THE DEVELOPMENT OF PERCEPTUAL COMPLETION

THE PERCEPTUAL COMPLETION PROCESS:

EVIDENCE FROM 8-YEAR-OLDS, 11-YEAR-OLDS, AND ADULTS

BY

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Abstract

Although objects in our visual environment are partially occluded at times, we perceive the world as being composed of complete objects. Three main theories have been proposed to account for the completion of occluded objects, namely local theories (e.g., Kellman & Shipley, 1991), global theories (e.g., Boselie & Leeuwenberg, 1986), and integrative models of completion (e.g., Sekuler, 1994; van Lier et al., 1994).

Here, we investigated age-related changes in the completion of a complex partially occluded object. We used a prime-matching task to test children and adults. In this task, a prime (global, local, occluded, or no prime) was presented and was followed immediately by two shapes (global and local) that were judged as being the same or different.

In Experiment 1, we tested adults (n = 36/group) at various prime durations (150 - 700 msec) to tap into earlier and later representations of the occluded object. Consistent with global theories, the occluded object primed the global shapes at 300 and 700 msec (*p*s < 0.05). Inconsistent with global and local theories, the occluded object primed both the global and local shapes at 150 and 500 msec (*p*s < 0.05). Overall, our results are most consistent with integrative models of completion.

In Experiment 2, we tested 8-year-olds (n = 20) at a prime duration of 700 msec and 11-year-olds (n = 30/group) at a prime duration of 300 or 700 msec. For 11-year-olds, unlike adults, the occluded object did not significantly prime either the global or local shapes at 300 msec ($p > 0.50$). For both 8- and 11-year-olds, the global, local, and occluded primes did not significantly prime either shape at 700 msec (ps > 0.50). Based on the current testing conditions, we found that the perceptual completion process may not be adult-like even at 11 years of age.

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Microgenesis of Perceptual Completion

Locating the boundaries between an object and its surrounding is necessary in order to perceive the object accurately. Yet, those boundaries are not always defined by real contours. In the case of partial occlusion, for example, we perceive the separated image fragments as a single coherent object behind an occluding surface. The process of perceptual completion allows individuals to connect edges across gaps, and thus organizes the visual environment into distinct objects (Kellman, 2003a). In adults, the completion process appears to be fast and effortless, taking approximately 100 – 250 msec for simple partially occluded objects (Sekuler & Palmer, 1992; Rauschenberger, Peterson, Mosca, & Bruno, 2004).

Three main theories have been proposed to explain the perceptual completion process, namely, local theories, global theories, and integrative models of completion. Local theories of completion take into account only the local information available at the contour junction, where the real contours intersect the occluder (Kellman and Shipley, 1991). Kellman and Shipley (1991, 1992) indicate that perceptual completion can occur only if the “two edges, separated by a gap or occluder are relatable” so that a continuous curve bending no more than 90° can be formed (Kellman, Guttman, & Wickens, 2001, p. 196). An example of local completion of the occluded object in Figure 1A is shown in Figure 1B. Although there is considerable support for Kellman and Shipley’s local theory of completion (e.g., Kellman, Yin, & Shipley, 1998), this theory has

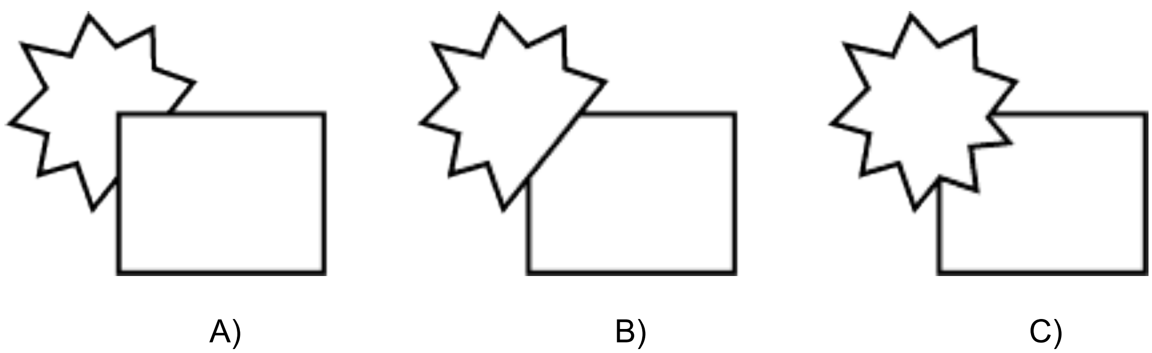

Figure 1: A) Quasi-regular shape occluded by a rectangle B) completion of the partly occluded shape in A predicted by local theories C) completion of the partly occluded shape in A predicted by global theories. After de Wit & van Lier (2002) Figure 4.

come under question based on cases suggesting that completion can occur even when the constraints of relatability are not met (Guttman, Sekuler, & Kellman, 2003). For example, when 32.5% of a circles contour is hidden behind a square, the relatability criterion is violated (Guttman et al., 2003). However, regardless of this violation, given enough time (~450 ms) the occluded object can be completed (Guttman et al., 2003).

Unlike local theories, most global theories of completion are based on the law of Prägnanz, which states that the “psychological organization will always be as 'good' as the prevailing conditions allow” (Koffka, 1935, p. 110). The global-minimum principle (Hochberg & McAlister, 1953), a modification of the law of Prägnanz, predicts that “a perceiver will see the simplest possible interpretation of a pattern” based on the Gestalt property of good form (Boselie & Leeuwenberg, 1986, p. 331). Properties of good form include the overall symmetry of the shape, as well as the number of repeated units (Boselie & Leeuwenberg, 1986; de Wit & van Lier, 2002). For partly occluded objects, these properties are predicted to influence the process of completion. Figure 1C shows an example of global completion of the occluded object shown in Figure 1A. Leeuwenberg (1969, 1971) formulated a coding system, based on the minimum principle, to describe and rank the complexity of all possible interpretations of a visual pattern. The coding system represents each visual pattern by a series of symbols formulating an initial code (i.e., primitive code, Boselie & Leeuwenberg, 1986). The initial code can carry redundant information; therefore, the model uses a set of formularized coding rules to simplify the code. The coding rules take into account factors such as repetition, symmetry, and alternations. The code is reduced until it can no longer be reduced further, and the resultant code is referred to as the final code. The final code is characterized by the information load (*I*), which indicates the number of parameters required to describe the interpretation (Boselie & Wouterlood, 1989). The minimum principle, predicts that the human perceptual system should reduce *I* to its minimum to choose the simplest possible interpretation (Boselie & Leeuwenberg, 1986).

Support for the minimum principle comes from studies investigating the congruency between human perception and model predictions. For example, the type of figures human observers perceive when shown illusory, partially occluded, or superimposed images, are consistent with the type of figures the minimum principle (as described above) would predict as the most likely completion (Boselie & Leeuwenberg, 1986). However, the simplest code does not always predict the preferred interpretation in adults (Boselie & Wouterlood, 1989). For example, of the 92 visual patterns Boselie and Wouterlood (1989) tested, only 51% of the shapes that the minimum principle predicted were consistent with the shapes subjects perceived.

Finally, integrative models predict that both local and global features influence the completion process. Van Lier, van der Helm, and Leeuwenberg (1994) suggest an integrative model in which the type of completion depends on the relative simplicity of the possible local and global completions -- the simpler completion is more likely to be perceived. The perceptual complexity of the pattern is described as the sum of the complexity of the internal (i.e., regularity within object), external (i.e., position between objects), and virtual structures (i.e., occluded portion of object). Of the 144 patterns tested, this model correctly predicted 95% of the most likely completions (van Lier et al., 1994). More support for integrative models comes from studies varying the amount of occlusion (van Lier, van der Helm, & Leeuwenberg, 1995). When subjects are asked to draw the occluded portion of a shape, they tend to draw globally completed shapes when a small amount of the object is occluded; however, subjects draw mostly locally completed shapes when a large portion of the object is occluded (van Lier et al., 1995).[1]

Another integrative model, proposed by Sekuler (1994), predicts different completions based on factors such as the collinearity of the real contours and symmetry. In this model, all possible completions that would be predicted by global and local theories of completion are formed. The possible representations are then assigned a saliency level based on factors like the presence and axis of symmetry (vertical symmetry has a stronger influence), collinearity of the real contours, and the simplicity of the solution (Sekuler, 1994). The most salient global and the local representations are advanced to the next stage of processing, which combines the two representations to compute a weighted solution. Therefore, although the internal representation of the occluded object is

[1] The authors did not indicate what percentage of the object was occluded.

not purely global or purely local, it may be biased towards a local or global solution. Based on the saliency ratings of each solution, the model predicts the preferred completion. For example, for Figure 2A, the local completion would yield symmetry along the vertical axis (one-fold symmetry), whereas, the global completion would yield symmetry along the vertical and horizontal axes (two-fold symmetry; Sekuler & Murray, 2001). In this case, the only difference between the global and local solution is the addition of horizontal symmetry for the globally completed object (Sekuler & Murray, 2001). The integrative model predicts that subjects should complete the occluded object locally, because the addition of horizontal symmetry to the global completion does not outweigh the complexity of the solution. The prediction of the model is consistent with the type of shape subjects perceive (local completion; Sekuler, 1994; Sekuler & Murray, 2001). In contrast, for Figure 2B, the local completion would yield only symmetry along the vertical axis (one-fold symmetry), whereas, the global completion would yield symmetry along the vertical, horizontal and two diagonal axes (four-fold symmetry; Sekuler & Murray, 2001). In this case, the overall regularity of the global completion outweighs the complexity of the globally completed shape. Therefore, the model predicts that subjects should complete the occluded object globally, which is consistent with the type of shape subjects were found to perceive (Sekuler, 1994; Sekuler & Murray, 2001).

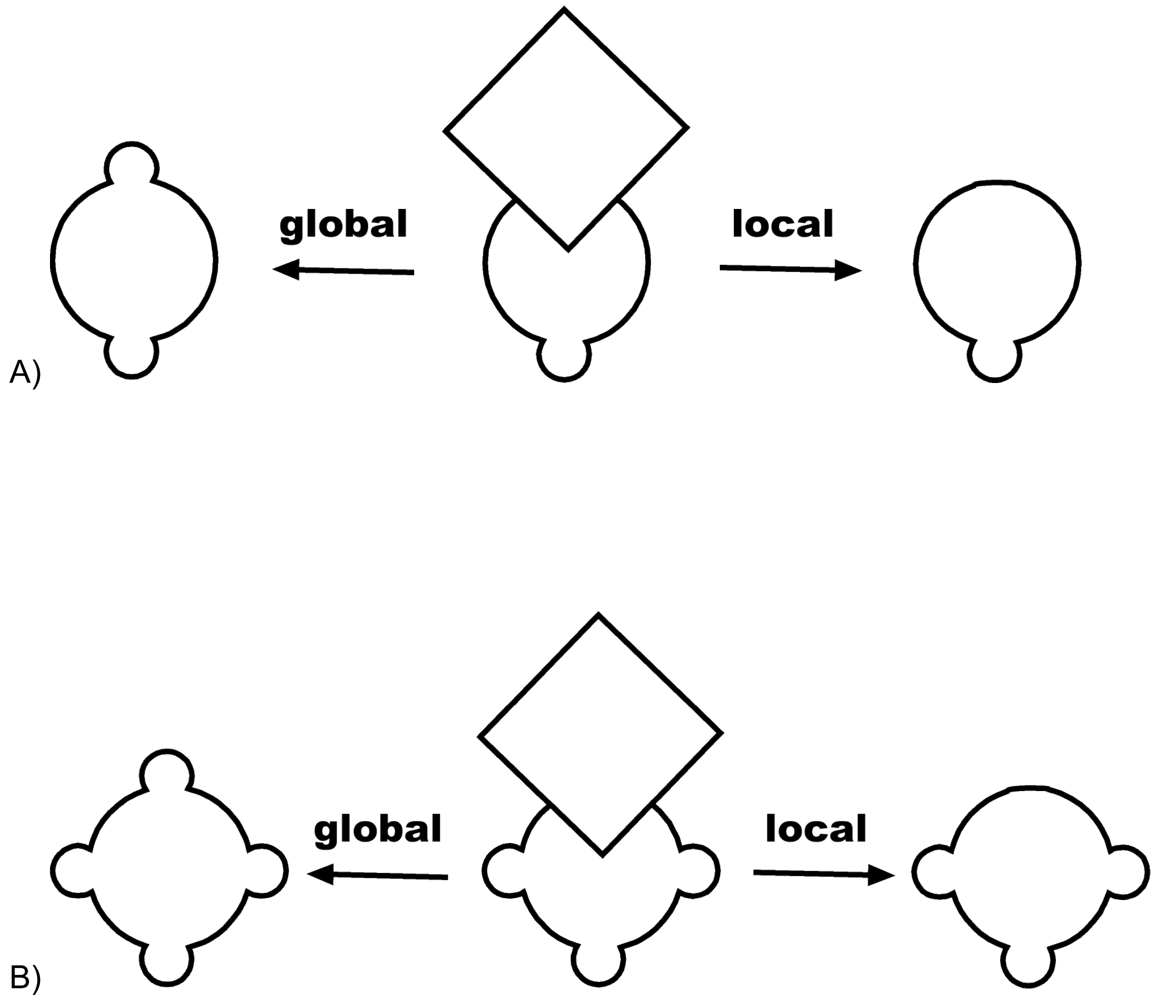

Figure 2: Stimuli used to test the importance of symmetry cues on local and global completion of a partially occluded object. For both A) and B), the central figure shows the occluded stimulus, and the two figures on the sides show the completed figure based on local processes (local) or global processes (global). After Sekuler (1994), Figures 4 and 6.

Recently, objective tasks have been used to measure the specific form of the completed representation in adults. One such task is the prime-matching paradigm, in which subjects are briefly shown a prime that is followed immediately by a test pair. The test pair consists of either two identical shapes or two different shapes. The subject must judge whether the two test shapes are the same or different from each other. The logic of the paradigm is that response times should be faster for test pairs that are similar to the prime in comparison to those that are not (Sekuler, Palmer, & Flynn, 1994). By presenting the prime for various durations, the prime-matching task can probe the representation of the occluded object during early and late stages of visual processing (Sekuler et al., 1994; Sekuler & Murray, 2001). For both line drawings and filled figures, previous studies suggest that it takes approximately 100 – 250 msec to form a complete representation of a simple partially occluded object (Sekuler & Palmer, 1992; Rauschenberger et al., 2004). However, the time to form a complete representation of the occluded object may vary depending on the complexity of the shape. For example, as the amount of occlusion increases, the time to complete the occluded object also increases (Guttman et al., 2003).

By varying the duration of the prime, the prime-matching task has also been used to study the salience of the local and global completion of a partly occluded object at different stages of processing. Subjects observed one of three primes (i.e., an occluded object, a symmetrical globally completed object, or an asymmetrical locally completed object) for 150, 300, or 1000 msec, followed by a test pair that was judged as being the same or different (Sekuler et al., 1994). For all exposure durations of the prime, response times were faster for globally completed objects when primed by either occluded or globally completed objects, whereas response times were faster for locally completed objects only when primed by locally completed objects. The pattern of results indicates that adults represented the partially occluded object globally when it was presented for 150 – 1000 msec.

Despite the clear results from previous studies investigating completion effects (e.g., Sekuler et al., 1994; van Lier et al., 1995), the completion process may not work in the same way under real world conditions, because objects in our visual world are usually not composed of perfectly regular or symmetrical shapes (de Wit & van Lier, 2002). Local theories can account for the completion of occluded non-regular shapes, because completion is based on local information where the real contour disappears behind the occluder. In contrast, current global theories are harder to apply to irregular shapes that are not perfectly symmetrical (de Wit & van Lier, 2002). However, since irregular shapes do contain some repeated units, allowing for regularity, global processes can still influence the completion of the occluded object (de Wit & van Lier, 2002). When asked to draw the occluded portion of a quasi-regular shape (e.g., Figure 1C), adults completed the shape in a global way (de Wit & van Lier, 2002). Similar results were found using a prime-matching paradigm (de Wit & van Lier, 2002). Since there is a lack of perfect symmetry in the quasi-regular shape, more than one global completion may be plausible. Therefore, de Wit and van Lier (2002) created multiple global completions of the partly occluded object to test the flexibility of the completion process. In a prime-matching task, subjects were shown seven different completions (one local completion and six global completions) of the occluded object, followed by a test pair. The occluded prime facilitated more than one global representation of the occluded object, indicating that the perceptual completion process was flexible (de Wit & van Lier, 2002).

Physiological studies in monkeys and neuroimaging studies in humans indicate the involvement of a number of visual areas for the processing of occluded objects. The primary visual cortex (area V1) of two Japanese monkeys was studied to determine whether V1 cells respond to displays containing a partially occluded bar (Sugita, 1999). The monkeys were shown either two separated line segments or two line segments hidden behind a rectangle. The location of the rectangle on the two retinae varied to create three different conditions: a no binocular disparity condition (i.e., rectangle appeared in the same plane as the line segments), a crossed disparity condition (rectangle appeared in front of the line segments as an occluder), and an uncrossed disparity condition (i.e., the rectangle appeared behind the line segments). Both simple (9 out of 73 simple cells) and complex cells (11 out of 113 complex cells) in area V1 fired preferentially when the rectangle partially occluded the line segments, but not when the rectangle appeared in the same plane or behind the line segments. Sugita interpreted this result as suggesting that V1 cells may have the capacity to respond to groupable image fragments.

