Development of local-global preference in vision and haptics

Chiara Tortelli
Department of Translational Research on New Technologies in Medicine and Surgery, University of Pisa, Pisa, Italy

Irene Senna
Department of Psychology, Liverpool Hope University, Liverpool, United Kingdom

Paola Binda
Department of Translational Research on New Technologies in Medicine and Surgery, University of Pisa, Pisa, Italy

Marc O. Ernst
Department of Applied Cognitive Psychology, University of Ulm, Ulm, Germany

We aimed to advance our understanding of local-global preference by exploring its developmental path within and across sensory modalities: vision and haptics. Neurotypical individuals from six years of age through adulthood completed a similarity judgement task with hierarchical haptic or visual stimuli made of local elements (squares or triangles) forming a global shape (a square or a triangle). Participants chose which of two probes was more similar to a target: the one sharing the global shape (but different local shapes) or the one with the same local shapes (but different global shape). Across trials, we independently varied the size of the local elements and that of the global configuration—the latter was varied by manipulating local element density while keeping their numerosity constant. We found that the size of local elements (but not global size) modulates the effects of age and modality. For stimuli with smaller local elements, the proportion of global responses increased with age and was similar for visual and haptic stimuli. However, for stimuli made of our largest local elements, the global preference was reduced or absent, particularly in haptics, regardless of age. These results suggest that vision and haptics progressively converge toward similar global preference with age, but residual differences across modalities and across individuals may be observed, depending on the characteristics of the stimuli.

Introduction

The discussion around the relationship between “global” wholes and their “local” components is rooted in the classic controversy between Structuralism, describing the global percept as the sum of local elements (Titchener, 1902; Wundt, 1894), and Gestalt theories, where the quality of a part depends on the global structure in which it is embedded (e.g., its symmetry, regularity, and closure) (Köhler, 1971; Wagemans et al., 2012; Wertheimer, 1923). Navon (1977) introduced a classic paradigm for studying this relationship: hierarchical figures, where a global form (e.g., the letter A) is composed of local parts (e.g., small letter ‘V’s) creating a conflict between the local and the global content. Navon observed that the global content usually dominates perception and introduced the concept of “global precedence” to indicate that global content emerges earlier than the local details—similar to the concept of “gist” that was introduced later for natural scene perception (Oliva & Torralba, 2006). However, further research gradually gave way to the concept of holistic processing (Kimchi, 1992; Kimchi, 2006), which does not imply a specific processing order and fits well with the Gestalt concept of wholes resulting from interrelations between parts (Ballesteros & Manga, 1996; Gerlach & Poirel, 2020).

The relative preference for local or global depends on a variety of factors, including properties of the stimulus and of the observers. Relevant stimulus properties include size and density. For example, in hierarchical figures, it is easier to focus on local elements when these are larger (Kimchi & Palmer, 1982; Martin, 1979) and sparser (Dukette & Stiles, 1996; Dukette & Stiles, 2001; Krakowski, Borst, Vidal, Houdé, & Poirel, 2018). When the density of local elements increases, as in a texture, the global configuration

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becomes dominant (Dukette & Stiles, 1996; Dukette & Stiles, 2001; Krakowski et al., 2018)—more so in adults than in children. The latter result exemplifies that some characteristics of the observer, such as age, have an impact on local-global preference. Several studies showed that global preference evolves during development (Bouhassoun, Poirel, Hamlin, & Doucet, 2022), and young children (four years old) tend to show local preference instead (Dukette & Stiles, 1996; Elkind, Koegler, Go, & Elkind, 1964; see Goodenough, 1976; Kimchi, 2015; Wagemans et al., 2012 for a review). In addition, a reduced global preference has been repeatedly reported in special populations, including individuals with autism spectrum disorder (Evers, Van der Hallen, Noens, & Wagemans, 2018 for a review) and with developmental prosopagnosia (Gerlach & Starrfelt, 2018; Liu & Behrmann, 2014). However, inconsistent results have frequently emerged (Baisa, Mevorach, & Shalev, 2019; Horlin, Black, Falkmer, & Falkmer, 2016 for reviews) suggesting that differences in methodologies and in the type of stimuli could lead to engaging different constructs and abilities (Chamberlain, Van der Hallen, Huygelier, Van de Cruys, & Wagemans, 2017; Gerlach & Krumborg, 2014; Milne & Szczerbinski, 2009).

