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# Perceptual completion of partly occluded contours during childhood

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ABSTRACT

An early functional onset of perceptual completion has been extensively documented during the first several months after birth. However, there is no indication for the developmental time periods at which these skills become fully developed. We used a version of an object-based attention task in which children and adults performed a same–different size judgment of two features appearing at two of four possible ends of overlapping objects. Single-object over two-object superiority (i.e., faster judgments when the features appeared on the same object than when they appeared on different objects) was observed for a complete object as early as at 4 years of age. However, it is only at 5 years of age that such a single-object advantage was obtained also for an occluded object, and even then the advantage of the single-object and occluded-object conditions over the two-object condition was observed only when the two features in the two-object condition were spatially distant, demonstrating the critical role of spatial proximity in perceptual organization during childhood. The results suggest that perceptual completion during infancy and early childhood demonstrates some rudimentary perceptual skills that become more firmly established with age.



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## Introduction

Visual objects often partially occlude one another, causing contour discontinuity. Yet, in most cases, visible contours and surface fragments are linked to form a single coherent object without generating any visually experienced structure in the interpolated area (known as amodal completion). These perceptual processes underlying completion of contours seem to emerge quite early during the first several months after birth. There is, however, no indication for the age at which these skills become fully developed. Here, we used a version of the well-established object-based attention task to determine the developmental time periods at which shape representation of partly occluded objects resembles that of a real physically specified object.

Research in adults suggests that partly occluded objects are represented in the visual system as complete forms (e.g., Behrmann, Zemel, & Mozer, 1998; Davis & Driver, 1998; Rensink & Enns, 1998; Sekuler, Palmer, & Flynn, 1994). However, completion takes a measurable amount of time (Murray, Sekuler, & Bennett, 2001; Ringach & Shapley, 1996; Sekuler & Palmer, 1992) that depends on the size of the occluded region (e.g., Guttman, Sekuler, & Kellman, 2003; Rauschenberger & Yantis, 2001; Shore & Enns, 1997), the presence of stereo cues (Bruno, Bertamini, & Domini, 1997), and context (Rauschenberger, Peterson, Mosca, & Bruno, 2004).

Developmental research suggests that visual completion emerges quite early in life, but there is a developmental progression in the perception of object unity that is highly constrained by the perceptual cues that infants are able to detect. Very early onset is seen for perceptual completion of partly occluded objects when the commonly moving visible parts of an object are made more detectable to the newborns' immature visual system (e.g., stroboscopic motion: Valenza, Leo, Gava, & Simion, 2006), but not when the common motion is less detectable (e.g., the parts undergo continuous motion; Slater, Johnson, Brown, & Badenoch, 1996; Slater et al., 1990). As infants develop, the variety of conditions under which they perceive object unity increases (Johnson & Aslin, 1995, 1996; Johnson & Náñez, 1995). Age-related changes in visual completion vary with spatial proximity between the visible parts; for example, 2-month-olds did not seem to perceive unity in displays with a relatively wide occluder but did so when the occluder's width was reduced (Johnson & Aslin, 1995), whereas 4-month-olds showed clear evidence for unity perception in wide-occluder displays (Johnson & Aslin, 1996). Similarly, 2-month-olds failed to perceive the continuity of a linear trajectory as a moving object became progressively occluded and disoccluded, whereas 6-month-olds provided evidence for such ability under the most demanding conditions employed. In addition, 4-month-olds showed an intermediate pattern of performance, perceiving the continuity of a moving object trajectory only under short, but not under long, durations of occlusion (Johnson et al., 2003). At around 7 months of age, infants perceive the unity, but not necessarily the shape, of stationary, partly occluded objects (Craton, 1996).

Despite this extensive evidence for an early functional onset of perceptual completion during the first several months after birth, there is no indication for the developmental time periods at which shape representations of partly occluded objects resemble those of physically specified objects. The evidence for early ability of perceptual completion does not necessarily imply that these processes mature during infancy or soon afterward. In fact, both neurophysiological (Burkhalter, Bernardo, & Charles, 1993; Shankle et al., 1998) and psychophysical (e.g., Kovács, 2000) studies suggest that infants' performance reflects some rudimentary perceptual–organizational skills but that these are not fully developed and continue to improve even beyond the first 10 years of age. Specifically, psychophysical studies indicate that for several domains of perceptual organization, early sensitivity observed at early infancy (e.g., Gerhardstein, Kovács, Ditre, & Feher, 2004; Sireteanu, 2000) is often characterized by a much longer developmental progression later during childhood (e.g., Enns, Burack, Iarocci, & Randolph, 2000; Gervan, Berencsi, & Kovács, 2011; Hadad & Kimchi, 2006; Hadad, Maurer, & Lewis, 2010a; Kimchi, Hadad, Behrmann, & Palmer, 2005; Kovács, 2000; Káldy & Kovács, 2003). For example, Sireteanu (2000) showed that although the earliest evidence for texture-based segregation was observed at 2 months of age, considerable improvements continued to be observed over the first several years in children tested in a more complex display. In clear contrast to the sensitivity to subjective contours observed during early infancy (e.g., Ghim, 1990), considerable improvement in this ability to perceive subjective contours is evident between 3 and 5 years of age (Abravanel, 1982) and even later during childhood (Hadad, Maurer, & Lewis, 2015; Hadad et al., 2010a). It has also been shown that only 10-year-olds, but not 5-year-olds, use collinearity to enhance closure for the perceptual grouping of shape (Hadad & Kimchi, 2006). Similarly, the detection of a global form in Glass patterns (Lewis et al., 2004) and the interpolation of subjective contours (Hadad et al., 2010a) are adult-like only at 9 years of age. Marked improvements in spatial integration have also been observed during late childhood (Hadad, Maurer, & Lewis, 2010b; Kovács, 2000; Kovács, Kozma, Feher, & Benedek, 1999).