To further examine the contribution of depth information to occlusion, neurons in area V1 and V2 of macaque monkeys were recorded during a flank facilitation task (Bakin, Nakayama, & Gilbert, 2000). The flank facilitation task is based on the finding that it is easier to detect elements forming a contour among noise elements when the number of individual elements composing the contour increases (Bakin et al., 2000). For a given receptive field, when a collinear flank was added outside the neurons' receptive field, the response of the neuron increased. However, if an orthogonal flank was added outside the neurons' receptive field, to interrupt continuity, the neurons' response decreased. Interestingly, when a depth cue was added to the orthogonal flank, providing a cue for occlusion, the neuron responded as if a continuous contour was present. A greater proportion of cells in V2 exhibited flank facilitation when depth cues were added than did cells in V1. Hence, neurons in area V2 can integrate depth information to resolve the problem of border ownership in partially occluded displays (Bakin et al., 2000).

Activation of early visual areas in humans has been observed using functional magnetic resonance imaging (fMRI). To investigate the brain regions associated with completion, Rauschenberger et al. (2004) studied the time course of completion of a simple partly occluded object (circle partially hidden behind rectangle, filled figure) in humans using an fMRI adaptation paradigm. In that paradigm, subjects were first shown an occluded shape for 100 or 250 msec, then a mask, followed by one of two probes: mosaic (notched circle beside rectangle) or complete shape (circle in front of rectangle). If the representation of the occluded figure is similar to the probe, then related or highly overlapping neural subpopulations should be activated, thus decreasing the fMRI signal for the second stimulus (adaptation). A decrease should not be observed if the occluded figure and the probe activate different subpopulations of neurons (no adaptation). When the occluded object was shown for 100 msec, the fMRI signal decreased for the mosaic shape; however, by 250 msec, the fMRI signal decreased for the complete shape. Both early visual areas (V1, V2, V3, & V4v) and higher visual areas (lateral occipital complex; LOC) were adapted at 100 and 250 msec (Rauschenberger et al., 2004). Consistent with single cell recordings in monkeys, the completed form of the occluded object activated visual areas as early as V1 (e.g., Sugita, 1999; Bakin et al., 2000). These results are also consistent with behavioural studies suggesting that the earliest form of the occluded objects is a mosaic, which is followed by the completed form (Sekuler & Palmer, 1992).

What remained unclear was what form of the occluded object was being coded in early and late visual areas. To address this question, Weigelt, Singer, and Muckli (2007) investigated brain activity during processing of the same simple occluded object (line drawing) using an fMRI adaptation paradigm. Subjects were first shown an occluded figure for 300 msec, followed by one of four possible representations of the occluded figure (test stimulus) for 300 msec: complete, mosaic, repeated (square), and control (mosaic rotated 180°). Brain activity decreased following the mosaic shape relative to the completed shape in early visual areas, suggesting that these areas process the local contours of the occluded shape. In contrast, at later stages of processing (i.e., LOC) brain activity decreased more following the complete shape than the mosaic shape, suggesting that the completed form of the occluded object was represented. At later stages of processing, there was no longer a representation of the mosaic shape. These results suggest that the occluded object is represented initially as a mosaic and then as a complete object (Weigelt et al., 2007).

Consistent with the conclusion that the LOC represents the complete object are results from a study that evaluated whether the LOC represented the low level contour information or the perceived shape of the occluded object. In an fMRI adaptation paradigm, images were presented sequentially that had the same shape or the same contour (Kourtzi & Kanwisher, 2001). In the same shape condition, although the local contours differed (one shape was occluded), the global shape was identical. In the same contour condition, the two stimuli had identical contours, but the global shape differed depending on the figure-ground assignment (Kourtzi & Kanwisher, 2001). Brain activity decreased in the LOC for the same shape condition, even though the local contour information differed between the shapes. In contrast, brain activity did not decrease when the shapes differed but the contours were identical. This suggests that the human LOC represents the perceived shape of an object, rather than the low level contour information of the object (Kourtzi & Kanwisher, 2001).

Although quite a lot is known about the regions of the brain involved in completion, a limited number of studies have investigated the timing of activation in the completion process. To study brain regions involved in completion with high spatial resolution and temporal accuracy, Liu, Plomp, van Leeuwen, and Ioannides (2006) used a magnetocephalography (MEG) in association with a priming task. Subjects were first shown a simple figure (local, global or mosaic representations of the occluded object) for 50 msec, and then an occluded figure for 50 msec. This was followed by a test pair that was judged as being the same or different. Note that unlike Sekuler et al. (1994) and de Wit, Mol, and van Lier (2005), in this case, the authors investigated the effect of priming of the simple figure on the occluded figure, rather than the priming of the occluded figure on the test pair. Their rationale was that priming of the occluded figure on the test pair is influenced not only by the similarity of the prime and the test pair, but also by other decision-related processes (Liu et al., 2006). Since, decision processes do not influence the priming effect between the simple figure and the occluded figure, this method can more accurately measure the influence of visual processes during priming. For all three figure interpretations (local, global, and mosaic), increased brain activity was first detected in area V1 and V2 at 90 msec, then the LOC at 100 – 110 msec, and finally the fusiform gyrus at 110 – 160 msec. These results are consistent with behavioural studies suggesting that completion takes between 100 – 250 msec in adults (Sekuler & Palmer, 1992; Rauschenberger et al., 2004).

Based on the time course of completion, these data suggest that a feed-forward model of processing may underlie perceptual completion. During early stages of completion, local image information is processed in the primary visual cortex (area V1; Liu et al., 2006; Weigelt et al., 2007). The next stage of processing may occur in area V2, where depth cues facilitate assignment of boundaries to objects (Bakin et al., 2000). Finally, the lateral occipital complex responds to the completed form of the occluded object (Lerner, Hendler, & Malach, 2002; Liu et al., 2006). Feedback connections may also influence or interfere with the process of completion (Weigelt et al., 2007).

These early studies have provided a basic understanding of visual processing of occluded objects; however, the results of these studies are limited in two ways. First, most of the figures used to examine the completed form of the occluded object are line drawings. There are two main problems with using these types of figures: 1) line drawings are not similar to the types of occluded objects we encounter in the real world and 2) Kellman and Shipley's (1991, 1992) local theory of completion applies only to filled figures. Therefore, to be able to apply this theory we need to test occluded objects that are filled figures. Only a few studies have compared directly line drawing and filled figure versions of the same occluded object (Sekuler, 1994; Sekuler et al. 1994). These authors found that for both line drawings and filled figures, subjects completed the occluded object globally (Sekuler, 1994; Sekuler et al. 1994). However, in these studies, the occluded shape was simple and highly symmetrical (e.g., Figure 2). Although more complex and irregular figures have been tested, only line drawing versions of these shapes were studied (e.g., de Wit & van Lier, 2002; de Wit et al., 2005). Therefore, one objective of the current study was to examine the completed form of a filled figure version of the complex occluded object studied by de Wit and van Lier (2002) and de Wit et al. (2005). A second limitation of the few previous studies that have tested a complex occluded figure (line drawing) is that they measured the influence of global and local processes only at a prime duration of 500 msec (de Wit & van Lier, 2002; de Wit et al., 2005). For complex occluded objects, local processes may influence completion at shorter prime durations. Therefore, another objective of the current study was to determine whether the representation of the completed form of the occluded object changed over a broad range of times (150 to 700 msec).

In Experiment 1, we used a prime-matching task to investigate the completion of a complex occluded shape that differed in its local and global completion in adults. Although the stimuli were similar to de Wit and van Lier (2002) and de Wit et al. (2005), we tested filled figure versions of these shapes to imitate real world objects. The primes consisted of a star-like object of four different types: the star-like object appearing behind a rectangle (i.e., occluded prime, Figure 3A), a locally completed version of the shape (i.e., local prime, Figure 3B), a globally completed version of the shape (i.e., global prime, Figure

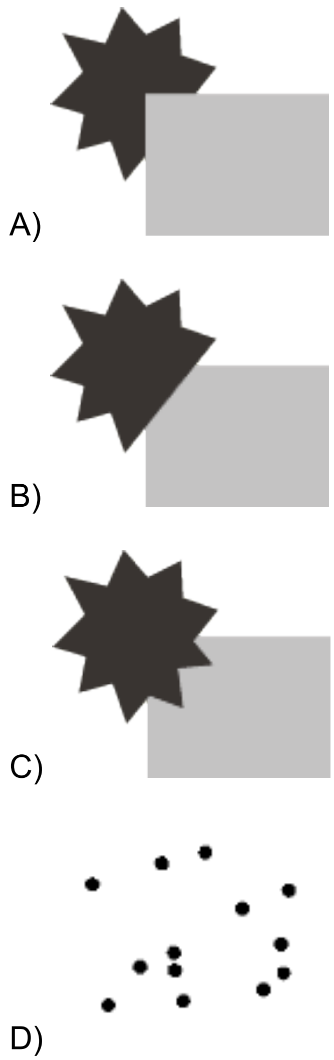

Figure 3: The four priming conditions in Experiment 1: A) occluded prime, B) local prime, C) global prime, D) no prime.

3C), and a no prime condition (a random group of dots; Figure 3D). Subjects made a same or different judgment about a pair of shapes (test pair) that immediately followed the prime, and the measure of interest was their response time. Half of the same trials were of the local same shape, and the remaining same trials were of the global same shape. The logic behind the method was that response times should be faster for “same” test pairs that were similar to the prime than for “same” test pairs that were dissimilar to it (Sekuler & Palmer, 1992). For example, priming afforded by the global prime should manifest in faster responses to the global same test pair than to the local same test pair. The critical question is the pattern of priming produced by the occluded prime: if the occluded prime is represented as a complete global or local shape it should produce priming effects that are equivalent to those of the global or the local prime, respectively.

The no prime condition served to determine baseline response for categorizing the global same and local same test pair. The prime was presented for various durations (150, 300, 500, & 700 msec) to tap into earlier and later stages of processing.

Experiment 1: Time course of perceptual completion in adults

Methods

Participants

The final sample consisted of 144 adults (mean age = 20.09 years; 17.0 – 28.1 years), 36 adults per prime duration condition (150, 300, 500, & 700 msec). Adults consisted of undergraduate students at McMaster University. All participants had normal or corrected-to-normal vision and passed a mandatory visual screening examination (see Procedure). Adults received either a course credit or $10 per hour for completing the study. An additional 20 adults were excluded from the final sample: 19 because they failed visual screening, and one because he was too tired to complete the experiment.

Apparatus and Stimuli

An Apple MacMini 10.4.2 computer was used to carry out the experiment controlled by SuperLab Pro version 4.0.7b. We used a keyboard to record the subject's response time to the nearest 3 msec. The stimuli were presented on a Dell Trinitron monitor (P1130), with a width of 40.6 cm and a height of 30.5 cm (39.1° x 31.4° when viewed from 50 cm). The pixel resolution was 1600 x 1200, with a refresh rate of 85 Hz. With the exception of the light from the computer monitor, the testing room was dark. Subjects were tested binocularly, seated 50 cm away from the monitor with their heads stabilized on a chin rest.

The stimuli consisted of a dark grey filled star-like object and a light grey filled rectangle, similar to the stimuli originally developed by de Wit and van Lier (2002) (See Figures 3 and 4). We used FreeHand MX version 11.0.2 to create the stimuli. Luminances were measured using a Minolta LS-100 photometer. The mean luminance of the dark grey star-like object was 11.42 cd/m^2, the light grey rectangle was 62.32 cd/m^2, and the background luminance was 101.38 cd/m^2. Therefore, the Michelson contrast for the dark grey star-like object was 79.8% and the light grey rectangle was 23.9%.

The four primes are illustrated in Figure 3: occluded prime (Figure 3A), local prime (Figure 3B), global prime (Figure 3C), and the no prime condition (Figure 3D). To form the occluded prime, a star-like object appeared behind a rectangle that was 1.8 cm (2.1°) long x 1.4 cm (1.6°) wide. The maximum horizontal and vertical protrusions of the star-like object were 1.7 cm (1.95°) x 1.7 cm (1.95°). The rectangle occluded approximately 20% of the area of the star-like object. To form the local prime, a straight line joined the real contours that disappeared behind the occluder, and the shape appeared in front of the rectangle in precisely the same position as the occluded shape. Similarly, for the global prime, the repeated units of the visual portion of the shape were continued to complete the shape, and the shape appeared in front of the rectangle. Both local and global theories of completion predict that the irrelevant portion of the prime will be completed as a rectangle (Sekuler et al., 1994). The maximum extent of the priming stimulus was 2.9 cm (3.31°) x 2.3 cm (2.63°).

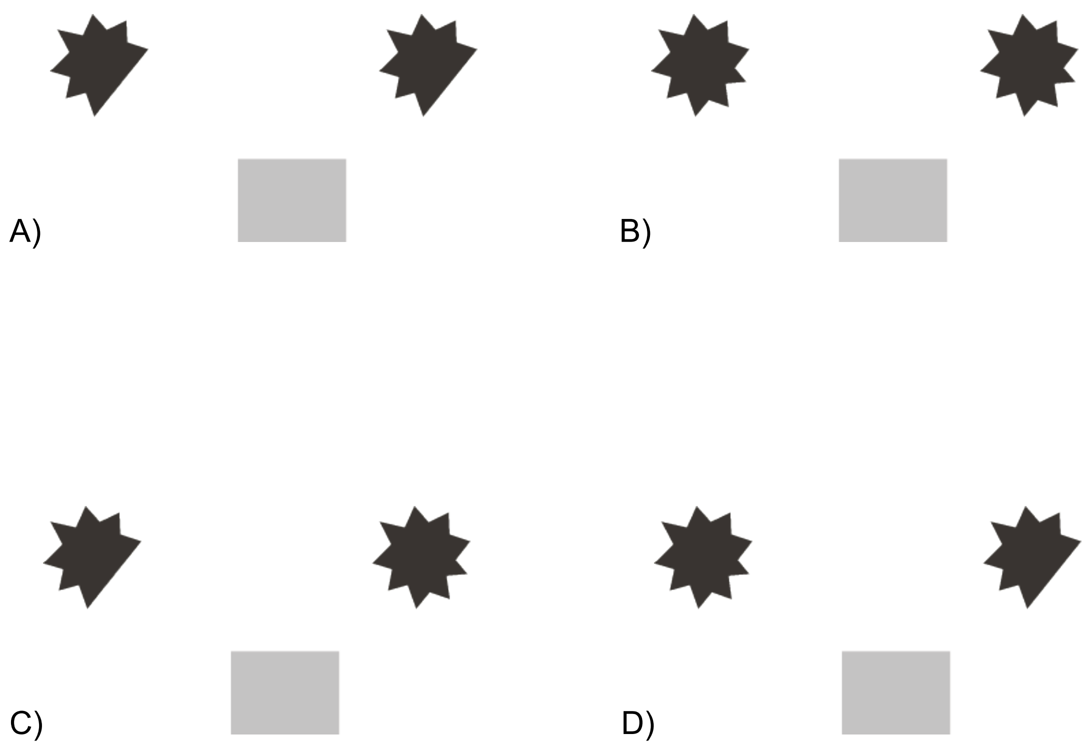

Figure 4: Test pairs consisted of two pairs of identical objects: A) local same and B) global same, and two pairs of different objects: C) local-global and D) global-local.

The test pair consisted of two shapes that appeared side-by-side. The test shapes were positioned equivalent distances away from the location of the original prime to prevent any masking of the prime (Sekuler et al., 1994). The local and global test shapes were identical in every aspect to their corresponding prime condition, except that the occluder (rectangle) was removed (Figure 4). The rectangle from the original prime appeared slightly to the right and below the test shapes. Hence, the test display contained two star-like objects and a rectangle. Two matching (global-global, local-local; Figure 4A/B) and two non-matching (local-global, global-local; Figure 4C/D) test pairs were created. The maximum extent of the entire test display was 7.4 cm (8.4°) x 3.9 cm (4.5°).

Progress in the task was specified by the extent to which a jellybean jar had been filled. To fill the jellybean jar, subjects collected jellybeans that appeared throughout the game (Figure 5A). Regardless of the subjects' accuracy, a quarter of the jellybean jar was filled every 24 trials (see Figure 5).

Procedure

Prior to the initiation of the experiment, experimental procedures were explained and informed consent was obtained from all subjects. To determine handedness, subjects completed a hand preference questionnaire (Peters, 1998). In the experiment, subjects used their dominant hand to make 'same' judgments on a keyboard. The McMaster Research Ethics Board approved all experimental protocols.

A)

B)

Figure 5: Example of stimuli used to indicate progress in the game: A) the jellybeans that needed to be collected and B) the four jellybean jars, one of which appeared after every 24 trials in the order shown above.

a) Visual Screening

To be included in the final sample, subjects had to meet our criteria on a visual screening examination, which consisted of tests of linear acuity, binocular fusion, and stereo-acuity.

We tested each adult's acuity with the Lighthouse Distance Visual Acuity chart from a distance of four metres. To participate in the study, each subject needed to have a minimum linear letter acuity of $20/20^{-2}$ for each eye when tested monocularly, with the subject's own optical correction if applicable. If the subject was unable to meet the $20/20^{-2}$ requirement, but was able to meet this requirement when using less than a -2 dioptre add, the subject was allowed to participate in the experiment as they would be able to focus clearly up to the required testing distance of 50 cm. To rule out hypermetropia (far-sightedness) greater than 3.00 dioptres, a +3.00 dioptre add was placed over each eye separately, and the subject was asked to read the Lighthouse Distance Visual Acuity chart. If subjects were able to read the chart equally well, with or without the +3.00 dioptre add, they were excluded from the study. All subjects in the final data set had worse acuity in each eye with a +3.00 dipotre add.

Each subject was tested with the Worth 4-Dot Test to assess binocular fusion. While wearing anaglyphic glasses (containing one green lens and one red lens) in a darkened room, a flashlight with four illuminated circles was presented to the subject from a distance of 33 cm. The flashlight contained one red light, two green lights, and one white light. Subjects who can fuse see four dots associated with the correct colours (one red light, two green lights, and one other – usually seen as orange). However, if subjects reported seeing fewer or a greater number of dots, they were excluded from the study, as seeing five dots is an indicator of diplopia, seeing two or three dots is an indicator of suppression of one eye, and alternately seeing 2-3-2-3 is an indicator of alternating between the two eyes.

