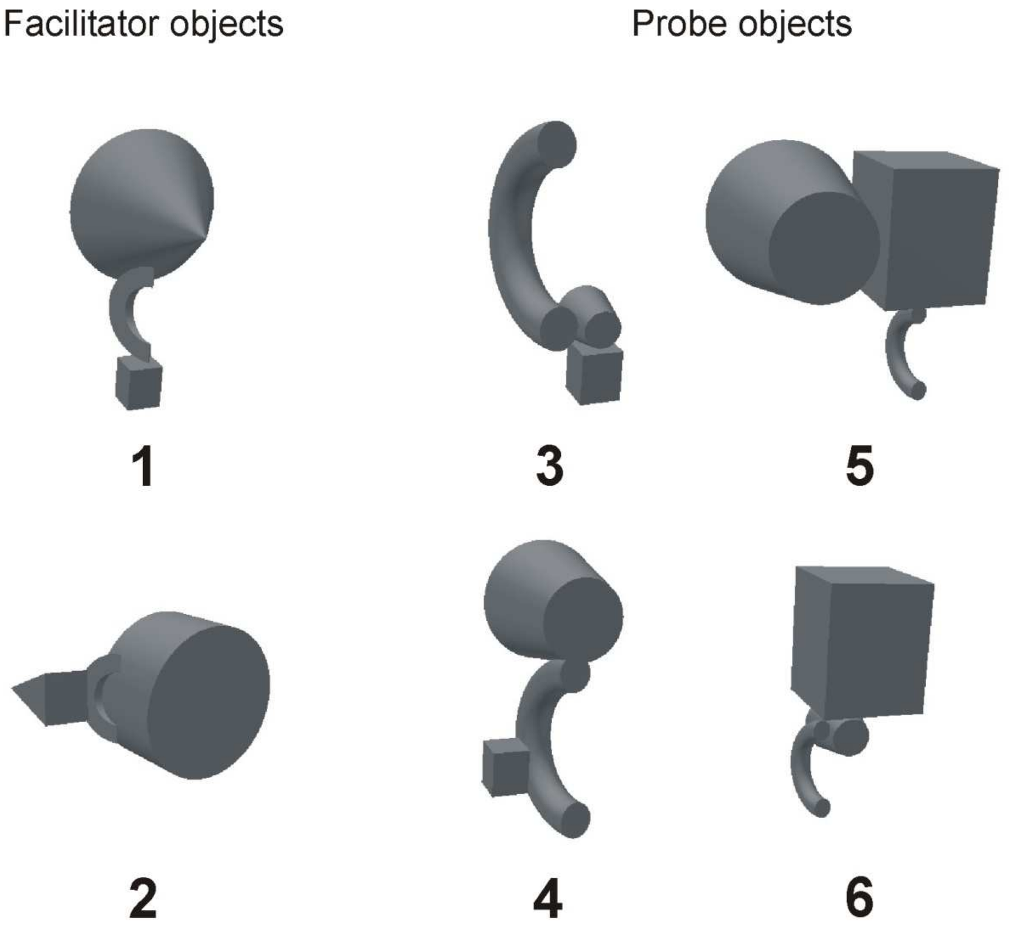

Fig. 1

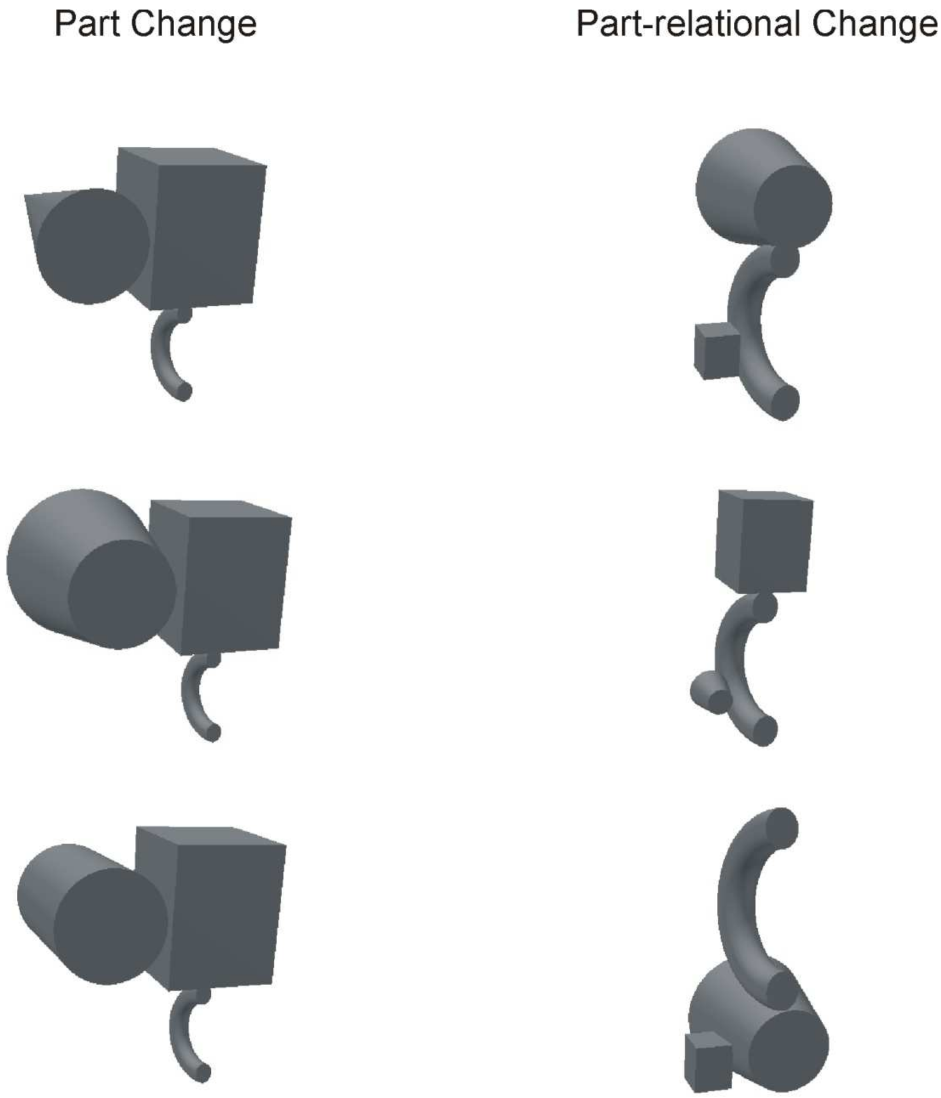