Most experimental findings supporting these conclusions have been obtained by visual stimulation. Given the architecture of the visual system, the analysis of local elements can proceed in parallel with the acquisition of a global "gist" and both emerge rapidly upon stimulus presentation (Breitmeyer, 1992; Stone, 2013) . Less attention has been paid to the other sensory modalities, such as haptics. The small body of research on local-global preference in haptics suggests that similar principles apply as in vision, including a shift from local to global preference during development (Berger & Hatwell, 1993; Schellingerhout, Smitsman, & Cox, 2005). However, there is also evidence suggesting that the analysis of haptic stimuli might follow different principles than for visual stimuli (Ballesteros, Millar, & Reales, 1998). For example, the haptic perception of an object that is large compared to our hands necessarily depends on the sequential exploration of its parts, implying that local analysis might take precedence over global haptic processing (Berger & Hatwell, 1993; Lakatos & Marks, 1999; Lederman & Klatzky, 1987; Lederman & Klatzky, 1993) . Consequently, a rapid and parallel processing in vision versus a gradual and sequential exploration in haptics may cause some stimulus characteristics to differentially affect local-global preference in the visual versus haptics modality or interact in different ways with age. These considerations motivated us to compare local-global preference across sensory modalities (vision and haptics) and over development, with a cross-sectional study of >100 individuals from six years of age through adulthood. Importantly, one of the strengths of the study is assessing similarities/differences between vision and haptics within participants: this allowed us also to explore possible differences between modality (modality mismatch) in global-local preference in each individual and to investigate how this possible mismatch may be influenced by the age of the participant and by the properties of the stimuli.

Methods

Participants

One hundred two children, adolescents, and adults (age range 6.01–35.37; 46 females, 56 males; six left-handed) volunteered to participate in the study. Participants or their legal guardians reported that they were healthy, with normal or corrected to normal vision, and gave written consent for their participation in the study. The study was carried out in accordance with the Declaration of Helsinki and approved by the German ethics committee of the University of Bielefeld and Italian regional ethics committee (Comitato Etico Pediatrico Regionale—Azienda Ospedaliero-Universitaria Meyer—Firenze [FI]).

Apparatus and stimuli

Stimuli were 3D printed hierarchical geometric forms (Figure 1) made of black plastic material. They differed in the shape of the local and global forms (triangles or squares), which could be consistent (e.g., square made of squares) or inconsistent (e.g., triangle made of squares).

Table 1 summarizes the main characteristics of the entire stimulus set. Local elements could take one of three sizes; the number of local elements forming the global shape varied inversely with their size, resulting in approximately constant global size. Orthogonal to this, we manipulated global size by varying the density of local elements; these could be separated by 2 or 4 mm, resulting in a variation of global shape by about a factor of two. We chose these values according to two main constraints: that the smallest local element was still clearly discernible both visually and haptically for all age ranges, and that the largest global shape was no larger than a child's hand. The combination of 2 shapes × 2 local-global consistency levels × 3 sizes × 2 densities gave a total of 24 different stimuli (Figure 1A). Tables 1 summarizes their key features: size of the global shape and size and number of the local elements (Table 1).

All stimuli were printed on 4 × 4 cm stands, and the global shape covered a variable amount of this area, depending on the shape of the global configuration and the density of the local elements. Stimuli were presented