Of particular relevance to the current study, interpolation of subjective contours and partially occluded figures was found to take at least 9 years to develop (Hadad, Maurer, et al., 2015). However, in Hadad, Maurer, et al.'s (2015) study, participants needed to discriminate shapes arising from partly occluded contours based on subtle difference in the curvature of the shape. Thus, the long trajectory can be attributed to the high precision of the representations that was required for discriminating the differences in the interpolated shapes. It is possible, then, that representation of an occluded object becomes functionally equivalent to a fully visible object much earlier in development. However, we do not know of any other studies testing this question during childhood, nor can we infer about the developmental course of this perceptual ability based on findings in infants.

The current experiment was designed to determine the developmental time periods at which perceptual representations of a partly occluded object evolve to function as a physically complete object. We used a version of the well-established object-based attention task. Children (4-, 5-, and 10-year-olds) and adults performed a same–different size judgment of two features (holes) appearing at two of four possible ends of overlapping objects. The two features appeared at the ends of a single physically complete object (single-object condition; Fig. 1A), at the ends of two different objects (two-object condition; Fig. 1B), or at the ends of two noncontiguous aligned portions of an occluded object (occluded-object condition; Fig. 1C).

Typically, when requested to respond to two features, participants are faster and more accurate when the features belong to a single object than when they belong to two separate objects (e.g., Duncan, 1984). In adults, this single-object over two-object advantage (henceforth single-object advantage) has been demonstrated also for partially occluded objects, indicating that partly occluded objects functioned as complete visible objects (Behrmann et al., 1998; Moore, Yantis, & Vaughan, 1998). Here, we examined whether, like in adults, children's representation of occluded objects resembles that of a completed single object. If an occluded object is represented as a complete object, features of an occluded object should have the same processing advantage as features of a fully visible

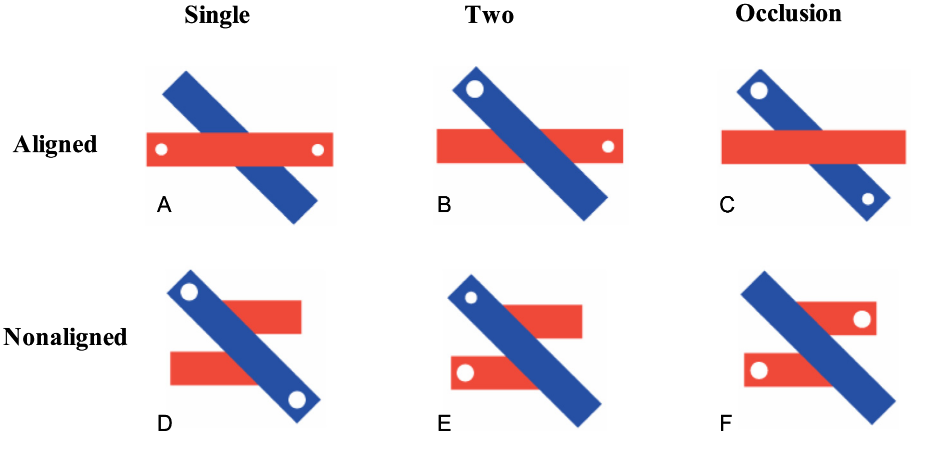


**Fig. 1.** Examples of the single-object, two-object, and occluded-object stimuli presented in the experiment. The two noncontiguous portions of the occluded object were either aligned (A–C) or nonaligned (D–F).

single object over features of two separate objects. If, however, perceptual completion is immature, so that the representation of the occluded object differs from that of a physically complete object, no advantage should be evident for processing two features that belong to the two parts of an occluded object over those that belong to two objects; the processing advantage for two features that belong to the same object would be observed only when the object is physically complete (single-object condition). To ensure that the single-object over two-object advantage obtained in the occluded condition does not result from any visual characteristics other than perceptual completion, performance was compared with a control condition in which the noncontiguous portions of the occluded object were misaligned (Fig. 1D–F) and, thus, do not support perceptual completion (e.g., Kellman & Shipley, 1991).

## Method

### *Participants*

A total of 75 participants with normal or corrected-to-normal vision were tested: 20 4-year-olds (mean = 4.3 years, range = 3.10–4.10), 16 5-year-olds (mean = 5.3 years, range = 4.11–5.90), 20 10-year-olds (mean = 10.5 years, range = 9.5–10.8), and 19 adults (mean = 22.6 years, range = 19–28).[1]

### *Stimuli*

Each stimulus contained two overlapping rectangles, one lying horizontally and the other diagonally, crossing each other at the center and forming an asymmetric "X". On each trial, two holes appeared at two of the four ends of the rectangles. The holes were either small or large (see Fig. 1). The experiment contained three different conditions defined by the location of the two holes: (a) *single-object condition*, in which the two holes appeared at the ends of a single complete rectangle (Fig. 1A and D); (b) *two-object condition*, in which one of the holes appeared at the end of one rectangle and the other hole appeared at the end of a different rectangle (Fig. 1B and E); and (c) *occluded-object condition*, in which the two holes appeared at the end of each of two noncontiguous portions (Fig. 1C and F). The noncontiguous portions were either aligned, forming a single occluded rectangle (Fig. 1A–C) or nonaligned (Fig. 1D–F).