Fig. 2

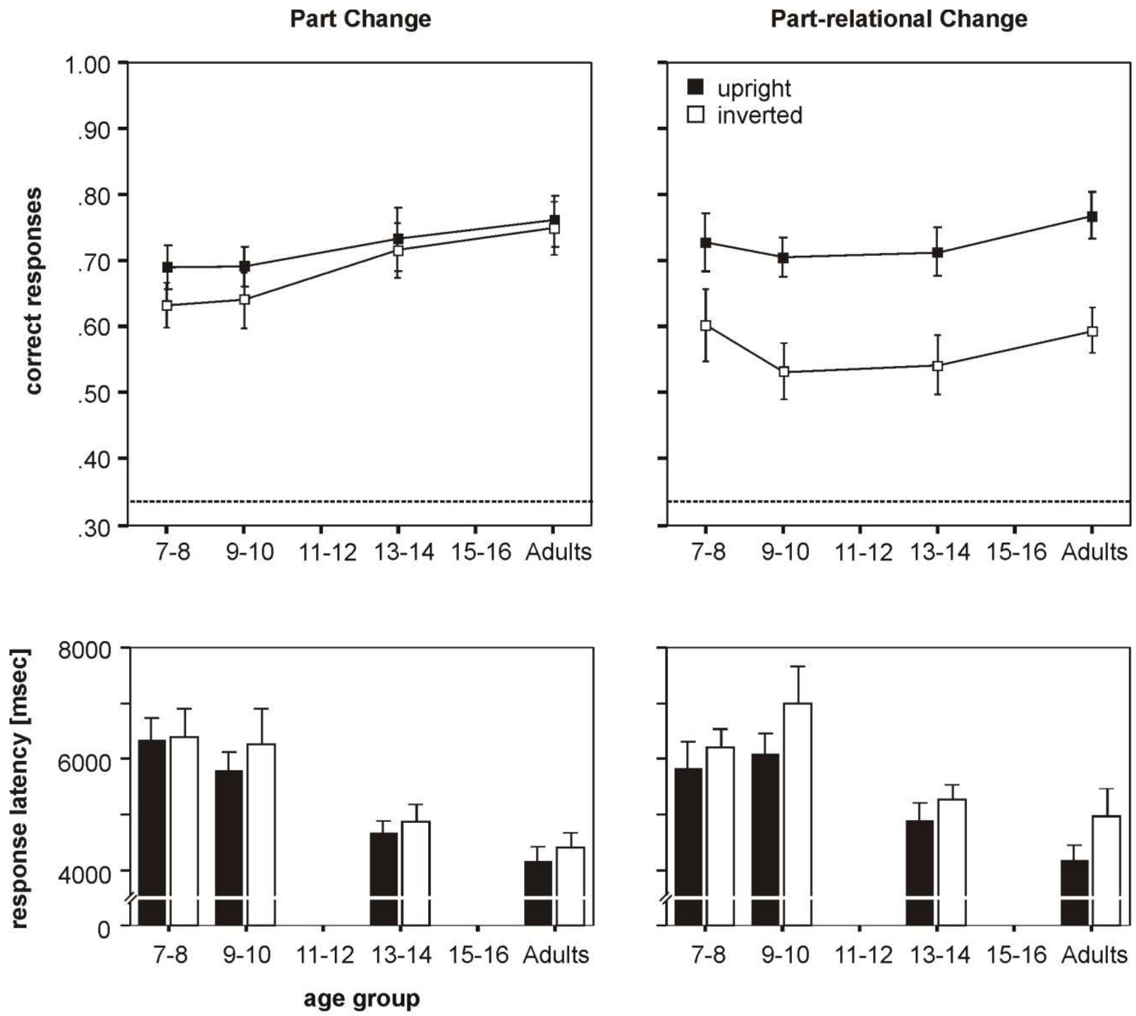
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