Each subject was tested for stereoacuity using a Titmus Stereotest. This clinical test presents various levels of binocular disparity, which an individual with normal binocular vision can fuse and resolve as one three-dimensional image. Subjects wore polarized glasses to determine which animal in each of three rows on the Titmus test was popping out by either identifying the animal verbally or pointing to it. As well, subjects identified which dot was popping out in each of nine groupings of dots by verbally responding top, bottom, left, or right for each grouping. All participants in the final sample passed the Titmus test by correctly identifying 3 out of 3 animals and 9 out of 9 dots.

b) Prime-Matching Task

In the prime-matching task, a prime was presented for approximately 150, 300, 500, or 700 msec, and was followed immediately by two simultaneously presented shapes (i.e., test pair) that were judged as being the same or different, by pressing the 'same' button for same judgments and a 'different' button for different judgments.[2] Response times were recorded to the nearest 3 msec.

The experiment employed an orthogonal combination of two factors: prime type (occluded, local, global, or no prime) and test pair (global or local). Prime type and test pair were manipulated within-subject, and were mixed within each block. Prime duration (150, 300, 500, & 700 msec) was manipulated between-subjects.

Eight test blocks were created, with the order of the trials being generated using Microsoft Excel 2008 (version 12.0.0). The prime type and test pair were chosen randomly for each trial in a block, with the following restrictions: the same prime could not appear more than two times in a row, the same test pair could not appear more than two times in a row, and the type of correct response (same or different) could not occur more than three times in a row. An equal number of same and different test pairs were presented. Subjects were tested on four test blocks, which were selected randomly from the set of eight test blocks. Subjects completed a demonstration, criterion, and practice phase prior to their first test block.

Demonstration Trials: Eight demonstration trials were shown, and the experimenter began each trial when the subject was looking at the centre of the monitor. We used the first two demonstration trials to instruct participants of the

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[2] The refresh rate was 85 Hz, and therefore each frame lasted 11.76 ms. The exact prime durations had to be multiples of 11.76, and therefore were 152.94, 305.88, 505.88 and 705.88 msec . For convenience, we have approximated the prime durations to 150, 300, 500, and 700 msec, respectively.

task to be completed. The subject was told that they would be helping Detective Holmes find out who stole the jellybeans from the jellybean jar. After finishing each block (or game), the subject would be given a clue to help them solve the mystery. For the third demonstration trial, we informed subjects that they would first see one shape (prime) and then three shapes (test display). The subject's job was to decide if the black shapes in the test display were the same or different from each other. For the third trial, the subjects were shown an example of a "same" trial. The fourth demonstration trial was identical to the third, except that subjects were shown an example of a "different" trial, and told that negative feedback would be given for making incorrect responses (low tone). For the fifth and sixth demonstration trials, the experimenter indicated which buttons needed to be pressed to make a "same" ('S' button) and "different" ('D' button) response. For the seventh and eighth demonstration trials, subjects were informed that they would be collecting jellybeans to refill the jellybean jar. Subjects were shown a picture of a few scattered jellybeans that would need to be collected (Figure 5A). Once they collected all the jellybeans and filled the jar (Figure 5B), they would receive their first clue.

Criterion Phase: Subjects were required to pass the criterion phase before starting their first test block. A trial began with a fixation cross with dimensions of 1.2 cm (1.4°) x 1.2 cm (1.4°) that appeared in the centre of the screen. After the experimenter called for a prime, a blank screen appeared for 50 msec for the 700 msec prime duration condition, and for 150 msec for the 150, 300, and 500 msec prime duration conditions.[3] After a 23.5 msec inter-stimulus interval, the test pair appeared and stayed on the screen until a response was made. In the test display, subjects judged whether the two star-like objects were the same or different from each other. After a response was made, the fixation cross re-appeared. The inter-trial interval varied in length because the experimenter had to initiate each trial; however, the duration of the interval was always greater than 1000 msec to reduce aftereffects. Subjects used their dominant hand for making ‘same’ judgments on a keyboard. We told subjects to categorize the shapes as quickly as they could without making mistakes. To be included in the study, subjects were required to judge correctly four out of five trials as same or different and had three chances to meet this criterion. All subjects passed the criterion on the first attempt.

Practice Run: Each subject completed a practice run before beginning the first test block. The practice run consisted of 17 trials that were identical in every aspect to the criterion trials, except for the addition of one jellybean trial. For the jellybean trial, subjects were required to press the jellybean button (spacebar) to collect the jellybeans.

Full Test Run: Every subject completed four test blocks based on his or her pre-selected block order. The test run was identical to the practice run,

[3] The inter-stimulus interval between the fixation cross and the prime differed between the 700 msec prime duration condition and the other three prime duration conditions (150, 300, & 500 msec). We do not believe that this difference affected the results because we were primarily interested in the effect of the prime on the response to the test pair. The inter-stimulus interval between the prime and test pair was equivalent across all four prime duration conditions.

except for the following changes: progress in the game was given every 24 trials to maintain motivation and attention, and there were five jellybean trials. Subjects were told that the proportion of jar that was filled would reflect progress in each game. Regardless of the subject's accuracy, after every 24 trials, a quarter of the jellybean jar was filled. Once the block of 96 trials was completed, subjects were given a clue to help them solve the mystery. Subjects needed to fill four jellybean jars, one for each test block, to complete the experiment.

For all subsequent test blocks (i.e., Blocks 2, 3, and 4), testing was identical to that described for test Block 1, except that there were no demonstration and criterion phases, and subjects were given only four practice trials prior to the beginning of the next block. Practice trials were randomly chosen for each test block.

Adults completed all four test blocks in a single 1-hour session. Subjects were required to take a 2 to 5 min break between Blocks 2 and 3, and had the option to take as many breaks as needed during the test blocks. A single test block contained 48 same trials and 48 different trials, preceded by 20 practice trials for test Block 1 and four practice trials for test Blocks 2, 3, and 4. We recorded 416 trials over all four test blocks.

Results

Analyses were conducted on correct responses for categorizing same test pairs (global same and local same) for each of the four conditions (occluded, local, global, and no prime conditions). A non-recursive, moving criterion, outlier removal procedure was used to calculate a mean response time (see van Selt & Jolicoeur, 1994). The outlier procedure modulated the exclusion criterion based on the number of correct observations collected for each condition. We also measured two different error rates: 1) the total number of errors in the experiment and 2) the total number of errors made for categorizing the ‘same’ test pairs. We calculated a Z-score for both error rate measures using the mean and standard deviation for that specific prime duration. Subjects with Z-scores greater than +3 or less than -3 were replaced. By this criterion, one subject was replaced for making more than 10% errors in the experiment. To check for a speed/accuracy tradeoff, we correlated each subjects’ speed and accuracy across conditions. A significant speed/accuracy tradeoff was found in one subject; therefore, we replaced this subject. We performed all subsequent analyses on the revised data set, and used Greenhouse-Geisser values when the assumption of sphericity was violated to correct for this violation.

Subjects were very accurate at all stimulus onset asynchronies (SOAs) in this task: mean error rate was 3.52% (range = 0.5 – 9.4%), 3.56% (range = 0.5 – 9.4%), 2.73% (range = 0.5 – 6.8%), and 3.04% (range = 0 – 6.3%), for a prime duration of 150, 300, 500, and 700 msec, respectively. We analyzed the accuracy data using a mixed-design analysis of variance (ANOVA) with prime type and test pair as within-subject factors and SOA as a between-subject factor. The analysis revealed a significant main effect of prime type (F (3, 420) = 4.53, *p*

< 0.005, $\eta_p^2 = 0.03$), test pair ($F(1, 140) = 173.76$, $p < 0.001$, $\eta_p^2 = 0.55$), and a significant two-way interaction between prime type and test pair ($F(2.80, 392.52) = 6.25$, $p = 0.001$, $\eta_p^2 = 0.04$). Although subjects made more errors for the local same test pair than the global same test pair for all prime types (Baseline: $t(143) = 9.50$, $p < 0.001$, Global: $t(143) = 10.58$, $p < 0.001$, Local: $t(143) = 7.27$, $p < 0.001$, Occluded: $t(143) = 8.86$, $p < 0.001$), the difference in error rate was greater for the local prime. No other main effects or interactions reached significance (*p*s > 0.10).

To determine whether subjects were faster at categorizing one of the two test pairs (global same and local same), a repeated measures ANOVA was conducted for the no prime condition, with test pair as a within-subject factor and SOA (150, 300, 500, & 700 msec) as a between-subject factor. There was a significant main effect of test pair ($F(1, 140) = 347.60$, $p < 0.001$, $\eta_p^2 = 0.71$), in which subjects were faster at categorizing the global same test pair (617.92 msec) than the local same test pair (695.22 msec). There was no significant main effect of SOA ($p > 0.50$) or any interaction between SOA and test pair ($p > 0.10$). Since response times differed significantly between the global same test pair and the local same test pair in the no prime condition, the baseline difference needed to be accounted for in order to compare priming effects accurately. As described previously by Sekuler et al. (1994), we calculated the priming effect as the difference in response time between the local and global test pairs following a prime, minus this difference following the no prime condition (refer to Equation 1).

A positive priming effect reflects priming of the global same test pair, whereas, a negative priming effect reflects priming of the local same test pair. A priming effect of zero may reflect either no true priming or equal priming of the local and global same test pair.

Equation 1

Priming effect = [RT(local test pair | prime) – RT(global test pair | prime)]
– [RT(local test pair | no prime) – RT(global test pair | no prime)]

A repeated measures ANOVA was conducted to analyze priming effects, with prime type (local, global, and occluded) as a within-subject factor and SOA as a between-subject factor. There was a significant main effect of prime type (F (1.65, 230.90) = 87.95, $p < 0.001$, $\eta_p^2 = 0.39$), SOA (F (3, 140) = 3.89, $p = 0.01$, $\eta_p^2 = 0.08$), and a significant two-way interaction between prime type and SOA (F (4.95, 230.90) = 10.40, $p < 0.001$, $\eta_p^2 = 0.18$, Figure 6).

For all SOAs, a significant main effect of prime type was observed [150 msec: F (1.60, 56.00) = 64.60, $p < 0.001$, $\eta_p^2 = 0.65$; 300 msec: F (1.57, 54.92) = 30.22, $p < 0.001$, $\eta_p^2 = 0.46$; 500 msec: F (1.50, 52.39) = 7.08, $p < 0.005$, $\eta_p^2 = 0.17$; 700 msec: F (1.72, 60.06) = 4.22, $p < 0.05$, $\eta_p^2 = 0.11$]. Planned comparisons indicated that for a prime duration of 150 msec, the global prime significantly primed the global same test pair (t (35) = 6.70, $p < 0.001$) and the local prime significantly primed the local same test pair (t (35) = -6.88, $p < 0.001$).

However, the occluded prime did not significantly prime either test pair (t (35) = 0.49, $p > 0.50$). To examine whether the occluded prime equally facilitated

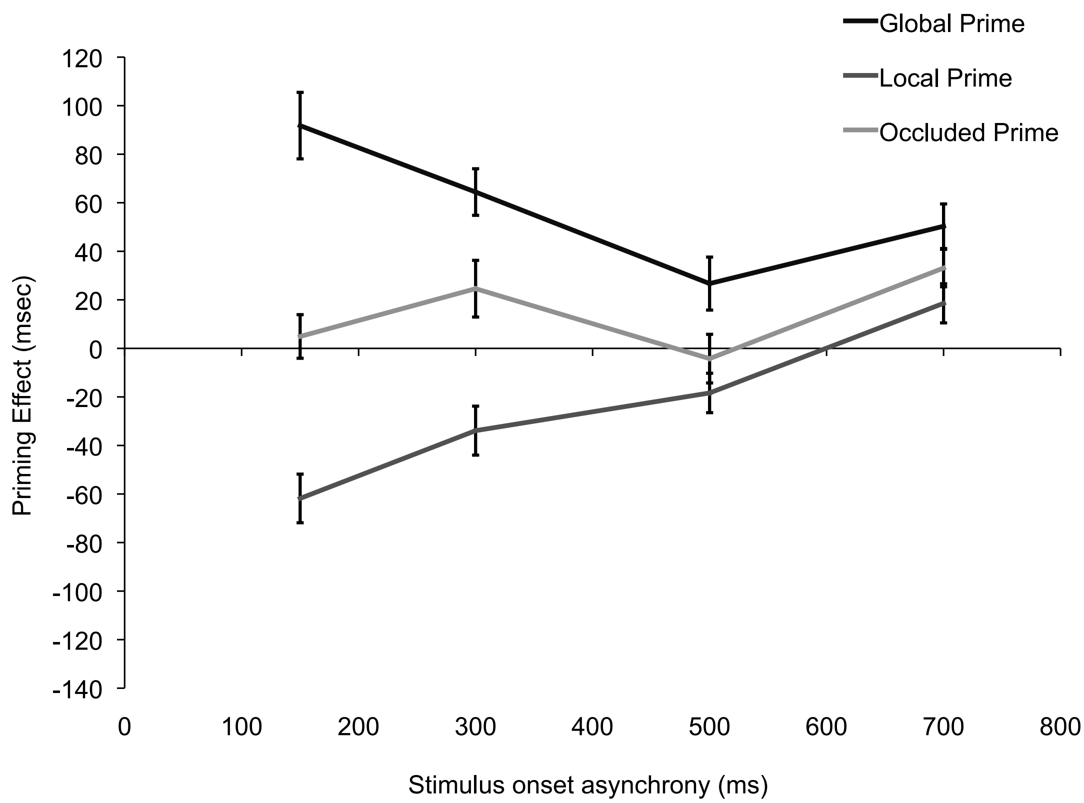

Figure 6: Mean priming effects, in milliseconds, as a function of stimulus onset asynchrony (150, 300, 500, and 700 msec). Error bars represent ±1 standard error.

response times for the global same and local same test pair, we calculated the priming afforded by the prime relative to the no prime condition (Equation 2). The occluded prime significantly facilitated response times for the global same test pair (t (35) = 3.32, $p < 0.005$) and the local same test pair (t (35) = 2.11, $p = 0.042$; Figure 7).

Equation 2

Priming effect = RT(test pair | no prime) – RT(test pair | prime)

At a prime duration of 300 msec, both the global prime and the occluded prime significantly primed the global same test pair (t (35) = 6.71, $p < 0.001$, t (35) = 2.44, $p < 0.05$, respectively); however, priming was stronger following the global prime (t (35) = 3.98, $p < 0.001$). The local prime facilitated response times for the local same test pair (t (35) = -2.90, $p < 0.01$).

By 500 msec, although the global prime significantly primed the global same test pair (t (35) = 2.45, $p < 0.05$), the priming effect of the local prime on the local same test pair was only marginally significant (t (35) = -1.83, $p = 0.075$). Surprisingly, the occluded prime did not significantly prime either test pair (t (35) = -0.52, $p > 0.50$). Similar to a prime duration of 150 msec, the occluded prime significantly facilitated response times for the global same test pair (t (35) = 2.89, $p < 0.01$) and the local same test pair (t (35) = 4.45, $p < 0.001$; Figure 8).

Finally, for a prime duration of 700 msec both the global prime and the occluded prime significantly primed the global same test pair (t (35) = 5.48, $p <$

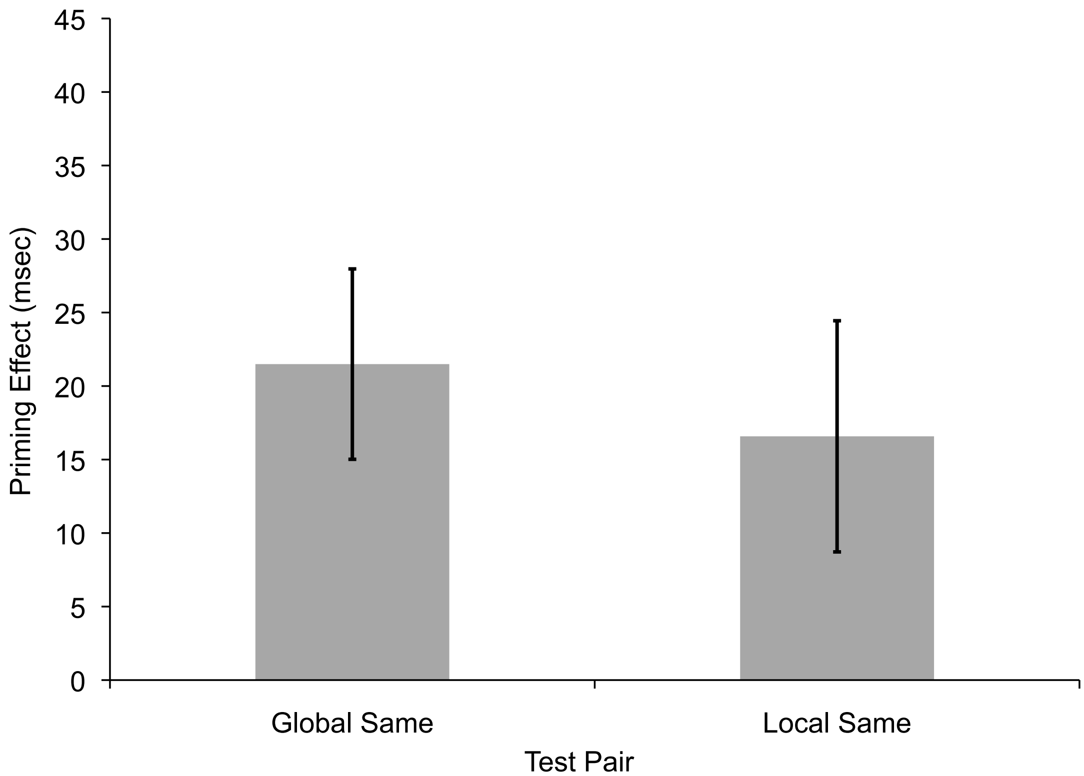

Figure 7: Mean priming effects, in milliseconds, of the occluded prime on the global same and local same test pair for a prime duration of 150 msec. Error bars represent ±1 standard error.