The two holes could be of the same size (either both small or both large; e.g., Fig. 1A) or of different sizes (e.g., Fig. 1B). There was an equal number of same (same hole size) and different (different hole size) trials in each of the three conditions. The locations of the small and large holes were evenly counterbalanced.

The participants' task was to decide, as accurately and quickly as possible, whether the size of the holes was *same* or *different*. Each trial started with a central fixation cross presented for 500 ms. Following a 500-ms interval, the display appeared and remained present until participants provided their response or 5 s had elapsed, whichever came first.

In each stimulus, one rectangle was blue and the other was red. On half of the trials the single object was oriented horizontally, and on the remaining half it was oriented diagonally. Both orientation of the rectangles and their colors were crossed orthogonally with the other variables. At a viewing distance of 60 cm, each rectangle subtended 4.6° in length and 0.8° in width. The diameter of the small hole subtended 0.28°, and that of the large hole subtended 0.42°. Four possible positions of the holes in the two-object condition were used. To ensure that any expected advantage of the single-object and occluded-object conditions over the two-object condition could not be explained by spatial proximity effects, the distance between the two holes in the two-object condition never exceeded that of the single-object and occluded-object conditions.

[1] We set the sample size in advance to match the sample size we typically use in our studies measuring developmental trends in visual perception. Past experience has indicated that this sample size is sufficient to show clear developmental trends (e.g., Hadad & Kimchi, 2006; Hadad et al., 2010a, 2010b; Hadad, Maurer, & Lewis, 2012).

### Design and procedure

The experiment employed an orthogonal combination of seven factors: age (4 years, 5 years, 10 years, or adult), condition (single-object, occluded-object, or two-object), alignment (aligned or non-aligned), response (same or different), orientation (horizontal or diagonal), color (red or blue), and hole size (small or large). Age was a between-participants factor, and all other factors were manipulated within participants and randomized within block, with each combination occurring on an equal number of trials. There were 96 trials in each of four experimental blocks, preceded by 24 practice trials. Experimental blocks were divided into eight sub-blocks of 12 trials each, with short breaks allowed between sub-blocks. Considerable practice and feedback were given to ensure that the children understood the task and were not distracted from it. Children were given initial training using cardboard pictures. For children, the four blocks were administered in two sessions.

### Data analysis

The main analysis focused on the four-way mixed-design analysis of variance (ANOVA), Age × Condition × Alignment × Response, conducted on correct response reaction times (RTs) and pooled across color, orientation, and size. All ANOVA results are provided in Greenhouse–Geisser values. Follow-up analyses examined whether a single-object over two-object superiority is obtained by testing the difference between responding to two features when present in a single object or in an occluded object versus responding to the same features when present in two separate objects, in aligned and non-aligned displays, in the different age groups. Perceptual completion is inferred if the single-object over two-object superiority, typically obtained for single objects, is obtained also for the occluded objects in the *aligned* condition. In the nonaligned condition, a single-object over two-object superiority is expected only for the single objects. In addition, to take into account the overall RT differences among the age groups (Table 1) and facilitate the presentation of the data, standardized difference scores were calculated, for each participant in each age group, as the difference in RTs between the two-object condition and the condition in question divided by the sum of these RTs {single object: [RT(two-object) − RT(single-object)]/[RT(two-object) + RT(single-object)]; occluded object: [RT(two-object) − RT(occluded-object)]/[RT(two-object) + RT(occluded-object)]}. These difference scores are presented in Fig. 2 as a function of condition and age. Positive values indicate single-object advantage. Specific comparisons were carried out on the standardized difference scores to test for a significant difference in the *magnitude* of the single-object advantage between the single and occluded objects within each age group; equal magnitude suggests that the occluded object is represented as a single complete object. This allows us to determine the age at which the representation of partly occluded object functions as that of a complete object.

## Results

The error rate in the youngest age group was relatively high (17%), whereas it was substantially lower in all other age groups (mean error rates = 5.8%, 1.9% and 2.2% for 5-year-olds, 10-year-olds, and adults, respectively). Mean RTs and error rates for "same" and "different" judgments as a function of condition for each age group are presented in Table 1. A mixed-design ANOVA (Age × Condition × Alignment × Response) conducted on the error rate data revealed a significant effect of age, $F(3,71) = 58.15$, $p < .0001$, $\eta_p^2 = .71$, as well as an interaction between age and response, $F(3,71) = 6.69$, $p < .0005$, $\eta_p^2 = .22$; "same" responses were significantly more accurate than "different" responses only for adults. Error rates for the two-object condition were substantially higher than those for the single-object and occluded-object conditions for the "same" nonaligned displays, as indicated by a three-way interaction among condition, alignment, and response, $F(2,142) = 6.57$, $p < .002$, $\eta_p^2 = .08$, presumably due to response competition (same hole sizes but two different perceived objects). No other significant effects were found, nor were any indications for speed–accuracy trade-offs found.