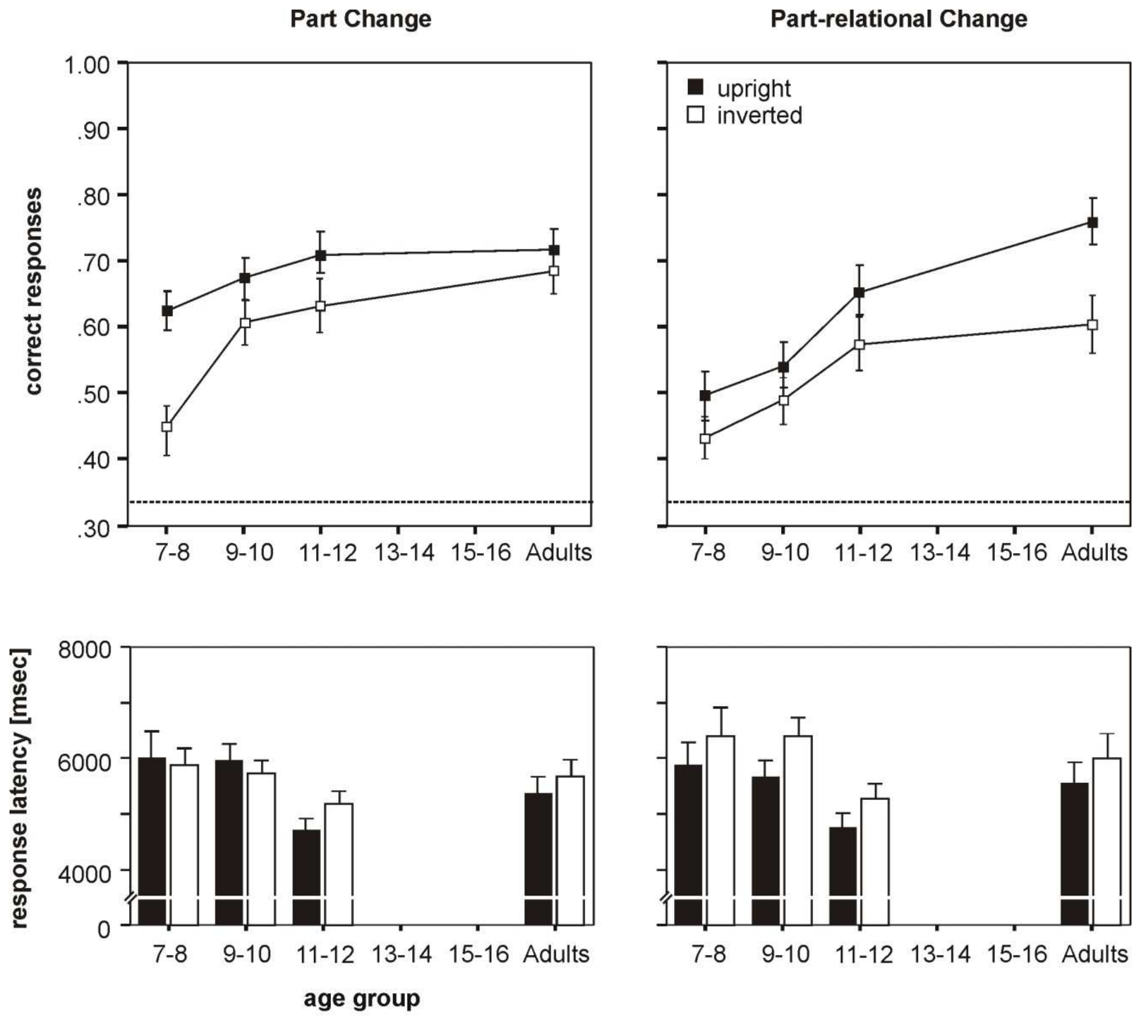
Fig. 3