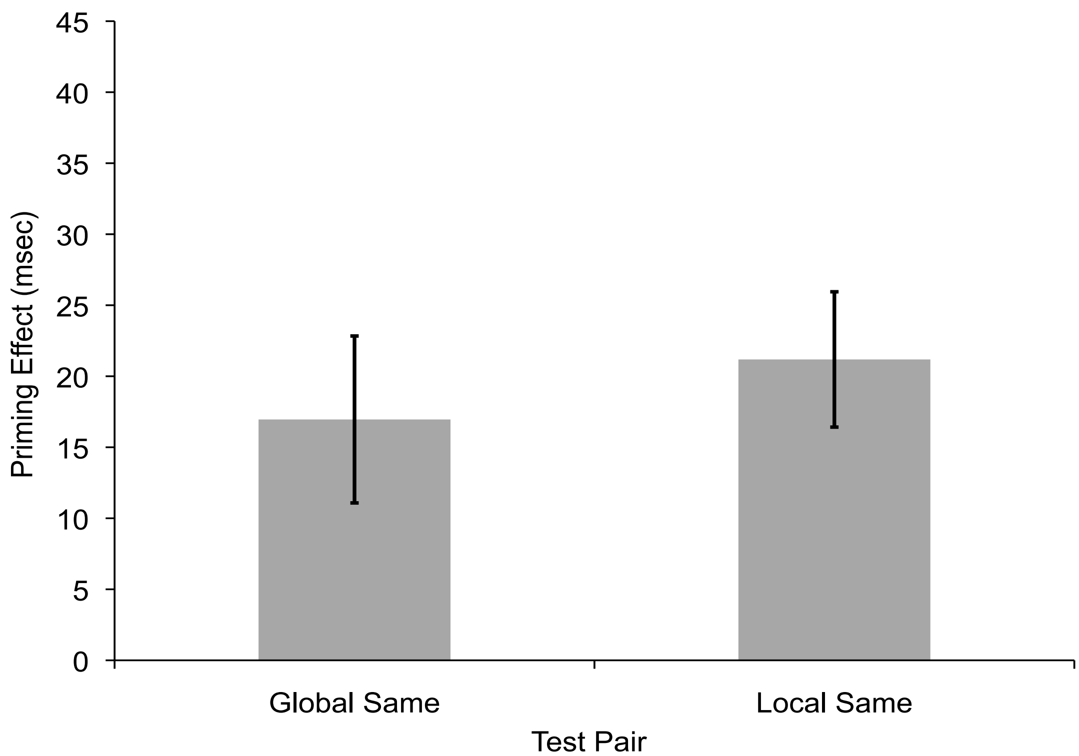

Figure 8: Mean priming effects, in milliseconds, of the occluded prime on the global same and local same test pair for a prime duration of 500 msec. Error bars represent ±1 standard error.

0.001, t (35) = 4.11, $p < 0.001$, respectively). The priming effects did not differ significantly between the occluded and global prime at this duration (t (35) = 1.73, $p > 0.50$). Surprisingly, the local prime significantly facilitated response times for the global same test pair, rather than the local same test pair (t (35) = 2.41, $p < 0.05$).

Discussion

In Experiment 1, we examined the representation of a complex partly occluded object during early and late stages of visual processing in adults. At a prime duration of 150 msec, the occluded object primed both the global and local representations of the hidden object. By 300 msec, the occluded object primed the global same test pair more than the local same test pair, suggesting a dominance of global processing. However, the magnitude of the priming effect was weaker than that produced by the global prime. The results at longer prime durations appear on the surface to be paradoxical. As the prime duration increased to 500 msec, the occluded object primed both the global and local representations equally. At the longest prime duration tested (700 msec), the occluded object primed the global same test pair more than the local same test pair, providing evidence for a re-emergence of global dominance. The level of priming afforded by the occluded prime was equivalent to that of the global prime at 700 msec.

Our results at a prime duration of 300 and 700 msec are consistent with evidence suggesting that global processes dominate the completion of occluded objects in adults (Sekuler et al., 1994; de Wit & van Lier, 2002; de Wit et al., 2005). However, our results also differ from previous work studying perceptual completion in four ways. First, we did not find global dominance at a prime duration of 150 and 500 msec, rather, at these durations the occluded object primed both the global and local shapes. Although previous work suggests that alternative versions of the occluded object may be available (e.g., van Lier et al., 1995; Plomp & van Leeuwen, 2006), to our knowledge, this is the first study to show that the occluded object can prime both the global and local shapes simultaneously.

Second, at 300 msec, but not 700 msec, the priming patterns between the occluded prime and global prime differed. There are two possibilities that may account for the observed differences at 300 and 700 msec. The first possibility is based on the flexibility of the completion process (e.g., de Wit & van Lier, 2002; Kellman, 2003b). Although the occluded object was completed globally, the interpolated edges may not be identical to the global shape, and if so, priming would be weaker than that produced by the global prime, as we observed at 300 msec. The second possibility is based on the priming afforded by the global and occluded prime on the global shapes. The priming effect of the occluded prime on the global shapes is slightly stronger at 700 msec (33.1 msec) than at 300 msec (24.6 msec), whereas, the priming effect of the global prime on the global shapes is weakened over time (300 msec: 64.4 msec and 700 msec: 50.33; Figure 6). Therefore, at 700 msec priming patterns between the global and occluded prime did not differ statistically. In conjunction, these two possibilities may explain our results at 300 and 700 msec.

Third, previous research has shown that for line drawing versions of the current shapes, adults completed the occluded object globally at 500 msec (de Wit & van Lier, 2002; de Wit et al., 2005). However, we found that at 500 msec the occluded object primed both the global and local representations. An important difference between these previous studies and our study is that we tested filled figure versions of the occluded object. Filled figures provide additional depth cues that may affect processing of the occluded shape. However, it is not clear how the addition of depth cues promotes local completion. An important next step would be to test a line drawing version of our stimuli at 500 msec, to determine whether the differences between the results of our study and those of de Wit and van Lier (2002) and de Wit et al. (2005) were a result of the type of stimuli used.

Fourth, although the global prime always facilitated response times for the global same test pair, the local prime did not significantly prime the local same test pair at longer prime durations (500 and 700 msec). The priming afforded by the local prime on the local same test pair decreased steadily over time, and surprisingly, the local prime sped up response times for the global same test pair at a prime duration of 700 msec. As the duration of exposure to the object increases, local processes may have less influence on the representation of objects. For example, at longer durations higher cognitive processes may have greater influence on the processing of the prime (Sekuler & Murray, 2001). In addition, since the local completion is irregular, it may take longer to process the shape at either the visual processing or decision processing stage. Furthermore, although priming effects are based on the similarity of the prime and the test pair, at longer prime durations, the prime may be able to facilitate shapes that are in the same general category (i.e., star-like), rather than to shapes that are only structurally identical (e.g., Miller, Li, & Desimone, 1993). It would be interesting to determine whether shapes that are not consistent with real-world experiences or expectations are also actively inhibited by feedback connections. Together, these various changes in processing over time may explain the observed shift in the priming afforded by the local prime.

Consistent with previous literature, although we did not find any support for local theories of completion, we did find some support for global theories of completion (e.g., Sekuler et al. 1994; de Wit & van Lier, 2002). I will discuss the evidence for these two theories in turn. Purely local theories of completion predict that the level of priming afforded by the occluded prime should be equivalent to that afforded by the local prime. At all prime durations tested, the occluded object either primed the global same test pair (300 and 700 msec) or equally primed the local and global same test pairs (150 and 500 msec).

Unlike local theories of completion, we found some support for purely global theories of completion. Purely global theories of completion predict that the level of priming afforded by the occluded prime should be equivalent to that afforded by the global prime. Although we did observe global dominance at 300 and 700 msec, only at the longest prime duration (700 msec) was the magnitude of the priming effect similar between the occluded and global prime. Neither global theories of completion, nor local theories of completion can account for the simultaneous priming of both the local and global shapes by the occluded prime.

Overall, these results suggest that neither a purely global theory nor a purely local theory of completion can account for the completion of complex occluded objects in adults. Our data support integrative models of completion, because these models take the complexity of both the global and local solutions into account (e.g., Sekuler, 1994; van Lier et al., 1994). Integrative models also suggest that both local and global solutions can be processed in parallel (Sekuler, 1994), which would be consistent with our results at 150 and 500 msec.

Development of Perceptual Completion

Although there is evidence for the type of processes that facilitate completion of simple and complex occluded objects in adulthood, little is known about the development of this process in childhood. Therefore, in Experiment 2 we tested 8- and 11-year-olds on the same rigorous paradigm that adults completed in Experiment 1.

Several studies have examined the completion of occluded objects during infancy. Infants, as young as 2 months of age, behave as if they perceive the separate visible portions of a partly occluded object as being part of the same object (e.g., Johnson & Aslin, 1995). However, young infants will show evidence of completion only when the occluded object is defined by motion (Craton, 1996; Jusczyk, Johnson, Spelke, & Kennedy, 1999). In these experiments, infants were habituated to a stationary rod, the centre of which was hidden behind a rectangle, and then were shown test displays of either a complete rod or two-rod pieces separated by a gap where the rectangle had previously been. The assumption is that infants will look longer at whichever test rod appeared novel—that is, most unlike the occluded display. For stationary displays, 4- and 5.5-month-old infants looked equally long at the complete rod and two-rod pieces (Craton, 1996; Jusczyk et al., 1999). By 6.5 months of age, infants looked longer at the two-rod-pieces, suggesting that they perceived the occluded object as a complete rod. However, when motion cues were provided (i.e., the rod moved back and forth behind the occluder), infants as young as 2 months of age looked longer at the two-rod pieces, suggesting that they perceived the occluded rod as a complete rod (Johnson & Aslin, 1995). These data suggest that infants as young as 2 months can interpolate the contours of occluded objects so long as they are defined by motion (Johnson & Aslin, 1995; Craton, 1996; Jusczyk et al., 1999).

The age at which completion of partly occluded objects first appears also varies with the amount of occlusion. Infants habituated to a moving rod-box-display, were then shown a complete rod or two-rod-pieces. Two-month-old infants looked at the two-rod pieces when 26% of the rod had been occluded during habituation (Johnson & Aslin, 1995), but looked equally long at the complete and two-rod pieces when 41% of the rod had been occluded during habituation (Johnson & Náñez, 1995). However, 4-month-olds provided evidence of seeing a unified rod during habituation even with widely separated pieces (38.5% occlusion; Johnson & Aslin, 1996). Therefore, the ability to perceive partly occluded objects as complete shapes during infancy depends on both the spatial proximity of the parts of the occluded object and the availability of motion information.

Infants also perceive partly occluded objects that undergo periods of occlusion as complete objects. Johnson et al. (2003) habituated 2-, 4-, and 6-month-olds to a ball-and-box stimulus in which a ball moved back and forth, sometimes being occluded by a stationary box and at other times appearing beside the box. In test displays, the stationary box was removed and either a continuous trajectory (i.e., ball always visible) or discontinuous trajectory (i.e., ball went out of, and back into, view as in the habituation trial but without the occluder present) was shown. Two-month-olds looked equally long at the discontinuous and continuous moving displays. In contrast, 6-month-old infants looked longer at the discontinuous test display, providing evidence of seeing a continuous moving object during habituation. Four-month-olds showed an intermediate level of performance: they looked longer at the discontinuous test display when the ball was occluded for short but not long durations. Together, these results demonstrate that perception of unified occluded objects depends on the age and the size of the occluded region across which completion is required.

Local and global processes for the completion of ambiguous partly occluded objects have also been studied in infancy. Four-month-olds habituated to a star-like object hidden behind a rectangle (Figure 1A) were then shown a test display with a locally (Figure 1B) and globally (Figure 1C) completed version of the occluded object (de Wit, Vrins, Dejonckheere, & van Lier, 2008). Infants looked longer at the globally completed shape, suggesting that they had completed the shape locally during habituation (de Wit et al., 2008).

Although there is some evidence for a change in the type of processing that facilitates perceptual completion of partially occluded objects between infancy (de Wit et al., 2008) and adulthood (e.g., Sekuler et al., 1994; de Wit & van Lier, 2002), little is known about the development of this process between these ages. Only one study to date has examined development after infancy. In that study, one group of 28 normally developing male children (control group) aged 9 to 13 years was compared to age-matched children with pervasive developmental disorder (PDD; de Wit, Schlooz, Hulstijn, & van Lier, 2007). Stimuli like those shown in Figure 1 were used in a prime-matching task. Subjects saw one of three primes for 500 msec: an occluded star-like object, a globally completed object, or a locally completed object. A test pair followed the prime and subjects judged whether the two items were the same or different. For both the control group and children with PDD, the occluded prime and the global prime facilitated response times for the global same test pair. Thus, similar to adults, the children completed occluded objects globally. Together, these results suggest a change from local to global completion between infancy and 9 – 13 years of age (de Wit et al., 2007).

Although de Wit et al. (2007) provide some evidence for global processing of partly occluded objects in children, the study has several limitations. First, the study included only a total of 28 children across a broad age-range (9 to 13 years of age), and thus cannot provide any information on the development of the perceptual completion process during this period. Second, it is unclear whether children between 9 to 13 years of age are adult-like in perceptual processing of occluded objects, because the time course of completion has not been studied in children. For example, although children completed the partly occluded object globally, they may require more processing time than adults to do so. Moreover, there was no adult comparison group in that study. Hence, one objective of the present study was to compare the relative influences of global and local processes in the completion of a complex partially occluded object in children (8- and 11-year-olds) and adults. The second objective of this study was to investigate the representation of the occluded object at an early and late stage of visual processing in children.

In the present study, we used a prime-matching task to compare the completion of a partly occluded object in children and adults. We tested two groups of children: 8- and 11-year-olds. We chose these ages because several lines of evidence show that many aspects of higher-level vision improve during this age period. For example, children's ability to integrate relatable contours embedded in background noise improves between 5 -14 years of age (Kovâcs, 2000; Hadad, Maurer, & Lewis, 2010a). Second, 10-year-olds, but not 5-year-olds, are influenced by collinearity in the perceptual grouping of shapes (Hadad & Kimchi, 2006; Hadad et al., 2010a). Third, sensitivity to global structure in hierarchical stimuli improves between late childhood to early adolescence (Mondloch, Geldart, Maurer, & de Schonen, 2003; Scherf, Behrmann, Kimchi, & Luna, 2009). Fourth, sensitivity to global form in glass patterns becomes adult-like between 6 and 9 years of age (Lewis et al., 2004). Fifth, sensitivity to subjective shapes is not adult-like even at 12 years of age (Hadad, Maurer, & Lewis, 2010b). All of these results suggest that systems integrating local information into global shapes are changing between 8 and 11 years of age.

We tested children in a subset of the conditions used with adults in Experiment 1. In Experiment 2A, we tested 20 8-year-olds at a prime duration of 700 msec, because we expected that it would take children longer than adults to complete complex partly occluded objects. However, the prime-matching task was not sensitive enough to detect priming effects in this age group at this prime duration. Therefore, in Experiment 2B we tested two groups of 30 11-year-olds, one at a prime duration of 300 msec and the other at a prime duration of 700 msec. We then compared their results to those from adults tested on the same conditions in Experiment 1.

Experiment 2A: Perceptual completion in 8-year-olds

Methods

Participants

The final sample consisted of 20 8-year-olds (mean age = 7.74 years; range = 7.1 – 8.0 years). All children had normal or corrected-to-normal vision and passed the same mandatory visual screening examination described in Experiment 1. Children were recruited from a database that contained a list of parents who were willing to be contacted about research studies. Eight-year-olds received a toy for their participation. An additional 14 8-year-olds were excluded from the final sample: 12 because they failed visual screening, one because he did not complete both sessions, and one because he was out of age range.[4]

Procedure

The apparatus, stimuli and procedure were identical to those described in Experiment 1, except for the following changes: 1) we obtained informed consent

[4] Most of these children did not pass visual screening because of a small acuity deficit that we could not correct with our visual screening protocol. However, we attempted to correct vision only with spherical lenses that increased in half dioptre steps up to -2 dioptres. Those who did not meet our acuity criterion likely had residual refractive errors.

from parents of children, 2) 8-year-olds were tested at a prime duration of 700 msec, and 3) children completed the study in two 1-hour sessions, within a 2-week period.

Results

Analyses were conducted on correct responses for categorizing same test pairs (global same and local same). We used the same outlier removal procedures described in Experiment 1 to calculate a mean response time and to replace subjects with high error rates. Two subjects had to be replaced for making more than 7% and 16% errors in the experiment. We did not find any significant speed/accuracy tradeoffs. All subsequent analyses were conducted on the revised data set and we used Greenhouse-Geisser values when the assumption of sphericity was violated to correct for this violation.

Eight-year-olds were very accurate in this task: mean error rate was 2.84% (range = 0 – 7.29%). We analyzed accuracy data using a repeated measures ANOVA with prime type and test pair as within-subject factors. A significant main effect of test pair was found ($F(1, 19) = 18.60$, $p < 0.001$, $\eta_p^2 = 0.50$). Eight-year-olds made fewer errors when categorizing the global same test pair (1.15%) than the local same test pair (4.53%), similar to adults (0.78% and 5.30%, respectively).