All RT summaries and analyses are based on participants' mean RTs for correct responses. RTs shorter than 250 ms and longer than 4000 ms were discarded. Preliminary analysis examined the

**Table 1**
Mean RTs (and error rates) for "same" and "different" judgments as a function of condition.

| | Age 4 | | | Age 5 | | | Age 10 | | | Adults | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | O | S | T | O | S | T | O | S | T | O | S | T |
| *Same* | | | | | | | | | | | | |
| Aligned | 2289 | 2163 | 2285 | 1984 | 1970 | 2062 | 1356 | 1351 | 1387 | 767 | 763 | 799 |
| | (21.5) | (23) | (30.6) | (6.5) | (7.1) | (6.9) | (2.6) | (1.7) | (1.6) | (2.1) | (1.1) | (1.6) |
| Nonaligned | 2300 | 2218 | 2273 | 2127 | 1962 | 2164 | 1404 | 1358 | 1420 | 814 | 763 | 826 |
| | (22.5) | (19.1) | (23.3) | (6.1) | (4.5) | (7.1) | (2.9) | (2.1) | (2.3) | (1.1) | (0.9) | (2.2) |
| *Different* | | | | | | | | | | | | |
| Aligned | 2252 | 2190 | 2205 | 2196 | 2089 | 2210 | 1445 | 1427 | 1473 | 833 | 825 | 867 |
| | (15.1) | (12.9) | (12.7) | (6.9) | (5.1) | (6.1) | (1.9) | (3.1) | (1.9) | (2.1) | (3.2) | (2.9) |
| Nonaligned | 2348 | 2205 | 2237 | 2165 | 2136 | 2188 | 1488 | 1444 | 1462 | 872 | 843 | 888 |
| | (14.6) | (13.3) | (9.7) | (4.2) | (4.7) | (3.7) | (2.4) | (3.9) | (0.5) | (3.3) | (3.2) | (2.6) |

*Note.* O, occluded-object condition; S, single-object condition; T, two-object condition.

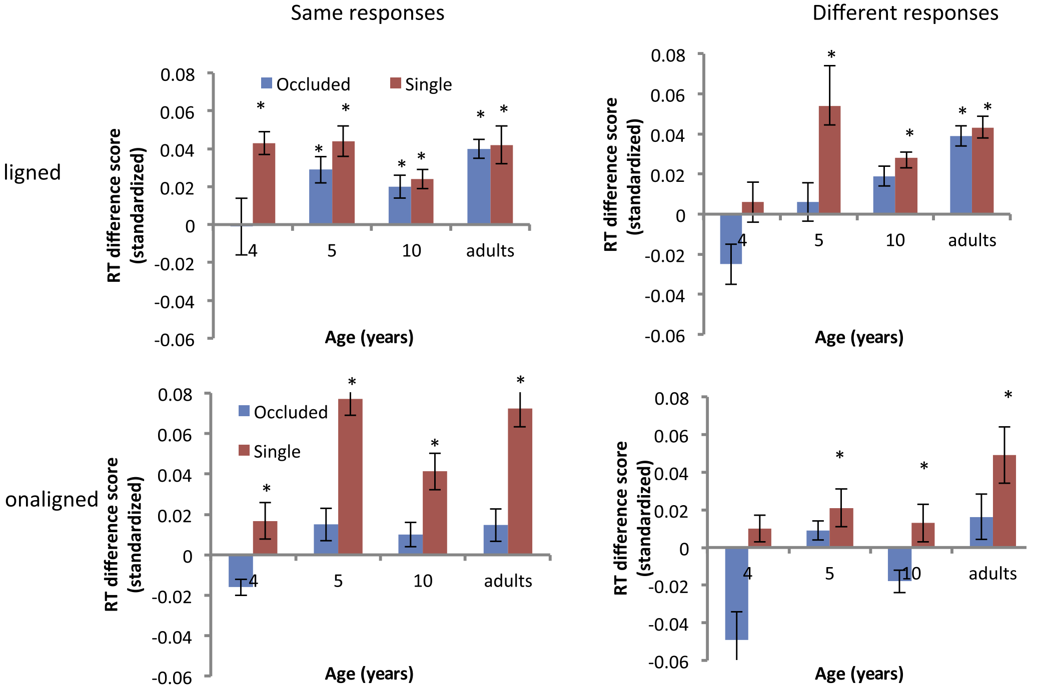


**Fig. 2.** Mean standardized RT difference scores for the single-object or occluded-object condition and the two-object condition as a function of age, for "same" and "different" responses, for the aligned and nonaligned displays. Standardized difference scores were computed, for each participant, as the difference in RTs in the two-object condition and RTs in a given condition divided by the sum of RTs of the two conditions {i.e., single object: [(two-object RTs – single-object RTs)/(two-object RTs + single-object RTs)]; occluded object: [(two-object RTs – occluded-object RTs)/(two-object RTs + occluded-object RTs)]}. Positive values indicate single-object advantage. Asterisks indicate significant single-object advantage. Error bars indicate within-participant 95% confidence intervals.

effect of orientation only for the single-object and occluded-object displays. This analysis yielded a significant effect of orientation on RT, demonstrating an advantage for horizontal judgments over diagonal judgments, $F(1,71) = 7.76$, $p < .006$, $\eta_p^2 = .15$, which was stronger for the "different" responses, $F(1,71) = 3.86$, $p < .05$, $\eta_p^2 = .08$. Because no other significant interactions involving orientation were found, and because further preliminary analysis showed no effects of color or size, or any significant interactions involving these factors, we pooled the data across orientation, color and size for the remainder of the analysis.