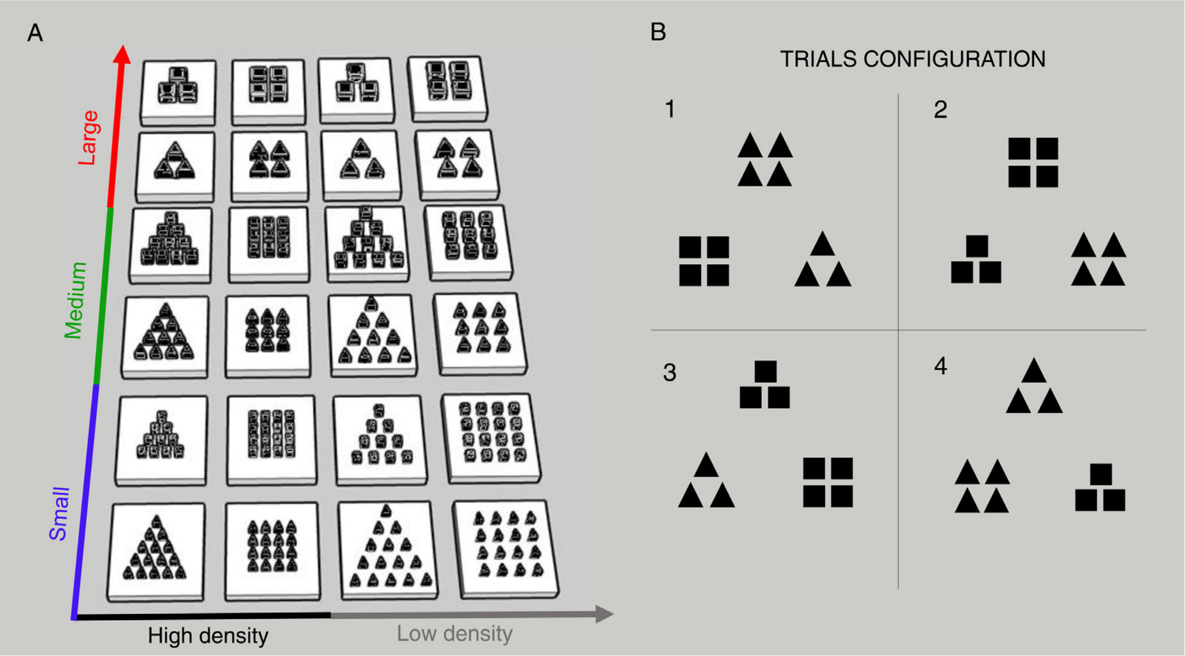

Figure 1. Stimuli examples. (A) Three-dimensional small-, medium-, and large-size stimuli are represented by the blue, green, and red colors on the y-axis, respectively. The black and gray colors on the x-axis represent the two densities: high- and low-density stimuli (with 2 and 4 mm of interelement distance, respectively). (B) The four possible trial configurations, with inconsistent target and consistent responses (1 and 3) or vice-versa (2 and 4). Each configuration was presented for each size and density and the comparisons were randomly swapped (left/right or right/left).

Size	Local area cm^2 (deg)	No. of local elements: Global square	No. of local elements: Global triangle	Global area: High-density cm^2 (deg)	Global area: Low-density cm^2 (deg)
Small	0.1 (0.19)	16	10–15	3.39 (6.47)	5.91 (11.25)
Medium	0.22 (0.42)	9	10	3.99 (7.61)	5.82 (11.08)
Large	0.65 (1.24)	4	3	3.41 (6.51)	3.96 (7.55)

Table 1. The area and number of the local elements (small, medium, and large). Global area refers to the size of the global form.

in groups of three: a target (top) and two probes (bottom left and right). They were chosen so that:

- No two identical stimuli were simultaneously presented
- Target and probes had the same local element size and the same density
- Target and probes had different local-global consistency (when the target was consistent, the comparisons were inconsistent and vice versa, see Figure 1B)

This yielded 24 stimulus triplets (4 configurations × 3 local element sizes × 2 densities); these were presented twice and the second time the left/right order of the probe stimuli was swapped. For eight of the youngest children, however, the task proved to be tiring and they only completed one series of 24 trials for the haptics modality; all participants except one child completed both series for the visual modality.

Following a predefined and randomized stimulus order, an experimenter manually inserted the selected stimuli in three placeholders positioned on a white platform (31 cm × 29.5 cm), 14.9 cm apart. The platform was placed on a table and tilted 45° from the horizontal; participants sat in front of it, with their head stabilized by a chinrest and we adjusted the height of the chair, so that viewing distance was 30 cm. Each of the three placeholders on the platform was equipped with an Arduino sensor (Arduino 1.8.10) connected with a PC laptop (ACER-swift, intel CORE i5; 7th Gen) that allowed for recording behavioral responses and their latencies.

Experimental procedure

Participants judged which of the two probe stimuli (bottom left or right) was more similar to the target (top), by pressing upon the selected stimulus with their dominant hand. Because of the way stimulus configurations were selected (see Figure 1B), participants were forced to choose between a probe stimulus that had the same global configuration as the target (but made with differently shaped local elements), or a probe made of the same local elements as the target (but forming a different global configuration). Judgments were categorized as “global” when the chosen comparison had the same global configuration as the target and “local” otherwise. In separate sessions (two visual sessions and two haptic sessions), stimuli were presented visually or haptically. The order was counterbalanced across participants.

In the visual sessions, participants started each trial with a blindfold on. This allowed the experimenter to set up the stimuli. At the start signal (verbally provided by the experimenter) the blindfold was removed and participants were instructed to respond as fast as they could.

In the haptic sessions, participants were blindfolded for the entire session. At the beginning of each trial, they were invited to rest their hand in a standard position, at the bottom center of the platform. At the start signal, they haptically explored the three 3D stimuli placed on the platform with their dominant hand. After five seconds, an acoustic signal indicated that participants had to stop the exploration and give their response.

Statistical analysis

Responses from individual trials were entered a generalized linear-mixed-model with a probit link function (Agresti, 2003) and maximum-likelihood estimation routines. We used fixed effects to represent stimulus modality (categorical variable with two levels: vision/haptics), size (categorical variable with three levels: large/medium/small size), density (categorical variable with two levels: high density/low density) and participants’ age (continuous variable: exact age for each participants, expressed as base 10 logarithm); we included a random intercept to account for interindividual variability.