To determine whether 8-year-olds were faster at categorizing one of the two test pairs (global same and local same), independent of priming, we conducted a repeated measures ANOVA for the no prime condition with test pair as a within-subject factor. There was a significant main effect of test pair (F (1, 19) = 22.77, p < 0.001, η_p^2 = 0.55). Subjects were faster at categorizing the global same test pair (1152.57 msec) than the local same test pair (1276.95 msec). Since children responded faster to the global same test pair than the local same test pair, we calculated a priming effect (Equation 1), as previously described in Experiment 1.

A repeated measures ANOVA was conducted to analyze priming effects, with prime type (local, global, occluded) as a within-subject factor. There was no significant main effect of prime type (F (2, 38) = 1.39, p = 0.26, η_p^2 = 0.07). The global, local, and occluded primes did not significantly prime either the global same or local same test pair (Global: t (19) = -0.14, p > 0.80, Local: t (19) = -1.70, p > 0.10, Occluded: t (19) = 0.44, p > 0.50) in 8-year-olds (see Figure 9).

Discussion

We examined the representation of a complex occluded object in 8-year-olds by showing them one of four primes (global, local, occluded, and no prime) at a prime duration of 700 msec. We found that, the global, local, and occluded prime did not speed up response times to either the global same or local same test pair. Since the global prime and local prime did not speed up response times for their respective test pairs, we assume that the prime-matching task may not be sensitive enough to detect priming effects in children as young as 8 years of age.

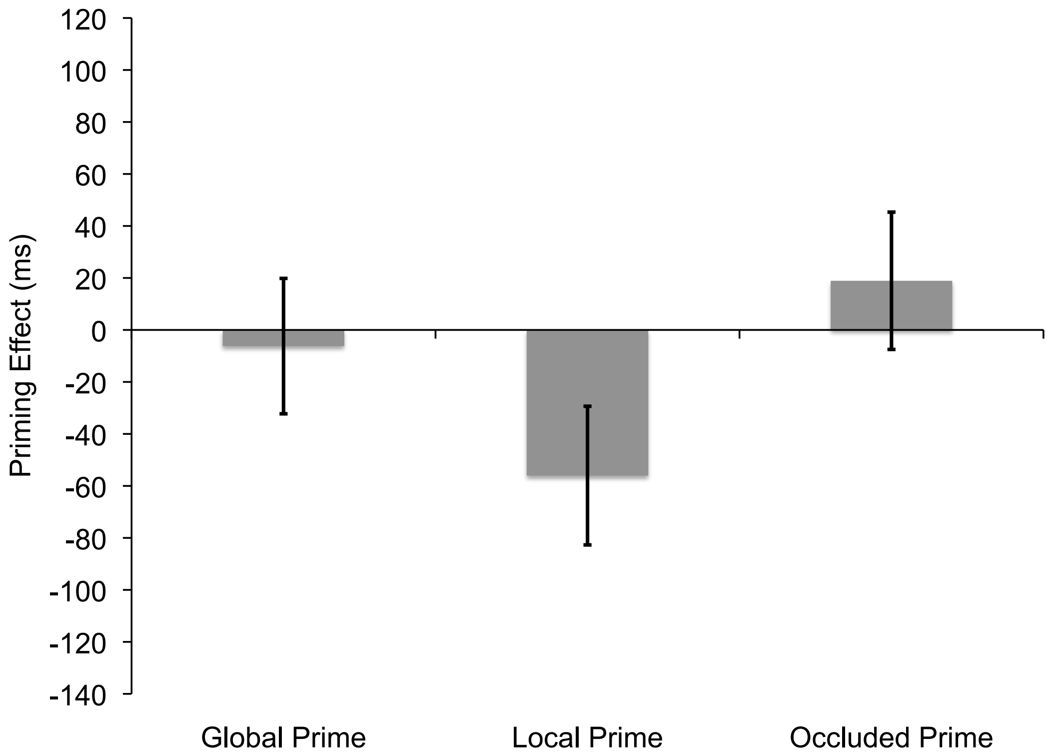

Figure 9: Mean priming effects, in milliseconds, as a function of prime type in 8-year-olds tested at a prime duration of 700 msec. Error bars represent ±1 standard error.

There are several reasons that may explain the lack of priming in 8-year-olds. First, response times are generally much slower in 8-year-olds than in adults (Kail, 1991). In this study, for example, the average response time in the baseline condition at 700 msec was 1214.76 msec in 8-year-olds and 559.88 msec in adults. The longer response times are consistent with evidence suggesting that children generally require more time to process information (Kail, 1991; Kail & Ferrer, 2007). In addition, response times were more variable in children than in adults. Since the prime-matching paradigm relies on measurable differences between baseline response time and a primed response time, it is plausible that this difference is not large enough to be detectable when responses are already relatively slow and variable.

Second, an important assumption of the prime-matching task is that response times should be faster for test pairs that are similar to the prime than those that are not (Sekuler et al., 1994). However, in 8-year-olds, the global prime and the local prime did not speed up response times for the global same and local same test pair, respectively. Even in adults (Experiment 1), at longer prime durations (500 and 700 msec) we did not observe basic shape priming for the local prime. In adults, at a prime duration of 700 msec the local prime facilitated response times for the global same test pair, perhaps because of top-down influences. It is possible that at a shorter prime duration (e.g., 300 msec) we may be able to measure priming effects that are less influenced by higher cognitive processes, and thus probe visual processing of the occluded object more accurately.

Third, to our knowledge, only one study to date has tested 8-year-olds using the prime-matching paradigm (Scherf et al., 2009). However, in that study, 15 children across a broad age range were tested (8 to 13 years of age; mean age = 11 years), and therefore, we cannot conclude that the prime-matching paradigm will provide reliable results from 8-year-olds. For these reasons, in Experiment 2B we tested older children.

Experiment 2B: Perceptual completion process in 11-year-olds

In Experiment 2B, we tested 11-year-olds at two prime durations. We chose to test 11-year-olds because the prime-matching paradigm has been shown to provide reliable results in this age group (e.g., de Wit et al., 2007, Scherf et al., 2009). Moreover, previous literature suggests that 11-year-olds may process occluded objects globally, at least at a prime duration of 500 msec (de Wit et al., 2007). We used prime durations of 300 and 700 msec in separate groups of 11-year-olds to tap into the representation of the occluded object during early and late stages of visual processing, respectively. Although we did not observe any clear patterns of priming in 8-year-olds at 700 msec, it is possible that this prime duration will yield good priming effects at an older age with less variable response times.

Methods

Participants

The final sample consisted of two groups of 11-year-olds (n = 30 per group), one group tested at a prime duration of 300 msec (mean age = 10.86 years; range = 10.1 – 11.1 years) and one group tested at a prime duration of 700 msec (mean age = 10.76 years; range = 10.1 – 11.1 years). We compared their results to the subset of adults tested in Experiment 1 at the same prime durations (mean age = 20.75 years; range = 18.0 – 28.1 years; n = 36 per condition). Contact information and inclusion criteria for children were identical to those described in Experiment 2A. For their participation, 11-year-olds received either a book or a $10 gift certificate for the bookstore. An additional five 11-year-olds were excluded from the final sample because they failed visual screening.

Procedure

The apparatus, stimuli and procedure were identical to those described in Experiment 1, except that: 1) we obtained informed consent from parents of children and informed assent from children and 2) each 11-year-old was tested on only one of two prime durations: 300 or 700 msec.

Results

Analyses were conducted on correct responses for categorizing global same and local same test pairs. We used the same outlier removal procedures described in Experiment 1 to calculate a mean response time and to replace subjects with high error rates. Three 11-year-olds had to be replaced for making too many errors in the experiment: one at a prime duration of 300 msec (11% error) and two at a prime duration of 700 msec (13% and 15% errors). We did not find any significant speed/accuracy tradeoffs. All subsequent analyses were conducted on the revised data set and we used Greenhouse-Geisser values when the assumption of sphericity was violated to correct for this violation. Data from 11-year-olds were compared to the subset of adults who had been tested at a prime duration of 300 and 700 msec in Experiment 1.

Eleven-year-olds were very accurate in this task: the mean error rate was 4.03% (range = 0 – 11.5%) and 4.15% (range = 0 – 9.9%), for prime durations of 300 msec and 700 msec, respectively. Accuracy was analyzed with a mixed-design ANOVA, with prime type and test pair as within-subject factors, and age and SOA as between-subject factors. There was a significant main effect of prime type ($F(3, 384) = 6.50$, $p < 0.001$, $\eta_p^2 = 0.05$), test pair ($F(1, 128) = 147.25$, $p < 0.001$, $\eta_p^2 = 0.54$), and a marginally significant main effect of age ($F(1, 128) = 3.16$, $p = 0.078$, $\eta_p^2 = 0.02$). Error rates were greater for 11-year-olds (4.09%) than adults (3.30%). A significant two-way interaction between prime type and test pair was also found ($F(3, 384) = 8.29$, $p < 0.001$, $\eta_p^2 = 0.06$), which did not interact further with age ($p > 0.10$). Although error rates were higher for the local same test pair than the global same test pair for all prime types (Baseline: $t(131) = 7.51$, $p < 0.001$, Global: $t(131) = 10.57$, $p < 0.001$, Local: t

(131) = 8.33, $p < 0.001$, Occluded: t (131) = 7.90, $p < 0.001$), this difference was greater for the local prime. No other main effects or interactions reached significance (*p*s > 0.10).

To determine whether 11-year-olds were faster at categorizing one of the two test pairs (global same and local same), independently of the prime, a repeated measures ANOVA was conducted for the no prime condition, with test pair as a within-subject factor and SOA (300 and 700 msec) as a between-subject factor. A significant main effect of test pair ($F (1, 58) = 29.74$, $p < 0.001$, $\eta_p^2 = 0.34$) was found, in which subjects were faster at categorizing the global same test pair (873.06 msec) than the local same test pair (969.36 msec). There was no significant main effect of SOA ($p > 0.05$), nor an interaction between test pair and SOA ($p > 0.50$). Since 11-year-olds responded faster to the global same test pair than the local same test pair, we calculated a priming effect (Equation 1), as previously described in Experiment 1. These results are identical to the pattern of results observed in adults in Experiment 1.

A repeated measures ANOVA was conducted to analyze priming effects, with prime type (local, global, and occluded) as a within-subject factor, and age group and SOA as between-subject factors. There was a significant main effect of prime type ($F (1.84, 235.15) = 46.69$, $p < 0.001$, $\eta_p^2 = 0.27$) and a marginally significant main effect of age group ($F (1, 128) = 3.65$, $p = 0.058$, $\eta_p^2 = 0.03$). These effects were qualified by a significant two-way interaction between prime type and SOA ($F (1.84, 235.15) = 24.89$, $p < 0.001$, $\eta_p^2 = 0.16$), and a significant three-way interaction between prime type, age group and SOA (F (1.84, 235.15) = 4.38, $p < 0.05$, $\eta_p^2 = 0.03$). No other main effects of interactions reached significance (*p*s > 0.10).

To analyze the three-way interaction further, we conducted separate repeated measures ANOVA for each SOA, with prime type as a within-subject factor and age group as a between-subject factor. At a prime duration of 300 msec, there was a significant main effect of prime type (F (2, 128) = 48.65, $p < 0.001$, $\eta_p^2 = 0.43$) and a significant two-way interaction between prime type and age group (F (2, 128) = 3.81, $p < 0.05$, $\eta_p^2 = 0.06$; see Figure 10). The main effect of age group did not reach significance ($p > 0.10$). To analyze the two-way interaction, we conducted post-hoc analyses for each age group. For 11-year-olds, as for adults, the global prime significantly primed the global same test pair (t (29) = 3.16, $p < 0.005$), and the local prime significantly primed the local same test pair (t (29) = -3.50, $p < 0.005$). However, for 11-year-olds, unlike for adults, the occluded prime showed no significant priming effect (t (29) = 0.24, $p > 0.80$). As shown in Figure 11, the occluded prime did not significantly facilitate response times for either the global same test pair (t (29) = 1.77, $p > 0.05$) or local same test pair (t (29) = 1.11, $p > 0.10$). However, if anything there was a positive facilitation of both the global same and local same test pair. For adults, the occluded object significantly primed only the global same test pair (Experiment 1).

For a prime duration of 700 msec, there was a marginally significant main

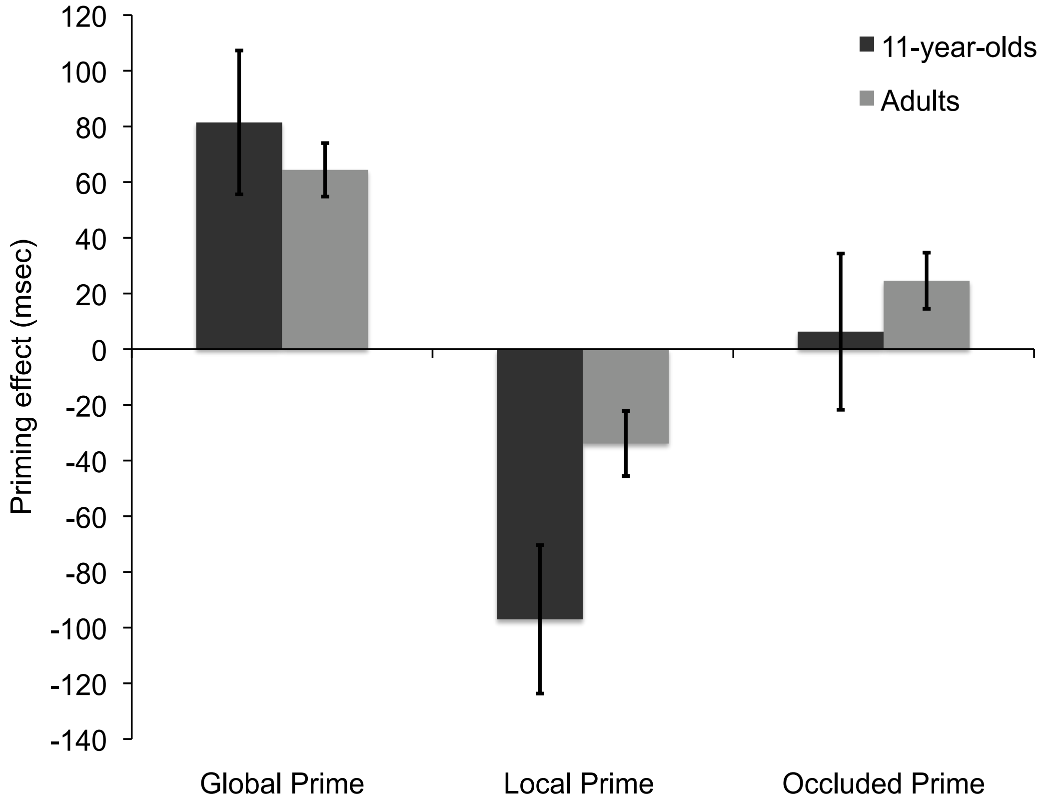

Figure 10: Mean priming effects, in milliseconds, as a function of prime type (global, local, and occluded) in 11-year-olds (dark grey) and adults (light grey) tested at a prime duration of 300 msec. Error bars represent ±1 standard error.

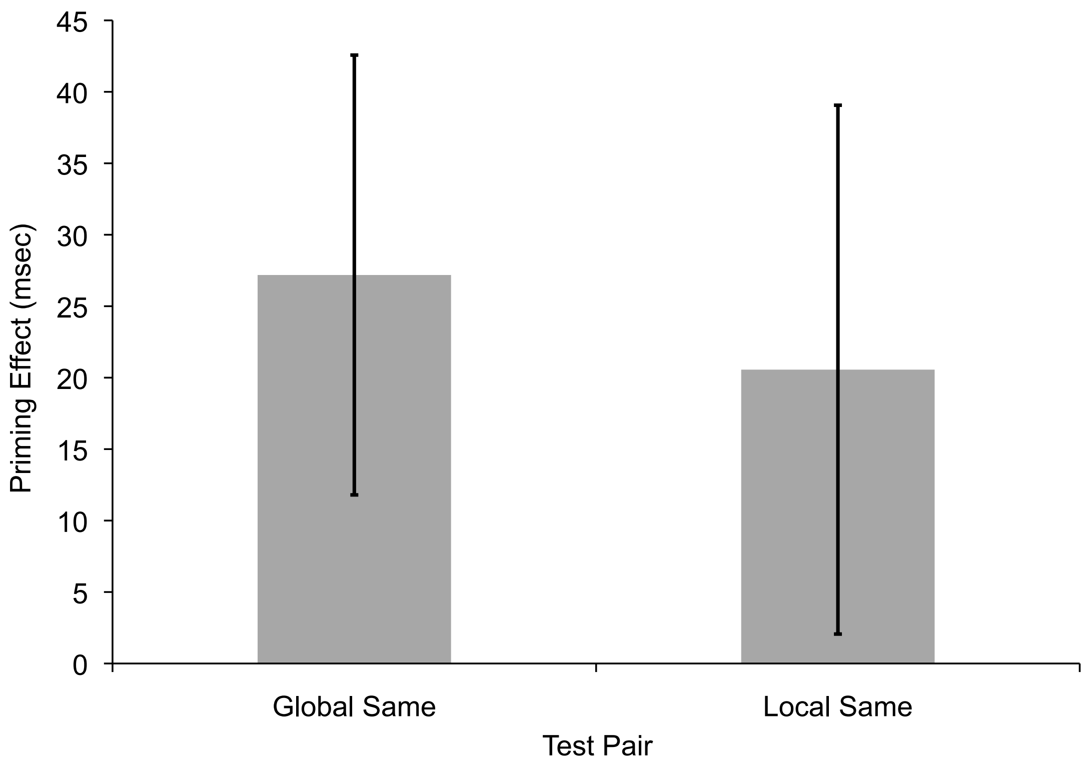

Figure 11: Mean priming effects, in milliseconds, of the occluded prime on the global same and local same test pairs in 11-year-olds tested at a prime duration of 300 msec. Error bars represent ±1 standard error.

effect of prime type (F (1.76, 112.71) = 3.05, $p = 0.058$, $\eta_p^2 = 0.05$). The magnitude of the priming effect differed between the global prime and the local prime (t (65) = 2.25, $p < 0.05$); the occluded prime did not differ from either the local or global prime. There was also a marginally significant main effect of age group (F (1, 64) = 3.96, $p = 0.051$, $\eta_p^2 = 0.06$). The overall priming effect was much weaker in 11-year-olds (2.76 msec) than adults (34 msec). The two-way interaction between prime type and age group did not reach significance (p > 0.10, see Figure 12). The global, local, and occluded primes did not significantly prime either the global same or local same test pair (Global: t (29) = 0.41, $p > 0.50$, Local: t (29) = -0.20, $p > 0.80$, Occluded: t (29) = 0.20, $p > 0.80$) in 11-year-olds (see Figure 12). For adults, the global prime, local prime and occluded prime facilitated response times for the global same test pair (Experiment 1; see Figure 12). The global prime and the occluded prime did not significantly differ from each other.