A four-way mixed-design ANOVA (Age × Condition × Alignment × Response) conducted on RTs showed that response times improved with age, $F(3,71) = 155.81$, $p < .0001$, $\eta_p^2 = .86$, "same" responses were reliably faster than "different" responses, $F(1, 71) = 27.21$, $p < .0001$, $\eta_p^2 = .27$, and responses to aligned displays were faster than those to nonaligned displays, $F(1,71) = 13.88$, $p < .0004$, $\eta_p^2 = .16$. There was a significant effect of condition (single-object, occluded-object, or two-object) on RTs, which (most important) varied with age, $F(6,142) = 3.16$, $p < .006$, $\eta_p^2 = .12$. As can be seen in Fig. 2, there are age-related changes in the advantage of judging features from the same object relative to two objects for the occluded object condition; the advantage appears to emerge only at 5 years of age and at this age for "same" responses only. To further examine these age-related changes, separate follow-up analyses were conducted for the different age groups on RTs and on difference scores.

### *10-year-olds and adults*

The effect of condition on RTs, $F(2,36) = 28.02$, $p < .0001$, $\eta_p^2 = .65$ and $F(2,38) = 5.23$, $p < .01$, $\eta_p^2 = .21$, was qualified by the alignment of the displays, $F(2,36) = 3.46$, $p < .04$, $\eta_p^2 = .16$ and $F(2,38) = 3.41$, $p < .04$, $\eta_p^2 = .14$, for adults and 10-year-olds, respectively. When the displays were aligned, planned comparisons showed significantly faster processing for features that belong to a single object over those that belong to two different objects, demonstrating a single-object over two-object advantage for both the single objects, $F(1,18) = 15.22$, $p < .001$, $\eta_p^2 = .45$ and $F(1,19) = 8.62$, $p < .008$, $\eta_p^2 = .31$, and the occluded objects, $F(1,18) = 11.48$, $p < .003$, $\eta_p^2 = .38$ and $F(1,19) = 5.43$, $p < .03$, $\eta_p^2 = .22$, for adults and 10-year-olds, respectively. The analysis conducted on the standardized difference scores further showed that when the visible parts were aligned (Fig. 2, top panels), the single-object advantage did not vary between the single-object and occluded-object conditions, $F(1,18) = 1.95$, $p > .18$ and $F(1,19) = 1.25$, $p > .27$, for adults and 10-year-olds, respectively, indicating a single-object advantage of similar magnitude in the two conditions for the two age groups. For the nonaligned displays, in contrast, a significant single-object over two-object advantage was observed only for the single objects, $F(1,18) = 35.64$, $p < .0001$, $\eta_p^2 = .66$ and $F(1,19) = 7.23$, $p < .01$, $\eta_p^2 = .27$; performance in the occluded condition was now equivalent to that in the two-object condition, *F*s < 1, for adults and 10-year-olds.

As can be seen in Fig. 2, the expected pattern of single-object advantage for the occluded object in the case of aligned displays and for the single object in the case of the nonaligned displays seems stronger for the "same" responses than for the "different" ones for the 10-year-olds but not for the adults. Presumably, the 10-year-olds were more distracted than the adults while responding "different" when the holes were on the same single object due to response competition (same object but different hole sizes). This weakened object advantage effect for "different" responses was previously observed in adults, albeit when more complicated displays than those used here were involved (Behrmann et al., 1998, Experiment 3).

### *Perceptual completion of partially occluded objects in 5-year-olds*

The 5-year-olds showed a similar pattern to that of the older observers. The effect of condition on RTs, $F(2,30) = 9.13$, $p < .0008$, $\eta_p^2 = .28$, was marginally qualified by the alignment of the display and the response type, $F(2,30) = 2.67$, $p < .08$, $\eta_p^2 = .13$. When the displays were *aligned,* planned comparisons for "same" responses showed significantly faster processing for features that belong to a single object over those that belong to two different objects for the single object, $F(1,15) = 8.66$, $p < .01$, $\eta_p^2 = .23$, and for the occluded object, $F(1,15) = 4.90$, $p < .04$, $\eta_p^2 = .24$. However, for "different" responses, a significant single-object over two-object advantage was observed only for the single objects, $F(1,15) = 19.04$, $p < .0006$, $\eta_p^2 = .33$, but not for the occluded objects, $F(1,15) = 2.68$, $p > .13$. The analysis conducted on the standardized difference scores for the aligned displays further showed that for "same" responses (Fig. 2, top panel), the single-object over two-object advantage did not vary between the single and occluded objects, $F < 1$, indicating a single-object advantage of similar magnitude for the single completed object and the partly occluded one.

Similar to the 10-year-olds, the 5-year-olds were also more distracted than adults while responding "different" when the holes were on the same single or occluded object, presumably due to response competition (same object but different hole sizes). For the 5-year-olds, however, response competition hindered performance for the *aligned* displays; the expected pattern of findings (single-object = occluded object, and both better than two-object) was found for "same" responses but not for "different" responses, whereas for adults this pattern was found for both responses (we discuss this point in more detail later).