Fig. 4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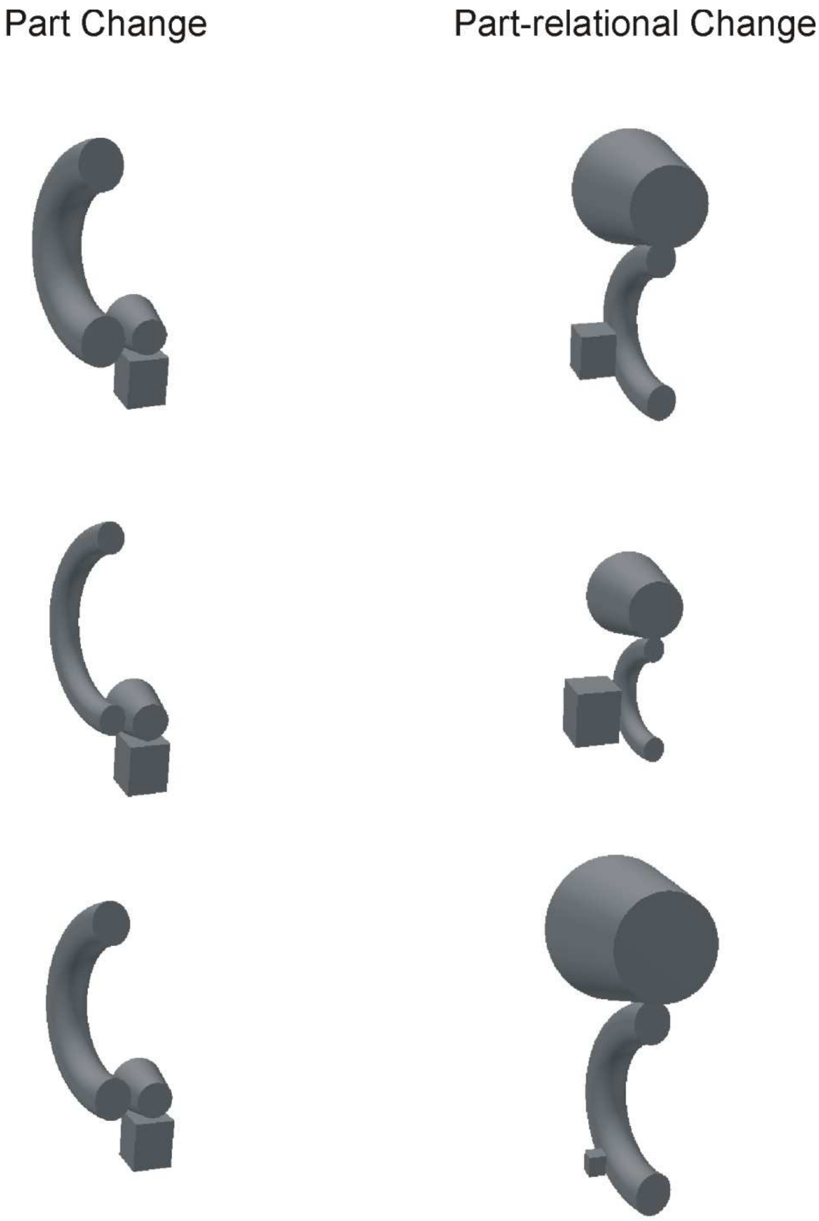