Discussion

In Experiment 2B, we compared the representation of a complex occluded object during early and late stages of visual processing in 11-year-olds and adults. For 11-year-olds tested at a prime duration of 300 msec, the global prime sped up response times for the global same test pair, and the local prime sped up response times for the local same test pair. We found similar patterns of priming in adults. Consistent with previous literature, these results suggest that children as young as 11 years can be reliably tested with the prime-matching task (de Wit

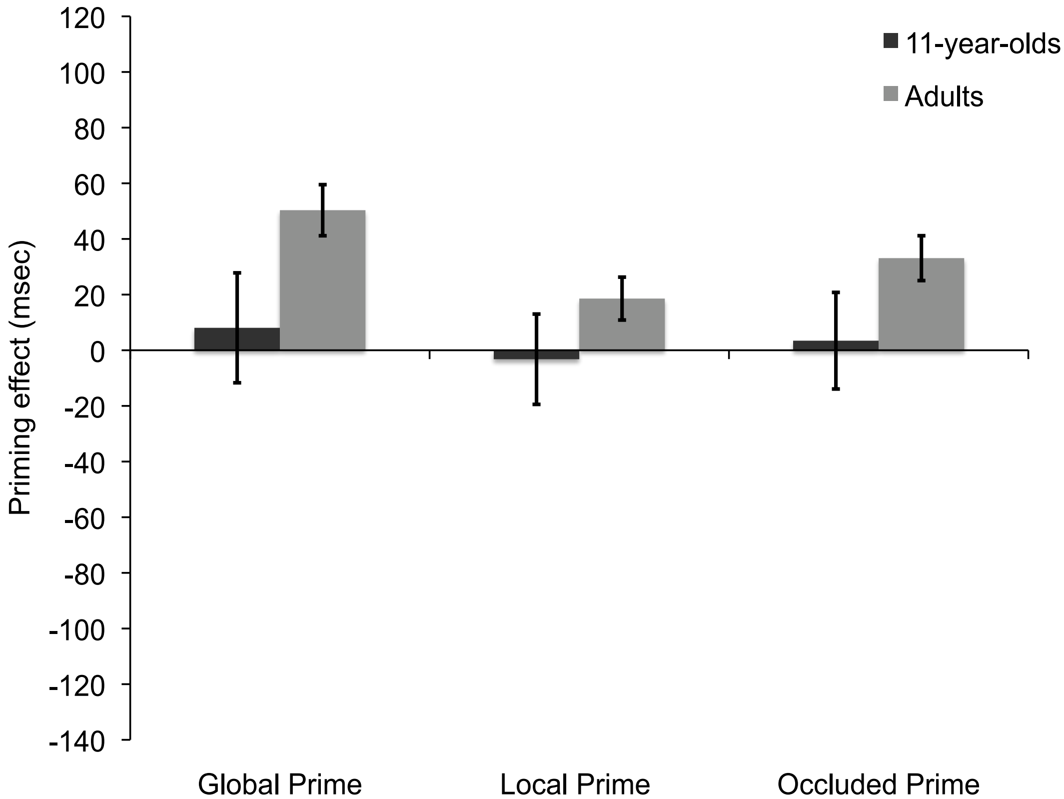

Figure 12: Mean priming effects, in milliseconds, as a function of prime type for a prime duration of 700 msec. Other details as in Figure 10.

et al., 2007).

However, for 11-year-olds, unlike adults, the occluded prime did not significantly prime either test pair when it was presented for 300 msec. Since we did observe basic priming effects in 11-year-olds at 300 msec, we cannot attribute the lack of priming for the occluded condition to the sensitivity of the prime-matching paradigm. One possibility is that 11-year-olds require more time than adults to complete the occluded object. Therefore, we tested a new group of 11-year-olds at a longer prime duration of 700 msec. However, the global, local, and occluded prime did not significantly prime either the global same or local same test pair at this prime duration. Hence, similar to 8-year-olds, we did not find any consistent patterns of priming in 11-year-olds at 700 msec. Below I consider the implications of the priming data from 300 msec before turning to the results at 700 msec.

One possibility is that 11-year-olds did not complete the partially occluded object at 300 msec. However, since we did not test the mosaic representation of the occluded object, we cannot be sure that the occluded object was not completed. A second possibility is that both representations were primed. Although the occluded prime did not significantly facilitate response times for either test pair, the global and local shapes did show positive facilitation, suggesting that both representations may be available in 11-year-olds. This would be consistent with the pattern of priming found at 150 and 500 msec in adults (Experiment 1). If both representations were present in 11-year-olds, this would further support integrative models of completion. A third possibility is that the observed differences between 11-year-olds and adults arise from variations in attention or motivation. However, we minimized these factors by providing frequent breaks and using a child-friendly task. If attention and motivation were responsible for immaturities in children, we expect that priming effects would be weaker across all conditions. The magnitude of the priming effect for the global and local prime were similar between 11-year-olds and adults, suggesting that attention and motivation cannot solely account for differences in the occluded condition.

Previous research suggests that global processes dominate completion in 9- to 13-year-olds by 500 msec (de Wit et al., 2007). However, we did not find evidence for global dominance at shorter (300 msec) or longer (700 msec) prime durations. There are several possible reasons for this discrepancy. First, de Wit et al. (2007) tested children of a broad age range (9- to 13-year-olds), whereas, the current study tested a restricted age range (10.9- to 11.9-year-olds) to measure priming effects more specifically in 11-year-olds. It is possible that younger and older children differ in the amount of time required to complete the occluded object. Second, although we tested prime durations of 300 and 700 msec, we did not test a prime duration of 500 msec directly, the duration which de Wit et al. (2007) tested. Thus, it is still possible that global processes dominate completion in 11-year-olds by 500 msec. For example, although global processes did not dominate completion at 150 msec in adults, by 300 msec global processes did dominate completion. Similarly, although we did not observe global dominance at 300 msec in 11-year-olds, we may be able to observe global dominance by 500 msec. Third, de Wit et al. (2007) tested line drawing versions of the current shapes. It is unclear whether filled figures are processed in the same way as line drawings. Hence, in the future it would be interesting to test a line drawing version of our stimuli to compare more directly our results to de Wit et al. (2007).

There are two possibilities that may explain the lack of priming for 11-year-olds at a prime duration of 700 msec. One reason that priming effects may be difficult to detect in children (8- and 11-year-olds) is because response time are more variable and longer in children. Longer response times reduce the difference between the baseline and primed trials, making it more difficult to detect significant priming (refer to Equation 1). Another possibility is that higher-level processes may influence shorter and longer prime durations differently. In adults, only after 100 msec may feedback connections influence processing (Lamme & Roelfsema, 2000). Since processing times are slower in children, we expect that at shorter prime durations (300 msec) feedback connections influence processing less that at longer prime durations (700 msec). However, it is not clear how these feedback connections influence the processing of the primes. Whatever the explanation, these results suggest that the representation of the occluded object differs in children compared to adults.

General Discussion

The current study investigated the representation of a complex, partially occluded object during early and late stages of visual processing in children and adults. We tested subjects, using a prime-matching task, to calculate the priming effect of the global, local, and occluded prime on the global same and local same test pair. If the occluded prime was represented as a complete global or local shape, it should produce priming effects that are comparable to those of the global or local prime. We compared the magnitude of the priming effect between the global or local prime and the occluded prime only when the occluded prime sped up response times for the global or local same test pair, respectively.

In Experiment 1, we tested adults and found that the representation of the occluded object varied with the duration of exposure. At the earliest stage of processing we tested (150 msec), the occluded object primed both the global and local completions. By 300 msec, although the occluded object primed only the global completion, the magnitude of the priming effect was weaker than that produced by the global prime. Surprisingly, at a prime duration of 500 msec, the occluded object once again primed both the global and local completions.[5] We

[5] For the 150 and 500 msec prime duration conditions, we did not compare the magnitude of the priming effect of the occluded prime to that of the global prime or local prime. We compared the magnitude of the priming effect to evaluate whether our results are consistent with purely global or purely local theories of completion, since these theories predict priming patterns to be similar between the occluded condition and the global and local conditions, respectively. However, neither of these theories predicts simultaneous priming of both the global and local shapes, and therefore we did not compare the magnitude of the priming effect at 150 and 500 msec.

observed a re-emergence of the global dominance at the longest prime duration tested (700 msec). In fact, only at 700 msec was the magnitude of the priming effect similar between the occluded prime and the global prime.

Our findings at 300 and 700 msec are consistent with previous evidence suggesting that, under various testing conditions, global processes can dominate the completion of both simple and complex occluded objects in adults (e.g., Sekuler et al., 1994; de Wit & van Lier, 2002). This seems to be true for both line drawings (de Wit & van Lier, 2002; de Wit et al., 2005) and filled figures (Sekuler, 1994; Sekuler et al., 1994). Global processes dominate completion of occluded objects that are not only highly symmetrical (Sekuler, 1994; Sekuler et al., 1994) but also irregular (e.g., de Wit & van Lier, 2002). For stimuli similar to those tested in this study, de Wit et al. (2005) have shown that at a prime duration of 500 msec, global processes dominate completion regardless of the overall size of the occluded object. In addition, although these studies tested different processing times (i.e., between 150 to 1000 msec), adults consistently completed the occluded objects globally (e.g., Sekuler et al., 1994; de Wit & van Lier, 2002; de Wit et al., 2005).

Our results differ from one previous study that has tested filled figures at a prime duration of 300 msec. We found that although the occluded object primed the global shapes, the priming effect was not as strong as that following the global prime. In contrast, Sekuler et al. (1994) found that the occluded object primed the global shapes as strongly as the global prime. There are three major differences between the previous study and the current study. First, the occluded object in our study is more complex (i.e., star-like object) than that tested by Sekuler and colleagues (i.e., circle with four knobs at corners). The completed edges of the star-like occluded object may not be as precisely defined as that of the four-knob occluded circle. Second, the occluded objects differed in the number of repeated units. In our study, when the occluded object was completed globally, it was composed of nine repeated units; whereas, the occluded object in the previous study was composed of four repeated units. Third, Sekuler et al. (1994) tested a symmetrical occluded object (four axes of symmetry), whereas, we tested an irregular figure. These overall differences in stimuli may contribute to the observed differences in priming effects. One possibility is that the occluded star-like object, used in our study, may require additional processing because it is a more complex shape.

Our results at 150 and 500 msec are not consistent with previous literature (Sekuler, 1994; Sekuler et al., 1994; de Wit & van Lier, 2002; de Wit et al., 2005). For example, previous research suggests that the occluded object is completed globally as early as 300 msec for filled figures, and as early as 150 msec for line drawings (Sekuler et al., 1994). However, for the filled figures we tested, both the global and local representations of the occluded object were primed at 150 and 500 msec.

Interestingly, for the occluded condition, the magnitude of the priming effects that we observed at 150 and 500 msec were similar to those reported by

Sekuler and colleagues at 150 and 400 msec (Sekuler, 1994; Sekuler et al., 1994). In those studies, rather than testing whether the primes significantly facilitated the global or local shapes, the authors compared the pattern of priming between the occluded and global or local conditions. Since the direction of the priming effect for the occluded condition was positive, the authors interpreted those results as suggesting that the occluded object facilitated global shapes. However, based on visual inspection of their figures, we suspect that the priming effects reported by Sekuler et al. (1994) at 150 msec and Sekuler (1994) at 400 msec were likely not significantly different from zero. Therefore, had these authors tested if the occluded prime significantly facilitated decisions about the global shape, they may have found that the magnitude of the priming effect did not differ significantly from zero. If the priming effect did not differ significantly from zero it could mean one of two things: 1) the occluded object did not prime either the global or the local shape or 2) the occluded object primed both shapes equally (Sekuler, 1994; Sekuler et al., 1994). If these authors found significant priming of both the global and local shapes at 150 and 400 msec, this would be consistent with our results at 150 and 500 msec. It is important to note that these predictions would not explain all of the results from Sekuler (1994) and Sekuler et al. (1994).

Our finding that the occluded prime facilitates both the global and local representations at some prime durations (150 and 500 msec), suggests that both representations may be available. The pattern of priming we observed at 150 and 500 msec are consistent with the idea of parallel processing, since both the global and local representations were primed by the occluded object at these durations. Several lines of evidence indicate that alternative versions of the occluded object are available (van Lier et al., 1995; Sekuler & Murray, 2001; Plomp & van Leeuwen, 2006). For example, during the process of completion, context can affect the chosen representation of an occluded object. If subjects were shown the global solution before the presentation of the occluded figure, the global shape was primed; however, if the local solution was presented before the occluded figure, then the local shape was primed (Plomp & van Leeuwen, 2006). Consistent with these results, we found that at both 150 and 500 msec the occluded object could be represented as either a global or local shape.

Our results are not consistent with previous studies that have tested a line drawing version of the current shape at 500 msec (e.g., de Wit & van Lier, 2002; de Wit et al., 2005). The present study found that for filled figures, both the global and local completions were primed at 500 msec. In contrast, others have found that the occluded figure consistently primed the global same test pair at 500 msec (de Wit & van Lier, 2002; de Wit et al., 2005). The discrepancy between previous studies and our results may be related to the design of the stimuli. Filled figures may make repeated units more obvious and may provide additional depth cues, compared to line drawing versions of the same shape. However, it is unclear how these cues would facilitate local completion. In addition, Sekuler et al. (1994) have shown that filled figures take longer to complete than their line drawing equivalents. For line drawings, priming effects did not differ significantly between the global and occluded prime at 150 msec. In contrast, for filled figures, priming effects did not differ significantly between the global and occluded prime until 300 msec. Therefore, filled figures may take longer to process than line drawings. Based on these findings, it would be interesting to test both line drawing and filled versions of our stimuli in the same subjects.

Another difference between previous studies and our study is the amount of occlusion. In the current study, we tested only one amount of occlusion (i.e., 20%). Previous studies have shown that the amount of occlusion can affect the type of completion (e.g., van Lier et al., 1995) and the amount of time required for completion (Guttman et al., 2003). For example, van Lier et al. (1995) tested the effect of the amount of occlusion on the perception of occluded objects. Two subsets of an occluded object were created, for Subset 1, a small amount of a symmetrical shape was occluded, whereas, for Subset 2, a relatively large part of the shape was occluded.[6] For both subsets, the global completion was the same, but the local completion differed. Subjects asked to draw the occluded portion of the shape completed the shape globally when the amount of occlusion was small. However, when the amount of occlusion was increased subjects completed the shape locally. Therefore, the type of occlusion can also affect

[6] The authors did not indicate what percentage of the object was occluded. The position of the occluder also varied between the two conditions of occlusion. Therefore, the observed differences may be a result of either the change in position of the occluder or the amount of occlusion.

completion. It is important to note that the amount of occlusion in the stimuli used by de Wit & van Lier (2002) and de Wit et al. (2005) is unclear, and thus the different outcomes at 500 msec between our study and these two studies may be attributable, at least in part, to differences in the amount of occlusion.

In the current study, although we were primarily interested in the occluded condition, we also had specific expectations for the global and local conditions. Based on the logic of the current paradigm, the global prime should facilitate decisions about the global shapes and the local prime should facilitate decisions about the local shapes (i.e., basic shape priming). At a prime duration of 150 and 300 msec, we observed basic shape priming for the global and local prime. However, at a prime duration of 500 msec, the local prime sped up responses to the local same test pair only marginally. Surprisingly, at 700 msec the local prime began to speed up response times for the global same test pair. Unlike the local prime, at all prime durations, the global prime sped up decisions about the global same test pair. Thus, as the prime duration increased, the priming effect of the local prime on the local same test pair steadily decreased. To our know knowledge, none of these previous studies that included a no prime condition tested priming effects for the local prime beyond 400 msec for filled figures and beyond 500 msec for line drawings (Sekuler 1994; Sekuler et al., 1994; de Wit &

van Lier, 2002; de Wit et al., 2005).[7] For these studies (Sekuler 1994; Sekuler et al., 1994; de Wit & van Lier, 2002; de Wit et al., 2005), unlike the pattern of priming we observed at 700 msec, the local prime consistently sped up response times for the local shapes.

There are two possibilities that in conjunction may account for the observed reduction of basic shape priming by the local prime as the duration of the prime increased. First, as exposure time increases, the prime may be able to speed up responses to shapes that are in the same category as the prime (i.e., star-like), rather than to shapes that are only structurally identical. For example, matching stimuli or stimuli that were similar to the sample, reduced activity of neurons in the anterior inferior temporal cortex (indicating adaptation) more so than stimuli that were less similar to the sample (Miller et al., 1993).[8] Although this tendency was not significant statistically, it suggested that reduction in neuronal activity following a non-matching test stimulus might be related to the similarity of the test stimulus to the sample (Miller et al., 1993). Hence, priming

[7] Note however, that although Sekuler et al. (1994) tested a prime duration of 1000 ms, they did not account for the baseline response time (i.e., no prime condition) for sorting symmteric same and assymetric same test shapes. A no prime condition is critical for the interpretation of the results because differences in mean response time between conditions may be attributable to an inherent difference in response time to symmetric versus asymmetric test shapes. For example, it has been shown that symmetric shapes are responded to faster than asymmteric shapes (Garner, 1974).