We complemented this analysis with Pearson’s correlation analyses, comparing average performance across age groups or stimulus size and modality. Significance of these statistics was evaluated using both *p* values and log-transformed Bayes factors (Wetzels & Wagenmakers, 2012). The Bayes factor is the ratio of the likelihood of the two models H1/H0, where H1 assumes a correlation between the two variables and H0 assumes no correlation. By convention, when the base 10 logarithm of the Bayes factor (logBF) > 0.5 is considered substantial evidence in favor of H1, and logBF < -0.5 substantial evidence in favor of H0.

Results

We analyzed global preference (defined as the proportion of global responses in a similarity judgment task with Navon-like hierarchical stimuli) as a function of four main factors: one characteristic of the participants (their age) and three characteristics of the stimuli (the sensory modality in which they were delivered, visual or haptic, the size of their local components, and the size of the global shape—as set by the density of the local elements). We used a generalized linear-mixed model to establish which of these factors had a significant impact. Table 2 shows the results of the complete model including all factors and their interactions.

We then proceeded to simplify the model by removing each of the factors and testing whether this affected the goodness of the fit, as gauged from the likelihood ratio “LR” for the models with and without each factor. We observed that the only factor that could be removed at no cost is the size of the global shape (or the density of the local elements: LR = 10.53; delta DF = 12; *p* value = 0.57). This suggests that global size (density) failed to affect global preference, while both local element size and sensory modality had significant effects. Figure 2 supports this conclusion by showing the average global preference across all observers (irrespectively of their age), which was clearly affected by the size of local

Name	F	DF1	DF2	*p* value
Density	0.33	1	9269	.57
Size	**6.97**	**2**	**9269**	$\mathbf{9.43 \cdot 10^{-4}}$
Modality	0.30	1	9269	.58
Age	**9.80**	**1**	**9269**	**.002**
Density × Size	0.39	2	9269	.68
Density × Modality	0.23	1	9269	.63
Size × Modality	2.12	2	9269	.12
Density × Age	0.32	1	9269	.57
Size x Age	**8.94**	**2**	**9269**	$\mathbf{1.32 \cdot 10^{-4}}$
Modality x Age	0.55	1	9269	.46
Density × Size × Modality	0.95	1	9269	.39
Density × Size × Age	0.46	2	9269	.63
Density × Modality × Age	0.33	1	9269	.57
Size × Modality × Age	1.83	2	9269	.16

Table 2. Table of the fixed effects of the generalized linear effect model.

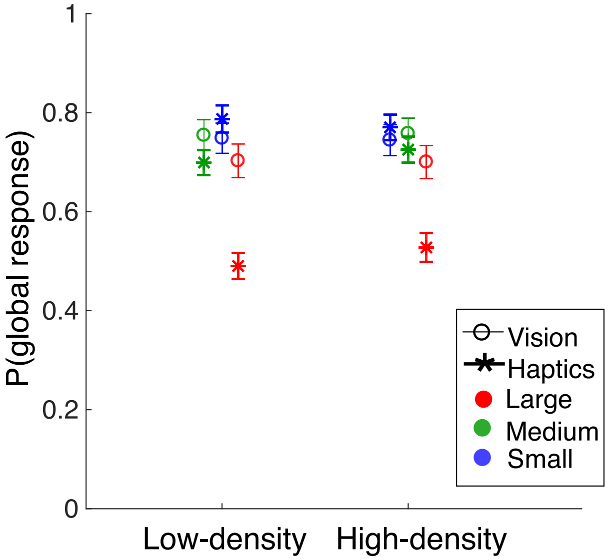

Figure 2. Proportion of global responses for low- and high-density stimuli, in vision and haptics (circles and asterisks) and for differently sized local elements (colors, see legend). Symbols show averages and SEM across all participants. Notice that low-density stimuli also take up larger global area and higher density stimuli take up a smaller global area.

Name	F	DF1	DF2	p value
Size	10.77	2	9281	$2.12 \cdot 10^{-4}$
Modality	1.32	1	9281	.25
Age	10.09	1	9281	$1.49 \cdot 10^{-3}$
Size × Modality	2.53	2	9281	.08
Size × Age	13.87	2	9281	$9.72 \cdot 10^{-7}$
Modality × Age	2.22	1	9281	.14
Size × Modality × Age	3.93	2	9281	.019

Table 3. Table of the generalized fixed effects model after the deletion of the density factor.

elements (different colors: higher global preference for smaller elements) and by stimulus modality (empty/filled symbols: higher global preference for vision, at least for larger elements), but not global size (circles and diamonds, nearly overlapping in all cases).