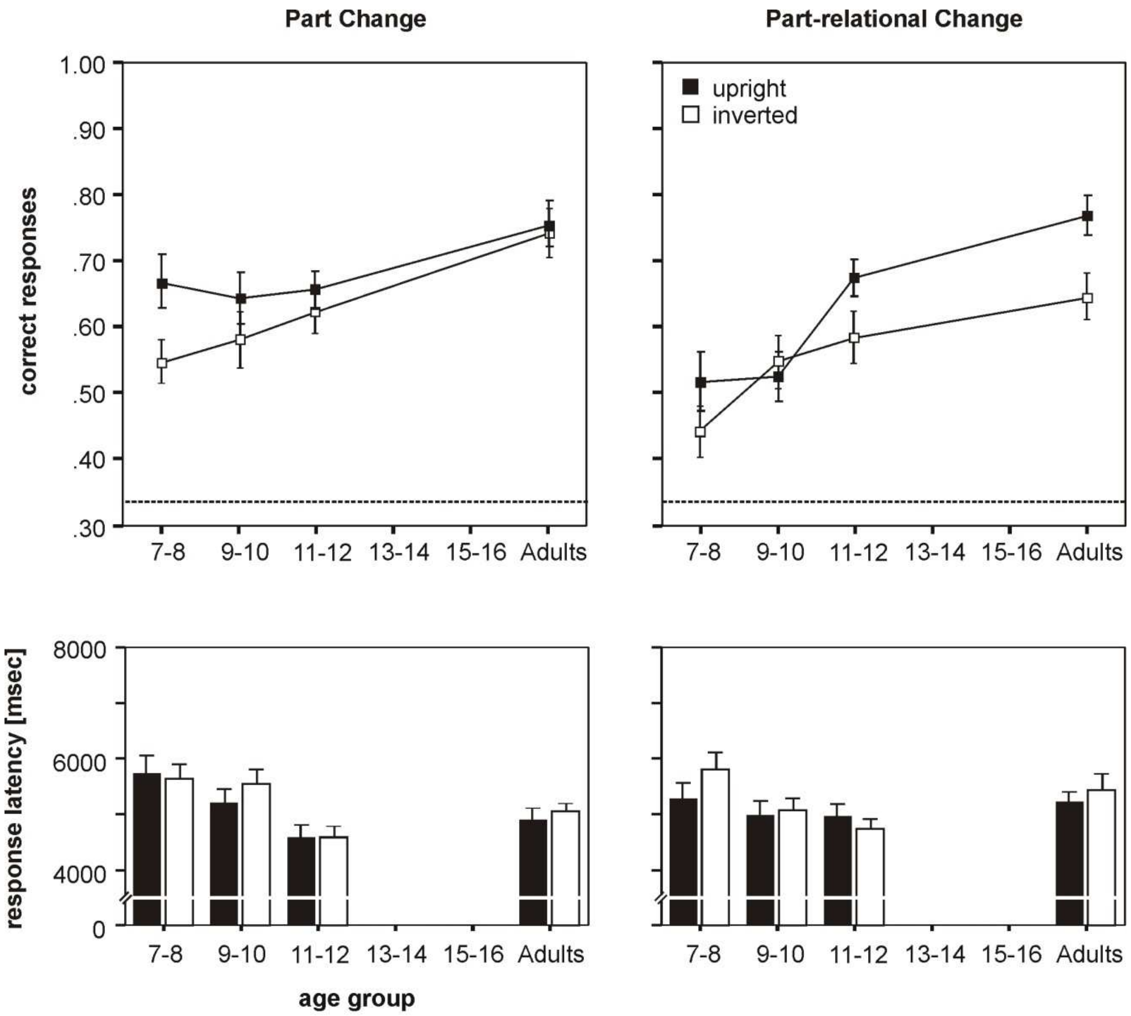


Fig. 6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