When the displays were *nonaligned*, planned comparisons revealed that for "different" responses no single-object over two-object advantage was observed for any of the conditions, *F*s < 1. On the other hand, for "same" responses, a single-object over two-object advantage was obtained for the single-object condition, $F(1,15) = 16.54$, $p < .001$, $\eta_p^2 = .29$, and for the occluded-object condition, $F(1,15) = 7.72$, $p < .01$, $\eta_p^2 = .15$. The latter finding, which was in contrast to the findings for the older groups, may suggest that the similarity in color between the two noncontiguous portions facilitated "same" responses to the nonaligned displays. One may then argue that it is not perceptual completion of the occluded object that accounts for the single-object advantage for the occluded aligned displays observed in the 5-year-olds but rather the common color that the two fragments share. However, two findings appear to be inconsistent with this alternative account. First and foremost, the analysis conducted on the standardized difference scores revealed a substantially larger single-object advantage for the single object compared with the occluded object, $F(1,15) = 4.47$, $p < .05$, $\eta_p^2 = .21$, indicating that, contrary to the aligned displays, the occluded object in the nonaligned displays was not treated as a single completed object. Second, the 5-year-olds' responses to the aligned occluded displays were significantly faster than responses to the nonaligned occluded displays, $F(1,15) = 10.13$, $p < .006$. Taken together, these findings, which show substantial differences in the 5-year-olds' responses to the occluded objects between the aligned and nonaligned displays, suggest that the single-object advantage observed for the occluded object in the aligned displays cannot be accounted for by color similarity per se.

Altogether, the results suggest that children as young as 5 years, like 10-year-olds and adults, show superiority in judging features that belong to the same object over those that belong to two different objects even when the features are located on two noncontiguous aligned portions of an occluded object. This demonstrates that a partially occluded object is perceptually represented as a complete one in 5-year-olds, although the perceptual representations from completion at that age are shown only for "same" responses. The findings for the nonaligned displays further confirm the conclusion of perceptual completion showing that the misaligned noncontiguous portions, as expected, were no longer treated as a single occluded object but more closely resembled the two-object condition.

Note that in the two-object condition, the two features could be spatially close to one another or spatially distant from one another. A closer inspection of the data showed that this factor affected the 5-year-olds' performance but not the adults' performance. The performance advantage for the single-object and occluded-object conditions over the two-object condition was observed in the 5-year-olds only when the two features in the two-object condition were spatially distant, $F(1,15) = 3.86$, $p < .05$. However, when the two features were spatially close, young children's responses in the two-object condition were facilitated and no longer differed from both the single-object and occluded-object conditions, $F(1,15) = 1.60$, $p > .32$. In contrast, at older ages, the performance superiority in the single-object and occluded-object conditions over the two-object condition held irrespective of spatial proximity between the two features in the two-object condition, $F(1,37) = 10.59$, $p < .0002$ and $F(1,37) = 7.37$, $p < .002$, for spatially close and spatially distant features, respectively.

Overall, superiority of the same object relative to two objects for the partly occluded object in the 5-year-olds was restricted by response type and was sensitive to spatial proximity between the two features in the two-object condition. We return to these factors restricting perceptual completion at that age in the Discussion.

*No evidence for perceptual completion of partially occluded objects in 4-year-olds*

RTs for "same" responses in the youngest group tested also varied as a function of condition, $F(2,42) = 3.79$, $p < .03$, $\eta^2_p = .16$. However, this effect of condition was similar for the *aligned* and *nonaligned* displays, $F < 1$. Specific comparisons showed significantly faster processing for features that belong to a single object over those that belong to two different objects for the single-object condition, $F(1,19) = 7.52$, $p < .01$, $\eta^2_p = .13$ and $F(1,19) = 3.89$, $p < .05$, $\eta^2_p = .11$, for aligned and nonaligned displays, respectively. Contrary to the older age groups, processing features that belong to an occluded object was no different from processing features that belong to two different objects, $F < 1$ and $F(1,19) = 2.05$, $p > .13$, for aligned and nonaligned displays, respectively. Specific planned comparisons, examining the single-object advantage for the occluded condition (i.e., occluded-object condition vs. two-object condition) in the aligned displays between the 4-year-olds and 5-year-olds shows a significant interaction between age and condition, $F(1,34) = 5.26$, $p < .028$. $\eta^2_p = .14$, indicating a significant single-object advantage for the 5-year-olds but not for the 4-year-olds. Critically, no such interaction of age and condition was observed for the single-object condition, $F < 1$, indicating a single-object advantage for the single-object condition in both age groups. The analysis conducted on the standardized difference scores also supports this difference between 4-year-olds and 5-year-olds. As can be seen in Fig. 2, in a clear contrast to the results of the 5-year-olds, in which difference scores did not vary between the single-object and occluded-object conditions, the difference scores for the 4-year-olds substantially varied between the single-object and occluded-object conditions for both aligned displays, $F(1,19) = 6.80$, $p < .01$, $\eta^2_p = .26$, and nonaligned displays, $F(1,19) = 11.36$, $p < .03$, $\eta^2_p = .37$. That is, unlike the older age group, for the 4-year-olds, the single-object advantage was obtained only for the single completed object, and there was no single-object advantage whatsoever for the partially occluded object even when collinearity supported completion (aligned displays; Fig. 2). These findings clearly suggest that perceptual completion continues to undergo substantial developmental changes after 4 years of age.