Table 3 shows the model (after removing the factor global size), which revealed a significant three-way interaction ($F(1, 9281) = 3.93$; $p = 0.019$) between factors modality, size and age, indicating that size differentially affected vision and haptics over development. Moreover, the simplified model (i.e., without global size) was preferable also according to the Akaike Information Criterion (AIC = 8997.8) as compared with the more complex one (i.e., including global size, AIC = 9011.2). Because the two models did not significantly differ, the simplest model was chosen (Agresti, 2003).

Inspection of Figure 3 allows for interpreting this interaction. For large stimuli, local-global preference was largely constant across age, and it was markedly different across modalities, with global preference emerging only for visual, not haptic stimuli (Figure 3C). However, for medium and small stimuli (Figures 3A, 3B), results were similar for the two modalities, both showing a gradual increase of global preference with age, with a trace of increased global preference for our stimuli composed of medium-sized elements.

In other words, the size of the local elements modulated the concordance across modalities: local-global preferences in haptics and vision covaried across age groups for stimuli made of the smallest local elements, whereas large cross-modal differences emerged for stimuli made of the largest local elements. This is also supported by the correlation analysis in Figure 3D, plotting the proportion of global responses in haptics (y-axis) versus vision (x-axis) across participants; although all correlations are highly significant, there is a trend for a steeper slope for stimuli made of smaller local elements. Figure 3D also highlights the scatter of individual participants' results, with some individuals expressing diametrically opposite judgments across modalities (e.g., 100% global responses for vision and <50% global responses for haptics or vice versa). To test whether these idiosyncratic cross-modal differences are related with age, we defined an index of visuo-haptic concordance as the absolute value of the difference in global responses across the two modalities (Figure 4).

For stimuli made of the largest local elements, cross-modal differences were large, as expected since the average global preference for visual and haptic stimuli were different (Figures 2 and 3; red symbols and lines). The results for stimuli made of the smallest local elements are more interesting. Although, on average, global preference was similar for visual and haptic stimuli, some participants showed large cross-modal differences (of opposite signs, which make them disappear in the averages of Figures 2 and 3, blue symbols and lines, and only emerge in Figure 4 where absolute values are used). These differences were particularly large in young children, smaller in adults. We verified that these trends are statistically significant with a new linear mixed model entered with the absolute value of the cross-modal difference for each stimulus configuration, studied as function of local element size (categorical variable with three levels: large, medium, small) and the participants' age (continuous variable, log-transformed), plus a random intercept to account for inter-individual variability. This revealed a significant local-size by age interaction ($F(1,2324) = 11.54$; $p = 6.94 \cdot 10^{-4}$) and no other significant main effects. Importantly, we excluded that the large cross-modal differences seen in young children could be explained by the