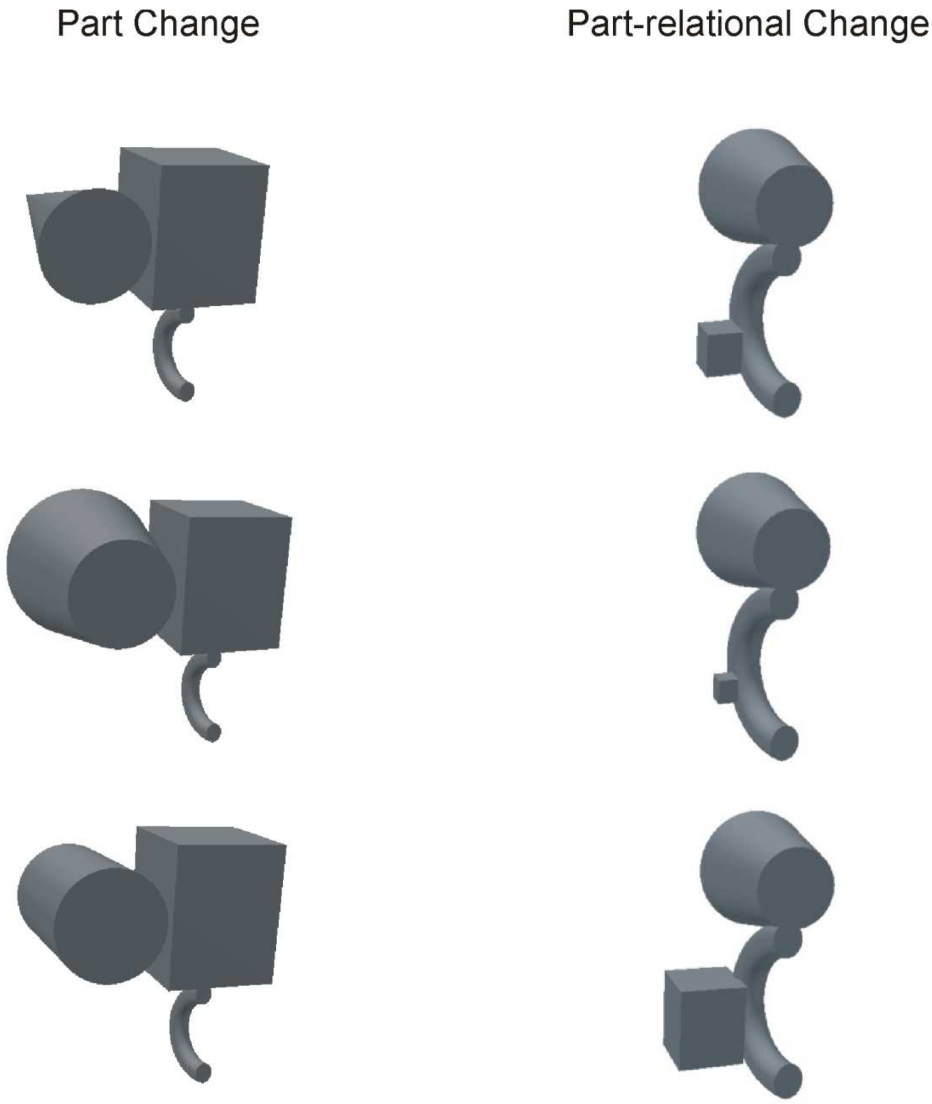

Fig. 8