## Discussion

The current results demonstrate perceptual completion in children at 5 years of age. Children aged 5 and 10 years, as well as adults, exhibited a similar pattern of results; features of an occluded object had the same processing advantage as features of an unoccluded single object relative to features of two different objects. The 5-year-olds, like the adults, treated the two noncontiguous aligned portions of an occluded object as though they were portions of a single object rather than two separate objects. When the relation between the two noncontiguous portions changed so that they were misaligned and, thus, no longer supported perceptual completion, performance in the occluded condition did not show the same single-object advantage, indicating that the occluded object in the nonaligned displays was not treated as a single complete object. Thus, the results show that the perceptual representation resulting from perceptual completion of occluded objects functions as a representation of a real object as early as 5 years of age.

The results for the 4-year-olds, however, showed no such evidence for perceptual completion. A single-object advantage was obtained for the single object but not for the occluded object. In fact, responses to the partially occluded object did not differ from those of the two-object condition regardless of the alignment of the displays. Critically, the finding of a single-object over two-object advantage for the single complete object for both the aligned and nonaligned displays indicates that the paradigm was largely successful in collecting reliable reaction times even at this young age. Thus, the finding of single-object advantage for the single object, but not for the occluded object, clearly shows that the different pattern of results for the youngest age group compared with the older ones can be taken to suggest immature perceptual completion of partially occluded objects at 4 years of age.

Studies examining the development of perceptual completion in infants have demonstrated an earlier ability to perceptually complete partly occluded objects (e.g., Johnson & Aslin, 1995, 1996; Spelke, 1990). These studies have shown that young infants looked longer at the disjointed fragmented forms than at the single continuous object after habituating to a center occluded object in which visible surfaces were homogeneously colored and the edges were collinear at the point of occlusion. These findings were often taken to suggest perceptual completion at early infancy. However, infants' dishabituated responses (i.e., looking longer at the disjointed fragmented forms) suggest that occluded object representation differs from that of an incomplete fragmented object but does not necessarily indicate that the representation of an occluded object is functionally equivalent to a fully visible object. Using the object-based attention paradigm, the current study suggests that it is only at 5 years of age that the occluded object acts as if it truly has the integrated status of a single complete object when perceptual cues support the existence of a unified object (i.e., in case of collinear fragments). Combined with these earlier findings in infants, the current study suggests that perceptual completion during infancy demonstrates some rudimentary perceptual skills that become more firmly established during infancy and early childhood. As already indicated for other forms of perceptual organization (e.g., Enns et al., 2000; Hadad & Kimchi, 2006; Hadad et al., 2010a; Kimchi et al., 2005; Kovács, 2000; Lewis et al., 2004), this early sensitivity to partial occlusion observed during infancy is followed by continued development of perceptual completion during childhood.

Consistent with this gradual improvement in perceptual completion skills during childhood, the pattern of results at 5 years of age, although generally resembling that of older observers, seems somewhat different in two important aspects. First, a single-object over two-object advantage for the partly occluded object was obtained in the 5-year-olds for "same" responses only. The 5-year-olds appeared to be more distracted than the adults while responding "different" when the holes were on the same single or occluded object, presumably due to response competition (same object but different hole sizes). Response competition seems somewhat detrimental also for performance of the 10-year-olds, although to a lesser degree: the advantage observed for the single complete object in the case of the aligned displays was stronger for "same" responses than for "different" ones, and although it did not interact significantly with response type, specific comparisons show that the single-object over two-object advantage for the occluded object reached significance only for "same" responses. Weakened single-object advantage effects for "different" responses at 10 years of age were also shown for the single *nonaligned* displays. Presumably, children are less efficient selectors than adults and become less susceptible to distractors as they grow older (e.g., Lane & Pearson, 1982; Tipper, Bourque, Anderson, & Brehaut, 1989). It is unlikely, however, that this competition hindered perceptual completion but rather produced interference with response decision. Indeed, weakened object-advantage effects for "different" responses were previously observed in the completely mature system when more complicated displays than those used here were involved (Behrmann et al., 1998, Experiment 3). Altogether, these findings suggest that even when completion does take place, producing perceptual representations of partly occluded objects that function as those of physically complete objects, the interpolated representations at this age are more vulnerable to general attentional factors such as response competition.

The second aspect concerns the critical role of spatial proximity in perceptual organization in young children. For the 10-year-olds and adults, the performance superiority in the single-object and occluded-object conditions over the two-object condition held irrespective of spatial proximity between the two features in the two-object condition. However, for the 5-year-olds, the advantage of the single-object and occluded-object conditions over the two-object condition was observed only when the two features in the two-object condition were spatially distant; when the two features were spatially close and young children's responses in the two-object condition were facilitated and no longer differed from both the single-object and the occluded-object conditions. This finding does not detract from the finding indicating that 5-year-olds are capable of perceptual completion of a partially occluded object, but it clearly suggests that in their perceptual processing of a visual scene, organization into coherent objects has no dominance over local spatial proximity, unlike for older children and adults. That is, to perform the task at hand (i.e., judging whether the two features are same or different), 5-year-olds can rely on close proximity between the two features, disregarding the fact that the two features are not in the same object. The important role of spatial proximity in perception at an early age has been demonstrated for several perceptual organization skills. Specifically, young children's performance critically depends on spatial proximity, which is shown to be restricted to a rather limited range of spatial distances regardless of the presence of other strong grouping cues