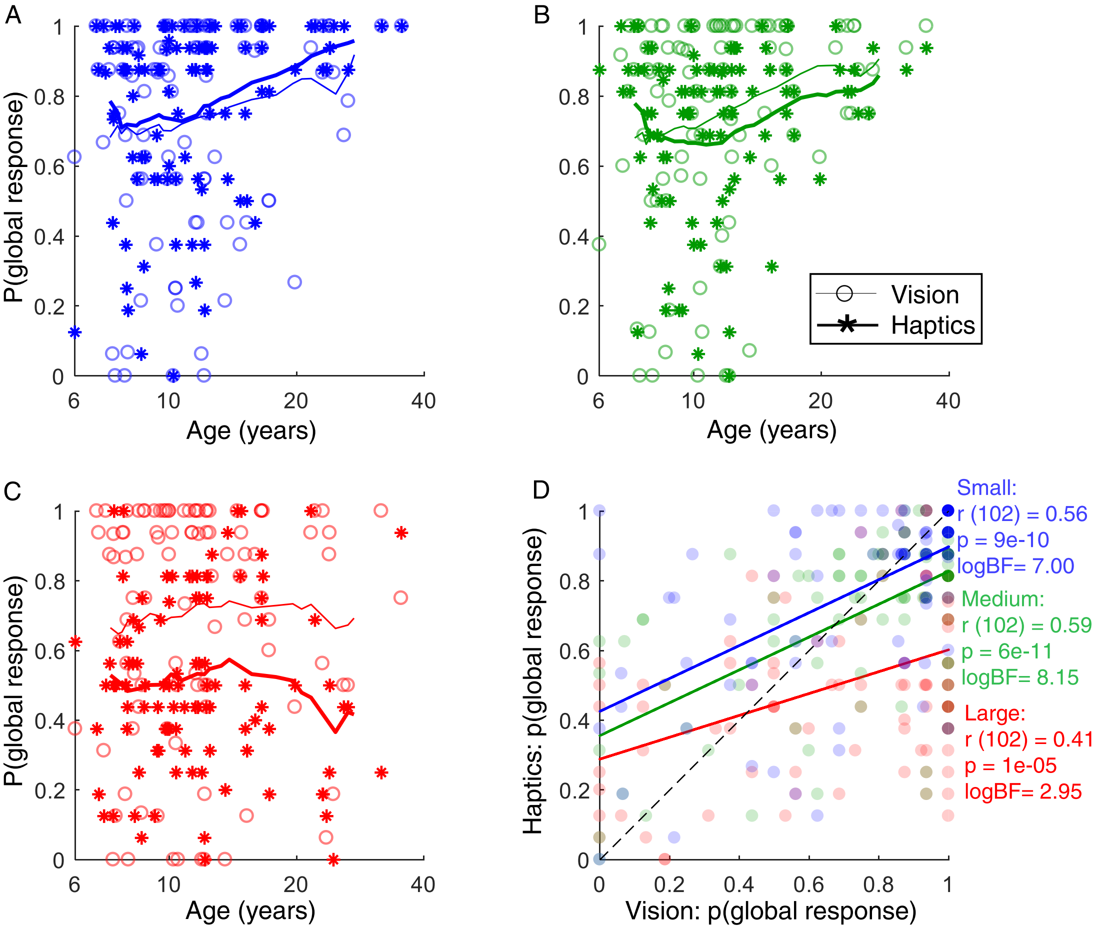

Figure 3. Individual proportion of global responses in small (A), medium (B), and large-size (C) stimuli for vision (open circles) and haptics (stars) as a function of age. Thin and dashed lines represent the running average of the proportion of global responses respectively for vision and haptics. (D) Correlation between global responses in vision (x-axis) and haptics (y-axis) for small (blueish dots), medium (greenish dots), and large size (reddish dots). The thick blue, green and red lines show the best-fitting linear regressions calculated on the average of individual proportion of global responses for small (blue line), medium (green line), and large (red line). The dashed black line shows the bisector of the axes. *Text inset* gives Pearson's correlation coefficient and associated *P* value and base-10 logarithm of the Bayes Factor (lgBF) for each size.

random variability of their judgments. We measured the split-half reliability by correlating the proportion of global responses on even and odd trials (within modality and local-element size). The results show that even young participants (from six years old to 35.37, median 11.6 years) had very high internal consistency, for both visual and haptic stimuli (split-half reliability in vision: $r(58) = 0.96$; $p = 8 \cdot 10^{-33}$, logBF $= 29.63$ and haptics: $r(58) = 0.87$; $p = 6 \cdot 10^{-19}$, logBF $= 16.03$).

As a final step of our analyses, we checked whether our results could be better accounted for by a covariate of the local element size, local element numerosity. One could imagine that the reduced global preference for stimuli made of largest (and fewer) local elements is driven by the degradation of the global information related to the low numerosity of components (Kimchi & Palmer, 1982; Martin, 1979).

We had the opportunity to test this hypothesis by comparing global responses for (target) stimuli of different global shapes: triangles and squares, that were necessarily composed of a different number of local elements (see Table 1). If the number of composing elements affected the quality of global information, one would predict higher global preference when the stimuli are composed of more numerous elements. Figure 5 shows that our results do not conform to this prediction – if anything, there is a trace of an opposite tendency. For example, triangles made of three large local items showed higher (not lower) global preference than squares made of four local items. Moreover, small local element stimuli, having the highest numerosity variation (global forms were composed of 10, 15 or 16 local items), show the smallest (not the largest) change in global preference across global shapes. Given the latter observation, we suggest that the tendency for slightly

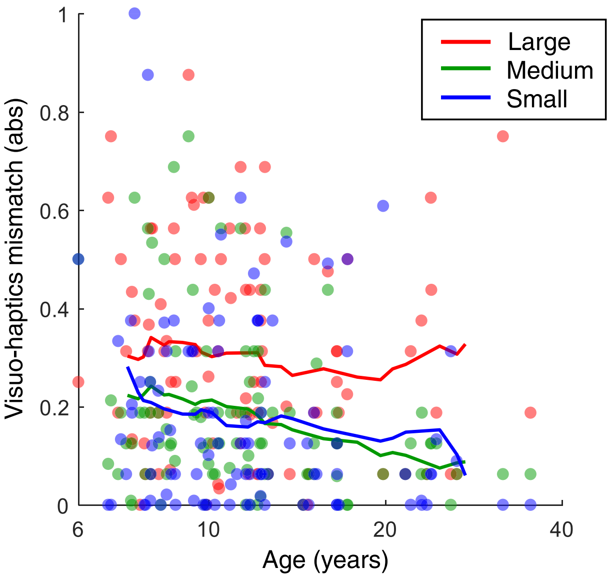

Figure 4. Absolute values of the difference of the proportions of global responses between modalities (visuo-haptics mismatch) as a function of age. Colored filled dots show the individual level of modality mismatch for large (reddish), small (blueish) and medium-size (greenish) stimuli. Different lines represent the running average for the modality mismatch in large (red); medium (green) and small (blue) size stimuli by function of age.