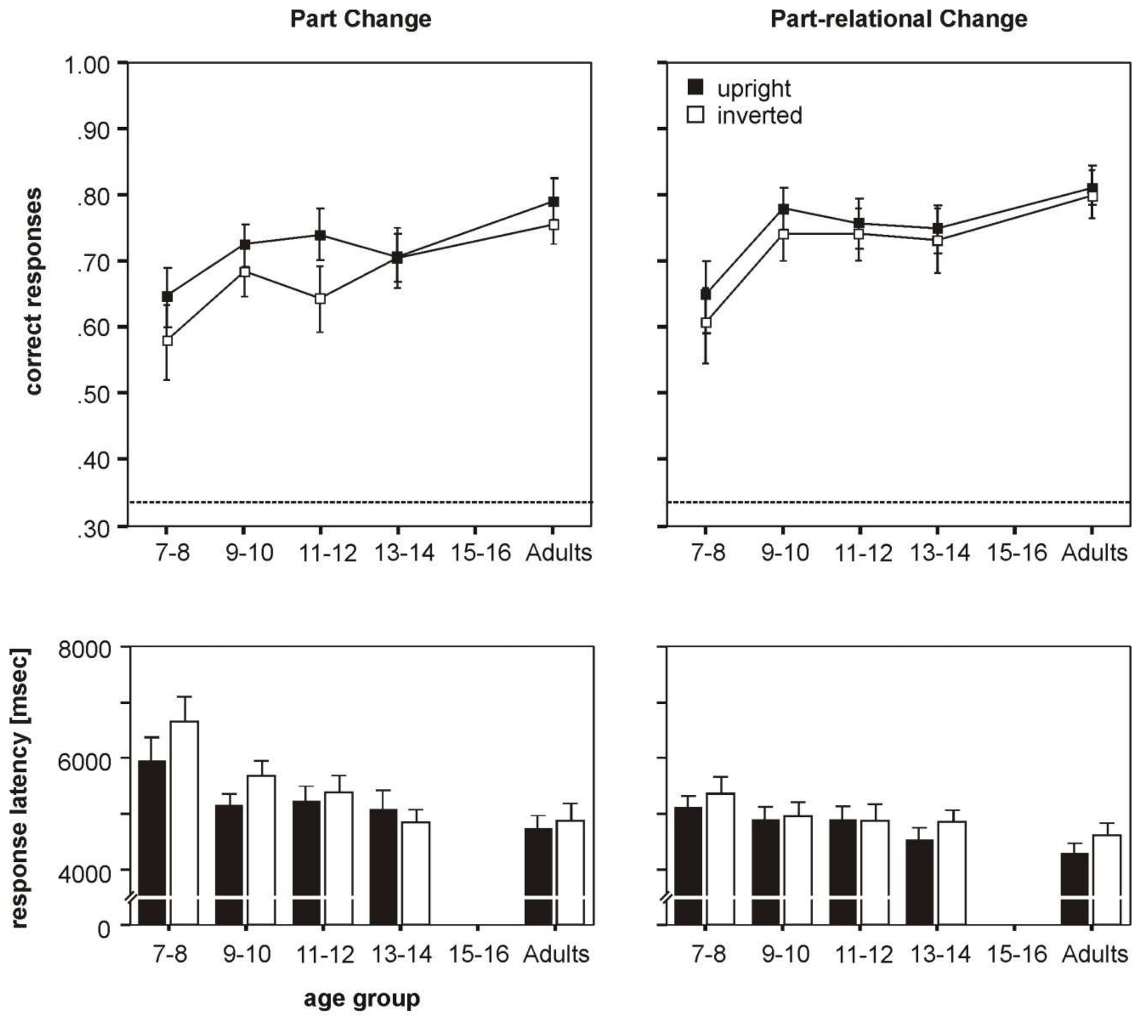

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Fig. 9