[8] The inferior temporal cortex of monkeys (Kovács, Vogels, & Orban, 1995) resembles the lateral occipital complex of humans (Kourtzi & Kanwisher, 2001; Lerner et al., 2002; Liu et al., 2006), in that both brain regions have neurons that respond to the completed form of occluded objects.

may be possible for shapes that are not only a match to the prime but also similar to the prime.

Second, as the duration of exposure to the object increases, top-down factors, such as attention, familiarity, additional depth cues, amount of occlusion, and context, can influence the speed with which the object is processed (for a review see Sekuler & Murray, 2001). In the current study, the global completion of the occluded star-like object was a “complete star”, whereas the local completion was a “half-star” (see Figure 3). The global solution was not only a regular shape, but also a shape that would be consistent with real world experiences (i.e., star). Top-down factors, such as familiarity, have been shown to increase the firing rate of neurons (see Engel, Fries, & Singer, 2001). Such top-down factors may increase the processing speed for the global shape. In contrast, the processing speed of the local solution may be slowed down because this shape is irregular. In this study, for the baseline condition, at all SOAs subjects were significantly slower at categorizing the local same shapes (695.22 msec) than the global same shapes (617.92 msec), suggesting that processing times may be longer for local shapes. Therefore, if the local prime facilitated similar shapes, which takes less time, and the processing speed for global shapes was shorter, it is not surprising that the local prime facilitated the global same test pair at 700 msec. However, although these predictions are consistent with our results at 700 msec, it is not clear why these predictions would not be true for shorter prime durations.

The pattern of results from adults is not consistent with local theories of completion and is only partially consistent with global theories of completion. Here I will consider the implications of the results for each theory in turn. Purely local theories of completion predict that the level of priming afforded by the occluded prime should be equivalent to that afforded by the local prime on the local same test pair (Kellman & Shipley, 1991, 1992). In addition, local theories do not predict simultaneous priming of both the local and global completions by the occluded prime. For all prime durations tested, the occluded prime facilitated either both the local and global completions (150 and 500 msec) or only the global completion (300 and 700 msec). Therefore, even at the shortest prime duration tested (150 msec), we failed to find evidence for a dominance of local processes. However, local processes may dominate completion under conditions different from those tested here. One possibility is that local processes influence the completion of occluded objects during the initial stages of visual processing. To our knowledge, no previous study has tested prime durations shorter than 150 msec when investigating global and local processes in completion. Therefore, examining the completion of a complex occluded object between 50 – 100 msec would allow evaluation of whether there are presentation times at which local processes dominate perceptual completion. However, the current paradigm may not be suitable for such investigations because it is difficult to detect priming effects at very short prime durations (Sekuler & Murray, 2001).

A second possibility is that local processes dominate completion of some types of occluded figures but not the quasi-regular figures tested in this study. In a prime-matching task, Sekuler (1994) tested the representation of an occluded object that had two-way or four-way symmetry at a prime duration of 400 msec. For the two-way symmetry condition, the occluded prime facilitated the local same test pair. The magnitude of the priming effect did not differ between the occluded prime and the local prime. However, for the four-way symmetry condition, the occluded prime facilitated the global same test pair. In this case, the magnitude of the priming effect was stronger following the global prime than the occluded prime. These results suggested that the amount of symmetry plays an important role in determining the degree of influence local processes have on completion (Sekuler, 1994).

Although symmetry can be an important cue for completion, other factors such as the number of repeated units, previous exposure to the object, and familiarity may also influence the type of completion (e.g., Sekuler, 1994; Plomp & van Leeuwen, 2006). However, to what extent each of these cues independently influences completion has not been tested. There is some evidence suggesting that past perceptual experience, such as contextual effects, can influence completion. For example, Sekuler and Murray (2001), based on preliminary results, concluded that the amount of exposure to a specific representation of the occluded object (global or local) could influence the form of the completion. Specifically, if during the practice phase 80% of the "same" trials in the prime-matching task were global shapes, then subjects tended to complete the occluded object globally. However, if only 20% of the "same" trials were global shapes, then subjects tended to complete the occluded object locally. In the present study, the occluded shape was composed of a number of repeated units, which may provide a stronger cue for global completion than local completion. Therefore, even at shorter prime durations, local processes may not influence completion as much as global processes for the shapes tested in this study.

In contrast to local theories, many of our results are consistent with global theories of completion. Purely global theories of completion predict that the level of priming afforded by the occluded prime should be equivalent to that afforded by the global prime on the global same test pair (e.g., Boselie & Leeuwenberg, 1986). In this study, at a prime duration of 700 msec, both the occluded and global prime facilitated the global same test pair, and did so equally well. Consistent with previous research, our results suggest that even for complex filled figures, global processes can influence the completion process strongly in adults (e.g., Sekuler et al., 1994; de Wit & van Lier, 2002; de Wit et al., 2005).

However, purely global theories of completion cannot account for all of our results. First, although global theories predict priming of the global same test pair, these theories also predict that priming levels should be equivalent between the occluded prime and the global prime. At a prime duration of 300 msec, the occluded object primed the global shapes, but not as strongly as the global prime. One possibility for this difference may be that the form of the completed object is more flexible and less stable (Kellman, Temesvary, Palmer, & Shipley, 2000; Sekuler & Murray, 2001; de Wit & van Lier, 2002; Kellman, 2003b). Second, global theories of completion do not predict simultaneous priming of the local and global completions by the occluded prime. At a prime duration of 150 and 500 msec, the occluded object primed both the global and local representations. Hence, neither purely global theories nor purely local theories of completion can fully account for the patterns of results we observed in adults. Rather, the pattern of priming that we observed for the occluded prime at 150, 300, and 500 msec, is most consistent with integrative models of completion.

Integrative models of completion can more easily be applied to explain the current results, since these models take the complexity of both the global and local solutions into account in predicting the relative strength of global versus local completions. An integrative model proposed by Sekuler (1994) predicts different completions based on factors such as collinearity of the real contours and symmetry. As the number of symmetry axes increase, the model predicts that the occluded object will be completed globally. Van Lier et al. (1994) propose an integrative model, which takes the internal (i.e., regularity within object), external (i.e., position between objects), and virtual structures (i.e., position between objects) of the object into account to predict the completion that should be preferred.

Although we did not apply these models to the current shapes, it would be informative to determine whether these models would predict equally the global and local solutions or whether the global solution alone would be predicted. It is not possible to apply Sekuler's (1994) integrative model because the predictions of this model are based on the symmetry of the shape. However, the occluded shape we used in this study does not contain any axes of symmetry. In addition, we did not use van Lier's et al. (1994) model to make predictions because it was not clear how the model accounts for the complexity of the external and virtual structures.

The current study has shown that although global processes can dominate the completion of a complex partially occluded object, local processes can also influence completion. At a prime duration of 150 and 500 msec, the occluded object facilitated both global and local representations, suggesting that both representations were available in parallel. However, at a prime duration of 300 and 700 msec, global processes dominated completion in adults. Only at a prime duration of 700 msec were priming patterns between the occluded and global prime equivalent. Purely global or purely local theories of completion cannot account for the simultaneous priming of both the global and local representations by the occluded prime. In addition, purely global theories of completion cannot account for the difference in magnitude of the priming effect between the occluded and global prime. In contrast, integrative models of completion can account for the current results, because these models take into account both local and global processes for the completion of occluded objects.

In Experiment 2, we investigated completion processes in children (8- and 11-year-olds) and compared their results to those of adults tested on the same conditions. To our knowledge, only one study to date has investigated the relative influence of global and local processes in the completion of a partially occluded object in childhood. In that study, children, of a mean age of 11, completed the complex partially occluded object globally at 500 msec (de Wit et al., 2007).

Since children younger than 11 years of age have not been tested, in Experiment 2A, we examined the representation of a complex occluded object in 8-year-olds using a prime duration of 700 msec. The global, local, and occluded prime did not significantly prime either test pair. Since the global prime and local prime did not significantly speed up response times for the global and local shapes, respectively, it was not possible to draw conclusions about the occluded prime. The negative results suggest that the prime-matching task may not be a sensitive technique for investigating the representation of an occluded object in 8-year-olds, perhaps because their response times are so variable. Therefore, in Experiment 2B we tested 11-year-olds at two prime durations (300 or 700 msec) and compared their results to adults tested on the same conditions in Experiment 1.

In adults, global processes dominated the completion of the occluded object at both 300 and 700 msec (but not 150 or 500 msec). The paradigm was effective for 11-year-olds at a prime duration of 300 msec: the local prime sped up response times for the local test pair and the global prime sped up response times for the global test pair. However, the occluded prime did not speed up response times for either test pair. There was some suggestion that the occluded prime might have facilitated both the global and local representations; however, this pattern of priming did not reach statistical significance. Hence, in 11-year-olds, unlike adults, neither global nor local processes dominated the completion of the partly occluded at 300 msec.

Since the occluded prime did not prime either test pair significantly, one possibility is that children require more time to perceptually complete complex, filled figures. To investigate this possibility, we tested a new group of 11-year-olds at a longer prime duration (700 msec). When adults were tested at a prime duration of 700 msec (Experiment 1), all three primes (global, local, and occluded) sped up decisions about the global same test pair. Unlike adults, 11-year-olds showed no significant priming effects at this duration. For both 8-year-olds (Experiment 2A) and 11-year-olds (Experiment 2B), there were no significant priming effects at the longer prime duration (700 msec). Below I consider the implications of the priming data from 300 msec before turning to the results at 700 msec.

Only one previous study has investigated the perceptual completion process in childhood. De Wit et al. (2007) tested a line drawing version of occluded object used in the current study. The authors found that children, of a mean age of 11, completed the complex occluded object globally at a prime duration of 500 msec (de Wit et al., 2007). However, the authors tested children of a broad age range (9 -13 years) and there was no adult comparison group. In addition, it is unclear whether the amount of occlusion was similar to our study. To our knowledge, there have been no previous studies comparing the developmental trajectory, across age, of the perceptual completion process. It is possible that younger children and older children require a different amount of processing time to complete the occluded object.

In the current study, we used a much tighter age range to measure priming effects, specifically at age 11 (10.9 - 11.9 years) and in adulthood. In addition, we tested both age groups on more than one prime duration in order to investigate the representation of the occluded object during early (300 msec) and late (700 msec) stages of visual processing. Our results are not inconsistent with those of de Wit et al. (2007). At a prime duration of 500 msec, de Wit et al. (2007) found that children of a mean age of 11 completed the occluded object globally. Although we did not test directly a prime duration of 500 msec, we found that for a prime duration of 300 msec the occluded object did not prime the global or local shape significantly. For our longer prime duration condition (700 msec), priming effects were too small to analyze. However, it is possible that by

500 msec global processes dominate completion in 11-year-olds. Direct comparisons between the two studies are difficult because the current study used filled figures, whereas de Wit et al. (2007) tested line drawing versions of the current stimuli. As discussed previously, it is unclear whether line drawings and filled figures are processed in the same way (Sekuler & Murray 2001).

For 11-year-olds, unlike adults, the occluded object did not significantly prime either the global same or local same test pair at a prime duration of 300 msec. One possibility is that 11-year-olds did not complete the partially occluded object. Since the time course of completion has not been studied in children, it is possible that complex occluded objects take longer than 300 msec to complete. Had we tested the mosaic representation in children, we could have determined whether the occluded object had been completed by 300 msec.

A second possibility is that both the global and local representations were primed at 300 msec. There was some suggestion that, even in children, the occluded prime facilitated both the global and local solutions. This pattern of priming would be consistent with the pattern of priming observed in adults at 150 msec. As described previously, several lines of evidence suggest that global and local representations of the occluded object may be processed in parallel. Depending on the properties of the occluded object (i.e., familiarity, context, symmetry, collinearity of real contours, etc.) the completed form can be biased towards a more global or local solution (e.g., Sekuler & Murray, 2001; Plomp & van Leeuwen, 2006).

There are two possibilities that may explain the lack of priming in 8- and 11-year-olds at a prime duration of 700 msec. First, the greater variability in response times makes it more difficult to detect significant priming effects in 8- and 11-year-olds. In addition, since the prime-matching task is sensitive to changes in response time, either an overall increase or decrease in response time should make it more difficult to detect priming effects. For example, when response times are longer, priming effects may be difficult to detect because the difference between the baseline and primed trials is reduced (refer to Equation 1). Response times were generally much longer in 8-year-olds (1214.76 msec) than in adults (655.65 msec). Although 11-year-olds (921.21 msec) are faster than 8-year-olds, they are still slower to respond than adults. The longer response times we recorded in children are consistent with evidence suggesting that younger children require more time to process information (Kail, 1991; Kail & Ferrer, 2007).

Second, feedback connections may influence the processing of the global, local, and occluded primes differently at longer prime durations in 8- and 11-year-olds. For example, in adults, the initial feed forward sweep of a stimulus takes approximately 100 msec (Lamme & Roelfsema, 2000). Activity can be observed in higher-level visual areas in the ventral stream by 100 msec (for a review see Lamme & Roelfsema, 2000). It has been suggested that only after 100 msec may feedback connections influence processing (Lamme & Roelfsema, 2000). Since processing times are slower in children, at shorter prime durations (300 msec) feedback connections may not influence processing as much as at longer prime durations (700 msec). Since it is not clear how such top down factors may influence processing of the primes, it is difficult to determine why priming effects were more difficult to detect at the longest prime durations tested (700 msec).

Overall, our results are consistent with evidence suggesting that integrating local information into a global shape changes between 8 and 11 years of age. For example, there is an improvement in the ability to integrate relatable contours in noise between 5 and 14 years of age (Kovács, 2000; Hadad, Maurer, & Lewis, 2010a). Ten-year-olds, but not 5-year-olds are influenced by collinearilty in the perceptual grouping of shapes (Hadad, & Kimchi, 2006; Hadad, Maurer, & Lewis, 2010a). Sensitivity to global form in glass patterns becomes adult-like between 6 and 9 years of age (Lewis et al., 2004). Finally, sensitivity to subjective contours is not adult-like even at 12 years of age (Hadad, Maurer, & Lewis, 2010b). Similarly, we observed that the perceptual completion process is not adult-like even at 11-years of age.

Several weaknesses limit the conclusions that can be drawn from the current study. First, the current study tested filled figures while previous studies using these shapes tested line drawings (e.g., de Wit & van Lier, 2002; de Wit et al., 2005). This made comparisons between previous studies and our study more difficult, because it is unclear whether filled figures, and line drawings are processed differently. In addition, we tested only one amount of occlusion, a factor that has been shown to affect completion (e.g., van Lier et al., 1995).

Second, we did not test the mosaic representation (i.e., incomplete version) of the occluded object. To form the mosaic representation the occluded star-like object would be displaced from the rectangle so that that occluded portion appears as a notch in the shape. Although the representation of the occluded object is incomplete initially (i.e., mosaic), several studies suggest that adults complete simple partly occluded objects within 100 – 250 msec (Sekuler & Palmer, 1992; Rauschenberger et al., 2004). Once the occluded object is completed, the mosaic representation is no longer present (Sekuler & Palmer, 1992; Rauschenberger et al., 2004). Thus, at least for the longer prime duration conditions (300 to 700 msec) used here, the representation(s) of the occluded object should be complete, and therefore it is unlikely that the incomplete version of the occluded object would have provided any useful information. However, for the shorter prime duration of 150 msec, it was possible that the occluded object may not have been completed (similar to Sekuler et al., 1994). In the current study, we found that the occluded prime facilitated both the global and local representations in adults, and therefore the mosaic condition was not necessary to test. In contrast to adults, at a prime duration of 300 msec we should have tested the mosaic condition for 11-year-olds. Since the occluded object did not significantly prime either test pair, it is not clear whether the occluded object was completed.

A third limitation of the current study stems from the drawbacks of the prime-matching task. The prime-matching paradigm is an objective measure for testing the representation of a partially occluded object; however, it is still only an indirect measure. A limitation of this paradigm is that the collected response times are influenced not only by the similarity of the prime and the test pair, but also by other decision-related processes. Specifically, the response time takes into account the processing time required to compare the two shapes, make a same or different judgment, and execute a response. Plomp and van Leeuwen (2006) overcame this problem by measuring the priming effect in the absence of decision-related processes. To do so, they used a modification of the prime-matching task. Specifically, subjects were first shown a composite figure (e.g., occluded figure) for 50 msec, then a single figure (e.g., global or local representation of the occluded figure) for 50 or 500 msec, followed by the test pair (e.g., same of different). The authors were interested in the priming afforded by the composite figure on the single figure. If the composite figure influenced the processing of the single figure, they expected a superadditive facilitation on congruent test pairs. For example, if the occluded prime was completed globally then it should facilitate processing of a global single figure, which in tern should facilitate the processing of a global same test pair (i.e., congruent test stimulus). This should lead to a superadditive facilitation for the test pair. Although the authors did not observe a superadditive effect on congruent test pairs, the occluded figure did speed up response times for the global same test pair. This result is consistent with previous studies showing that the occluded prime can speed up response times for a test figure (e.g., Sekuler et al., 1994; de Wit & van

Lier, 2002). However, this modified design has its own disadvantages, namely that it is difficult to measure the priming afforded by the composite figure on the single figure directly. This makes the paradigm less sensitive for detecting priming effects. The presentation of composite figure and single figure can also be reversed. However, a disadvantage of this design is that the single figure provides context, and therefore can influence the completion of the occluded figure (Plomp & van Leeuwen, 2006). Subjects that are shown a single figure before the composite figure complete the occluded object in a way that is consistent with the representation of the single figure (Plomp & van Leeuwen, 2006).