(Hadad & Kimchi, 2006; Hadad et al., 2010b; Kovács, 2000; Kovács et al., 1999), and it has also been demonstrated for dynamic displays in which integration of local motions into a global coherent motion is involved (Narasimhan & Giaschi, 2012; reviewed in Hadad, Schwartz, Maurer, & Lewis, 2015). Given this role of spatial proximity, developmental rates of perceptual completion are likely to vary with the spatial distance over which interpolation of the missing contours is required. It is reasonable to expect, then, that perceptual completion could have been obtained earlier, at 4 years of age, if the size of the occluder was reduced. Importantly, however, even with this possible finding, the conclusions of the current study remain that this basic perceptual skill, for which very early onset is seen during infancy, continues to develop into childhood.

The differences found between adults' and children's responses in the *nonaligned occluded* displays further imply that age-related changes may also be sensitive to the way perceptual cues govern interpolation and unity perception over development. Thus, the finding of a single-object advantage for the occluded objects in nonaligned displays at 5 years of age presumably results from facilitation in responses to the occluded object in these displays produced by common visual features, such as color, that the two fragments of the occluded object may share. This interpretation is consistent with studies showing that visual attributes, such as similarity in color and texture, influence object perception during infancy and early childhood (Spelke, 1990). It also seems possible that the process by which the occluded edges are interpolated has some tolerance around collinearity early in life so that object unity during early childhood is less sensitive to poor collinearity of the *nonaligned* fragments, particularly for displays where the two features are spatially close. This tolerance gradually decreases as perceptual experience accrues and children learn about objects and their likely properties, organizing the visual array and perceptually completing fragmented contours according to these properties (Helmholtz, 1866/1925). Indeed, children have been shown to become increasingly sensitive with age to the perceptual cues of collinearity and spatial proximity and to the particular combinations of these cues that best match the statistics of real contours (e.g., Hadad, 2012; Hadad & Kimchi, 2006; Hadad et al., 2010a).

How might processing change during early childhood to produce this pattern of results? The physiology supporting a mechanism for contour interpolation appears to be present early in infancy, at least in a rudimentary form (see Burkhalter et al., 1993; Gerhardstein et al., 2004; Kovács et al., 1999). Specifically, the basic structures of area V1 in the primary visual cortex are in place early in life, but the vertical connections between layers and horizontal connections within layers of the visual cortex take time to develop (Burkhalter et al., 1993). Functioning of the "end-stopped" cells in the visual cortex involved in junction detection has been shown to undergo substantial development (e.g., Pack, Livingstone, Duffy, & Born, 2003). Long-range facilitatory integrations between orientation-tuned spatial channels that are shown to become adult-like only toward the end of childhood (Kovács, 2000; Kovács et al., 1999) may well account for the sensitivity to spatial proximity observed here in our 5-year-olds.

Although computations of contours between collinear segments are based on a relatively local interpolation process based on contour relatability and mediated by long-range connections within early visual areas (e.g., Gilbert & Wiesel, 1989), they are likely to also be supported by higher-level processes (Lesher, 1995). Indeed, the development of feedback connections between areas V1 and V2 has been shown to undergo substantial development (Burkhalter, 1993). It has been suggested that cognitive processes might come into play in interpolation in a more substantial way with age, in particular for partial occlusion, leading to greater precision of the interpolated representations and a reduced influence of geometrical factors (Hadad, Maurer, et al., 2015). The observed age-related changes in the current data, thus, may reflect development in the local interpolation mechanism and in the use of the perceptual cues governing this process as well as in the increased contribution of cognitive processes with age, which together allow precise interpolated representations of partly occluded objects that gradually evolve to function as real physically present objects.

In addition to partial occlusion, the visual system is also called on to overcome fragmentation in the case of subjective contours at which completion yields a visual impression of contours or surfaces in locations where there is no local image contrast to support this percept (i.e., modal completion; Michotte, Thines, & Crabbe, 1964). The current results could be taken to suggest, particularly given the strong claim that the same perceptual mechanism underlies both modal and amodal completion (e.g., Kellman & Shipley, 1991), that contour interpolation in general develops at 5 years of age. There are, however, some indications for a more protracted development of completion in the case of subjective contours than in the case of partial occlusion (Abravanel, 1982; Hadad, Maurer, et al., 2015; Hadad et al., 2010a). In a direct comparison of contour interpolation of subjective and partially occluded contours during development, Hadad and colleagues recently showed that perceptual completion in the case of partial occlusion is faster to develop (Hadad, Maurer, et al., 2015). These differential age-related changes in the two types of visual completion might be attributed to the difference in the rate of occurrence of these two perceptual events in real-world settings. Given that the environmental conditions that give rise to camouflage are much more limited than those that give rise to partial occlusion (e.g., Anderson, Singh, & Fleming, 2002), it is reasonable to expect that the visual system has first developed a mechanism to transcend the latter source of input fragmentation, urging perceptual completion abilities to attain the ultimate level of functioning in relatively little time.

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