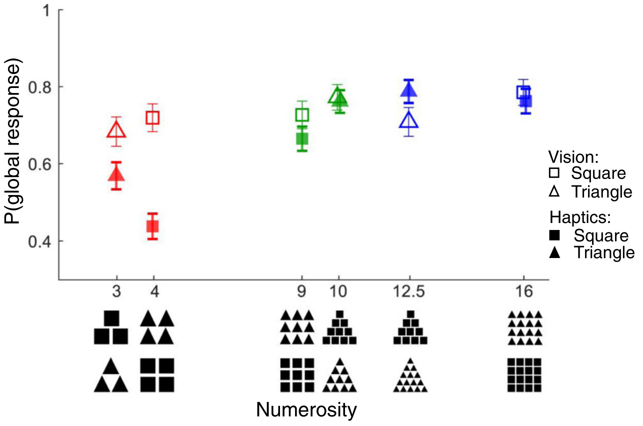

Figure 5. Proportion of global responses for different global shapes (squares and triangles) as a function of the number of local elements composing them. Notice that numerosity equal to 12.5 is the result of the average between 10 and 15 global triangles in small sizes stimuli. Examples of stimuli are given as icons under the numerosity line (x-axis). The figure reports three or four local items for large size stimuli, nine or 10 local items for medium size stimuli and 10, 15, or 16 local elements for small-size stimuli. Open and filled symbols refer, respectively, to visual and haptic stimuli and they show averages and SEM across all participants.

stronger global preference for triangle versus square global shapes is not a consequence of the numerosity of local elements. Rather, it may be an effect of shape complexity, where simpler shapes (defined by less vertices) are easier to segment or more salient.

Discussion

By comparing local-global preference for visually and haptically presented hierarchical stimuli in typical individuals, we found both similarities and discrepancies across modalities, depending on the size of the local elements comprising our stimuli. For stimuli made of our smallest local elements (0.1 cm^2), global preference was similar for visual and haptic stimuli, and it similarly changed with age, showing a progressive increase of global preference with increasing participants' age. Although children were nearly equally likely to match stimuli based on their local or global shape, adults systematically preferred to match them based on global shape. For stimuli made of our largest local elements (0.65 cm^2), however, there was no change in global preference with age, and there were notable disparities across modalities, with a less pronounced global preference for haptics than for vision. Thus increasing local element size interfered with our ability to reveal the expected development of global preference with age and with the coordination of global preference across modalities.

The interaction we observe between local element size and age is consistent with the few previous studies that looked at both of these variables together and generally found smaller age-related changes for stimuli made of larger local elements (Kimchi, Batsheva, Behrmann, & Palmer, 2005; Scherf, Behrmann, Kimchi, & Luna, 2009). Most previous studies separately looked at either variable, showing increased global preference for stimuli made of smaller local elements (Kimchi & Palmer, 1982; Martin, 1979) and a late progressive development of global preference through childhood and adolescence (Harrison & Stiles, 2009; Kimchi, 2015; Kimchi, Hadad, Behrmann, & Palmer, 2005; Poirel, Mellet, Houdé, & Pineau, 2008; see Goodenough, 1976; Wagemans et al., 2012 for reviews). The increase of global preference with age could be related to a variety of partially interdependent developmental factors. One is the maturation of visual integration, which progressively allows older children to piece together the local elements into a global whole or "Gestalt" (Akshoomoff & Stiles, 1995a; Akshoomoff & Stiles, 1995b; Kovács, 2000; Kovács, Kozma, Fehér, & Benedek, 1999). Another, related factor is the development of global attentional processing (Burack, Enns, Iarocci, & Randolph, 2000; Enns & Girgus, 1985), given that effective processing of global information is associated with the development of a right fronto-parietal brain network that begins to emerge around six years of age (Poirel et al., 2011) and continues to develop through childhood (Poirel et al., 2014) and adolescence (Mondloch, Geldart, Maurer, & de Schonen, 2003). The shift from local to global preference from childhood to adulthood has also been linked to the maturation of the object recognition system. Global precedence for Navon-like stimuli fits well with the coarse-to-fine temporal dynamics of the visual object recognition system (Gerlach & Poirel, 2017; Hegdé, 2008; Macé, Joubert, Nespoulous, & Fabre-Thorpe, 2009; Poncet & Fabre-Thorpe, 2014; Sanocki, 1993; Schyns & Oliva, 1994; Wu, Crouzet, Thorpe, & Fabre-Thorpe, 2014) and brain lesion patients with impairments in visual object recognition display atypical local-global preference (Behrmann & Kimchi, 2003; Gerlach, Marstrand, Habekost, & Gade, 2005; Gerlach & Poirel, 2017). However, only a few studies investigated how attention to local or global level may bias subsequent object processing (Large & McMullen, 2006; Lawson, 2007) and there is only one study that directly tested this hypothesis and found a positive correlation between performance in a Navon task and object recognition in adults (Gerlach & Poirel, 2017). Finally, global preference could be supported by the development of executive control (Krakowski et al., 2016), which involves the ability to inhibit salient information (e.g., inhibiting local processing to let the global configuration emerge) (Michael, Lété, & Ducrot, 2013).