Future research could focus on expanding findings in children. First, it is important to track the time course of completion for occluded objects in children to determine when the perceptual completion process becomes adult-like. In order to address this, researchers should use simple occluded shapes (circle behind rectangle) rather than a complex occluded shape, since we are only interested in the time course of completion, rather than the types of processes (global or local) involved in completion. Although the prime-matching task has been used to address this question in adults (Sekuler & Palmer, 1992), that paradigm may not be ideal for children at shorter prime durations (50 – 100 msec). Nor are the visual search tasks that have been used to study the time course of completion in adults (Rauschenberger et al., 2004) suitable for testing children because error rates tend to be too high in this task (Sekuler et al., 1994).

Finally, the shape discrimination task used by Murray, Sekuler, and Bennett (2001) may not be ideal for testing completion effects in children. In that task, subjects judge whether the horizontal or vertical axis of a rectangle is longer. Although adults are good at detecting deviations from perfect symmetry (Regan & Hamstra, 1992; Murray et al., 2001), it is unclear whether children would be as sensitive as adults to deviations from perfect symmetry. Therefore, it would be beneficial to develop a more sensitive task for objectively measuring the representation of the occluded object in children. Future studies should test exposure times between 70 to 500 msec, since we expect children will take longer to complete the occluded object than adults (150 – 250 msec).

It is important to note that although several tasks can be used to answer general questions about the development of the perceptual completion process, these tasks may not be ideal for addressing questions about local and global processing in completion. For example, shape discrimination tasks (Ringach and Shapley, 1996) can be used to investigate the sensitivity of the perceptual completion process in children (e.g., Hadad, Maurer, & Lewis, 2010b) and adults (e.g., Gold, Murray, Bennett, & Sekuler, 2000). In this task, a square is hidden behind a cross. Based on the angle of rotation of the visible corners of the square, the hidden shape can appear as either a skinny or fat square. Subjects judge whether a skinny or fat square was presented. Over trials, the task becomes more difficult; therefore, a more precise completion process would be required to accurately discriminate skinny and fat shapes. An advantage of this task is that it measures a threshold rather than a response time. In the current study, we found that response times were highly variable in young children making it difficult to reliably measure priming effects. A disadvantage of this task is that it cannot be easily adapted to address the question of global and local processing.

Second, it would be interesting to test children older than 11 years of age, at a prime duration of 300 msec, to track the development of the types of processes (global and local processes) involved in the perceptual completion of occluded objects. Children may differ in not only the amount of time they require to complete the occluded object, but also the type of processes that dominate completion. Since 11-year-olds do not show adult-like patterns at 300 msec, the next logical step would be to determine at what age children resemble adults.

Third, it would be informative to test a new group of 11-year-olds using filled figures at a prime duration of 500 msec. The only previous study of children suggests that a prime duration of 500 msec is long enough for children of a mean age of 11 to complete the occluded figure, at least for line drawings (de Wit et al., 2007). If global processes dominate completion by 500 msec, it would suggest that 11-year-olds do require more time to represent a complex, occluded object compared to adults.

Conclusions

Combined, the results suggest that both global and local processes can influence the completion of occluded objects in adults. The occluded prime facilitated the global and local solutions equally at 150 and 500 msec. Global processes dominated completion at 300 and 700 msec; however, only at a prime duration of 700 msec was the patterns of priming similar between the occluded and global condition. The current results are consistent with integrative models of completion, but not purely global or local theories of completion. Under the current testing conditions, we also found that the perceptual completion process is not adult-like even at 11 years of age.

List of References

Bakin, J. S., Nakayama, K., & Gilbert, C. D. (2000). Visual responses in monkey areas V1 and V2 to three-dimensional surface configurations. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience, 20*(21), 8188-8198.

Boselie, F., & Leeuwenberg, E. (1986). A test of the minimum principle requires a perceptual coding system. *Perception, 15*(3), 331-354.

Boselie, F., & Wouterlood, D. (1989). The minimum principle and visual pattern completion. *Psychological Research, 51*(3), 93-101.

Craton, L. G. (1996). The development of perceptual completion abilities: Infants' perception of stationary, partially occluded objects. *Child Development*, *67*(3), 890-904. doi:10.1111/j.1467-8624.1996.tb01771.x

de Wit, T. C., Mol, K. R., & van Lier, R. (2005). Investigating metrical and structural aspects of visual completion: Priming versus searching. *Visual Cognition, 12*(3), 409-428. doi:10.1080/13506280444000373

de Wit, T. C., Schlooz, W. A., Hulstijn, W., & van Lier, R. (2007). Visual completion and complexity of visual shape in children with pervasive developmental disorder. *European Child & Adolescent Psychiatry, 16*(3), 168-177. doi:10.1007/s00787-006-0585-9

de Wit, T. C., & van Lier, R. J. (2002). Global visual completion of quasi-regular shapes. *Perception, 31*(8), 969-984.

de Wit, T. C., Vrins, S., Dejonckheere, P. J. N., & van Lier, R. J. (2008). Form perception of partly occluded shapes in 4-month-old infants. *Infancy, 13*(6), 660-674. doi:10.1080/15250000802458864

Engel, A. K., Fries, P., & Singer, W. (2001). Dynamic predictions: Oscillations and synchrony in top-down processing. *Nature Reviews. Neuroscience, 2*(10), 704-716. doi:10.1038/35094565

Garner, W.R. (1974). *The Processing of Information Structure*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Gold, J. M., Murray, R. F., Bennett, P. J., & Sekuler, A. B. (2000). Deriving behavioural receptive fields for visually completed contours. *Current Biology : CB, 10*(11), 663-666. doi:10.1016/S0960-9822(00)00523-6

Guttman, S. E., Sekuler, A. B., & Kellman, P. J. (2003). Temporal variations in visual completion: A reflection of spatial limits? *Journal of Experimental Psychol*ogy*. Human Perception and Performance*, *29*(6), 1211-1227. doi:10.1037/0096-1523.29.6.1211

Hadad, B., Maurer, D., & Lewis, T. L. (2010a). The effects of spatial proximity and collinearity on contour integration in adults and children. *Vision Research, 50*(8), 772-778. doi:10.1016/j.visres.2010.01.021

Hadad, B. S., & Kimchi, R. (2006). Developmental trends in utilizing perceptual closure for grouping of shape: Effects of spatial proximity and collinearity. *Perception & Psychophysics*, *68(*8), 1264-1273. doi:10.3758/BF03193726

Hadad, B. S., Maurer, D., & Lewis, T. L. (2010b). The development of contour interpolation: Evidence from subjective contours. *Journal of Experimental Child Psychology, 106*(2-3), 163-176. doi:10.1016/j.jecp.2010.02.003

Hochberg, J., & McAlister, E. (1953). A quantitative approach to figural "goodness". *Journal of Experimental Psychology, 46*(5), 361-364. doi:10.1037/h0055809

Johnson, S. P., & Aslin, R. N. (1995). Perception of object unity in 2-month-old infants. *Developmental Psychology*, *31*(5), 739-745. doi:10.1037/0012-1649.31.5.739

Johnson, S. P., & Aslin, R. N. (1996). Perception of object unity in young infants: The roles of motion, depth, and orientation. *Cognitive Development*, *11*(2), 161-180. doi:10.1016/S0885-2014(96)90001-5

Johnson, S. P., Bremner, J. G., Slater, A., Mason, U., Foster, K., & Cheshire, A. (2003). Infants' perception of object trajectories. *Child Development*, *74*(1), 94-108. doi: 10.1111/1467-8624.00523

Johnson, S. P., & Náñez, Sr. J. E. (1995). Young infants' perception of object unity in two-dimensional displays. *Infant Behavior and Development*, *18*(2), 133-143. doi:10.1016/0163-6383(95)90043-8

Jusczyk, P. W., Johnson, S. P., Spelke, E. S., & Kennedy, L. J. (1999). Synchronous change and perception of object unity: Evidence from adults and infants. *Cognition*, *71*(3), 257-288. doi:10.1016/S0010-0277(99)00026-8

Kail, R. (1991). Developmental change in speed of processing during childhood and adolescence. *Psychological Bulletin, 109*(3), 490-501. doi:10.1037/0033-2909.109.3.490

Kail, R. V., & Ferrer, E. (2007). Processing speed in childhood and adolescence: Longitudinal models for examining developmental change. *Child Development, 78*(6), 1760-1770. doi:10.1111/j.1467-8624.2007.01088.x

Kellman, P. J. (2003a). Visual perception of objects and boundaries: A four-dimensional approach. In R. Kimchi, M. Behrmann & C. R. Olson (Eds.), Perceptual organization in vision: Behavioral and neural perspectives (pp. 155-200). Mahwah, NJ: Lawrence Erlbaum Associates.

Kellman, P. J. (2003b). Interpolation processes in the visual perception of objects. *Neural Networks : The Official Journal of the International Neural Network Society, 16*(5-6), 915-923. doi:10.1016/S0893-6080(03)00101-1

Kellman, P. J., Guttman, S. E., & Wickens, T. D. (2001). Geometric and neural models of object perception. In T. F. Shipley & P. J. Kellman (Eds.), *From fragments to objects: Segmentation and grouping in vision.* Amsterdam: Elsevier Science Publishers. doi:10.1060/S0166-4115(01)80027-3

Kellman, P. J., & Shipley, T. F. (1991). A theory of visual interpolation in object perception. *Cognitive Psychology, 23*(2), 141-221. doi:10.1016/0010-0285(91)90009-D

Kellman, P. J., & Shipley, T. F. (1992). Perceiving objects across gaps in space and time. *Current Directions in Psychological Science, 1*(6), 193-199.

Kellman, P. J., Temesvary, A., Palmer, E. M., & Shipley, T. F. (2000). Separating local and global processes in object perception: evidence from an edge localization paradigm. *Investigative Ophthalmology and Visual Science*, *41*(4), S741.

Kellman, P. J., Yin, C., & Shipley, T. F. (1998). A common mechanism for illusory and occluded object completion. *Journal of Experimental Psychology*. *Human Perception and Performance*, *24*(3), 859-869. doi:10.1037/0096-1523.24.3.859

Koffka, K. (1935). *Principles of Gestalt Psychology*. Harcourt, NY: Brace and World.

Kourtzi, Z., & Kanwisher, N. (2001). Representation of perceived object shape by the human lateral occipital complex. *Science, 293*(5534), 1506-1509. doi:10.1126/science.1061133

Kovács, K. (2000). Human development of perceptual organization. *Vision Research, 40*, 1301-1310. doi:10.1016/S0042-6989(00)00055-9

Kovács, G., Vogels, R., & Orban, G. A. (1995). Selectivity of macaque inferior temporal neurons for partially occluded shapes. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience, 15*(3), 1984-1997.

Lamme, V. A., & Roelfsema, P. R. (2000). The distinct modes of vision offered by feedforward and recurrent processing. *Trends in Neurosciences, 23*(11), 571-579. doi:10.1016/S0166-2236(00)01657-X

Leeuwenberg, E. L. (1969). Quantitative specification of information in sequential patterns. *Psychological Review, 76*(2), 216-220. doi:10.1037/h0027285

Leeuwenberg, E. L. (1971). A perceptual coding language for visual and auditory patterns. *The American Journal of Psychology, 84*(3), 307-349.

Lerner, Y., Hendler, T., & Malach, R. (2002). Object-completion effects in the human lateral occipital complex. *Cerebral Cortex, 12*(2), 163-177. doi:10.1093/cercor/12.2.163

Lewis, T. L., Ellemberg, D., Maurer, D., Dirks, M., Wilkinson, F., & Wilson, H. R. (2004). A window on the normal development of sensitivity to global form in glass patterns. *Perception, 33*(4), 409-418.

Liu, L. C., Plomp, G., van Leeuwen, C., & Ioannides, A. A. (2006). Neural correlates of priming on occluded figure interpretation in human fusiform cortex. *Neuroscience, 141*(3), 1585-1597. doi:10.1016/j.neuroscience.2006.04.062

Miller, E. K., Li, L., & Desimone, R. (1993). Activity of neurons in anterior inferior temporal cortex during a short-term memory task. *The Journal of Neuroscience : The Official Journal of the Society for Neuroscience*, *13*(4), 1460-1478.

Mondloch, C. J., Geldart, S., Maurer, D., & de Schonen, S. (2003). Developmental changes in the processing of hierarchical shapes continue into adolescence. *Journal of Experimental Child Psychology, 84*(1), 20-40. doi:10.1016/S0022-0965(02)00161-3

Murray, R. F., Sekuler, A. B., & Bennett, P. J. (2001). Time course of amodal completion revealed by a shape discrimination task. *Psychonomic Bulletin & Review, 8*(4), 713-720. doi:10.3758/BF03196208

Peters, M. (1998). Description and validation of a flexible and broadly usable handedness questionnaire. *Laterality: Asymmetries of Body, Brain, and Cognition, 3*(1), 77-96. doi:10.1080/713754291

Plomp, G., & van Leeuwen, C. (2006). Asymmetric priming effects in visual processing of occlusion patterns. *Perception & Psychophysics, 68*(6), 946-958. doi:10.3758/BF03193357

Rauschenberger, R., Peterson, M. A., Mosca, F., & Bruno, N. (2004). Amodal completion in visual search: Preemption or context effects? *Psychological Science, 15*(5), 351-355. doi:10.1111/j.0956-7976.2004.00682.x

Regan, D., & Hamstra, S. J. (1992). Shape discrimination and the judgement of perfect symmetry: Dissociation of shape from size. *Vision Research, 32*(10), 1845-1864. doi:10.1016/0042-6989(92)90046-L

Ringach, D. L., & Shapley, R. (1996). Spatial and temporal properties of illusory contours and amodal boundary completion. *Vision Research*, *36*(19), 3037-3050. doi:10.1016/0042-6989(96)00062-4

Scherf, K. S., Behrmann, M., Kimchi, R., & Luna, B. (2009). Emergence of global shape processing continues through adolescence. *Child Development, 80*(1), 162-177. doi:10.1111/j.1467-8624.2008.01252.x

Sekuler, A. B. (1994). Local and global minima in visual completion: Effects of symmetry and orientation. *Perception, 23*(5), 529-545.

Sekuler, A. B., & Murray, R. F. (2001). Amodal completion: A case-study in grouping. In T. F. Shipley, & P. J. Kellman (Eds.), *From fragments to objects - segmentation and grouping in vision* (1 ed., pp. 265-293). Amsterdam, The Netherlands: Elsevier Sciences. doi:10.1016/S0166-4115(01)80029-7

Sekuler, A. B., & Palmer, S. E. (1992). Perception of partly occluded objects: A microgenetic analysis. *Journal of Experimental Psychology: General, 121*(1), 95-111. doi:10.1037/0096-3445.121.1.95

Sekuler, A. B., Palmer, S. E., & Flynn, C. (1994). Local and global processes in visual completion. *Psychological Science, 5*(5), 260-267. doi: 10.1111/j.1467-9280.1994.tb00623.x

Sugita, Y. (1999). Grouping of image fragments in primary visual cortex. *Nature*, *401*(6750), 269-272. doi:10.1038/45785

van Lier, R., van der Helm, P., & Leeuwenberg, E. (1994). Integrating global and local aspects of visual occlusion. *Perception, 23*(8), 883-903.

van Lier, R. J., van der Helm, P. A., & Leeuwenberg, E. L. (1995). Competing global and local completions in visual occlusion. *Journal of Experimental*

Psychology. Human Perception and Performance, 21(3), 571-583. doi:10.1037/0096-1523.21.3.571

van Selt, M., & Jolicoeur, P. (1994). A solution to the effect of sample size on outlier estimation. *The Quarterly Journal of Experimental Psychology*, *47A*(3), 631-650. doi:10.1080/14640749408401131

Weigelt, S., Singer, W., & Muckli, L. (2007). Separate cortical stages in amodal completion revealed by functional magnetic resonance adaptation. *BMC Neuroscience, 8*, 70. doi:10.1186/1471-2202-8-70

Appendix:

Instructions for Experiment

SCRIPT

This is Detective Holmes. Today we will be helping Detective Holmes on a very special mission. Someone has stolen the jellybeans from the jellybean jar.

Detective Holmes needs your help to collect clues to find out who stole the jellybeans. In each game, we will be sorting shapes into two piles. Sorting the shapes and collecting jellybeans will help us to refill the jellybean jar. Once we fill the jellybean jar, we get a special clue to help solve the mystery. Are you ready to help Detective Holmes?

DEMO

Cue

Pay attention. The game starts when the cross appears on the screen.

Prime

First, you will see one shape.

Test pair

Then you will see three shapes. Your job is to decide if the black shapes are the same or different from each other. In this case, the black shapes are the same.

Cue

Now watch again.

Prime

Again, you will see one shape.

Test pair

Then three shapes. This time the black shapes are different from each other. But if you make a mistake and say that they are the same, you will hear this sound.

Cue

Watch carefully now, it will be faster.

Prime
Test pair

This time the shapes are the same, so press the “S” button.

Cue
Prime
Test pair

When the shapes are the different, you press the “D” button.

Jellybean

When you see these jellybeans you have to press the “jellybean” button to collect the jellybeans. You want to collect the jellybeans as quickly as you can.

Jellybean Jar

Once you collect the jellybeans they go into the jellybean jar. When you fill the jellybean jar, you will get your first clue to solve the mystery. The jellybean jars also let you know how far you are in the game.

Now it’s your turn to try the game. I want you be as fast as you can to sort the shapes, but don’t make any mistakes.

Ready. Now it’s your turn to try.

First Game
PRACTICE

Now we get to practice the game. Remember, I want you be as fast as you can, but don’t make any mistakes.

THE GAME BEGINS

Now the real game starts.

For the Second, Third, Fourth Game
Now you will only get four practice trials before the real game starts.