The effect of local element size could be understood as a failure of any or all these mechanisms: when the local elements become larger, they gain salience, and they become more difficult to integrate across, preventing the global shape from dominating perception (Lakatos & Marks, 1999). The observed interaction between the size of local elements and participants' age could follow from this. By reducing the impact of global integration and local inhibition processes, large local elements make adults behave like children, both failing to display a global preference.

Previous studies also documented an effect of local element density, modulated by participants' age (Dukette & Stiles, 1996; Dukette & Stiles, 2001; Krakowski et al., 2018). No such effect was evident in our data, possibly due to a methodological peculiarity of our approach. Contrary to previous researches (Dukette & Stiles, 1996, 2001; Krakowski et al., 2018), we manipulated the density and number of local elements independently (resulting in density covarying with global size). Instead, previous authors (Dukette & Stiles, 1996; Dukette & Stiles, 2001; Krakowski et al., 2018) kept global size constant so that density and number of elements covaried. Interestingly, we found initial evidence that global preference is influenced by the complexity of the shape (with a tendency for increased global preference for simpler shapes: triangles compared to squares). Because the number of local elements limits the complexity of the shapes that can be defined (e.g., four elements are sufficient to form a square, but more are required for more complex shapes like a star), we suggest that stimulus complexity may be primarily responsible for further variations of global preference besides those produced by changing the size of local elements.

Our study is also one of the few comparing local-global preference across modalities (Berger & Hatwell, 1996; Lakatos & Marks, 1999); in line with these, most of our conditions reveal a reduced global preference for haptics compared to vision. We submit that there is a fundamental difference between haptic and visual exploration. Although vision usually starts with a global appreciation of the whole, the "gist" (Oliva & Torralba, 2006), haptic exploration of large extents must necessarily proceed sequentially through the exploration of small parts: small enough to be covered with our hands. Our paradigm was designed to minimize this fundamental cross-modal difference by using stimuli with small global size, easily covered by a (child) participant's hand. The success of our design is supported by our finding that global preference in both modalities and across age groups was unaffected by the (limited) variations in global size, which we produced by varying the density of local elements. This observation also suggests that haptic acuity was not a limiting factor under the conditions of our experiment. However, although there is evidence for an adult-like visual acuity by six years of age (see Lewis & Maurer, 2005 for a review), it is unclear whether haptic acuity continues to vary after the maturation of tactile receptors. Some studies suggested that tactile acuity improves through adolescence (Bleyenheuft, Cols, Arnould, & Thonnard, 2006; Bleyenheuft, Wilmotte, & Thonnard, 2010), others failed to detect changes with age (Peters & Goldreich, 2013) and others reported a decline (Stevens & Choo, 1996), possibly reflecting the increases in the hand's surface area (Peters, Hackeman, & Goldreich, 2009). In our data, we did not find evidence in support of either possibility as stimulus density failed to affect local-global preference in all age ranges.

However, one factor that did affect haptic global preference and produced a disparity between haptic and visual performance was the size of local elements. We found reduced global preference for stimuli made of larger local elements, which was more evident for haptically than visually explored stimuli. We suggest that this may result from enhanced saliency of large local elements as they are explored haptically versus visually, which could bias processing towards local details. This might happen as a direct consequence of a property of haptic exploration: the sequentiality (Lakatos & Marks, 1999; Lederman & Klatzky, 1987, 1993). Our hypothesis raises the question whether haptic exploration strategy was influenced by local element size. Although we could not address this possibility in the current study, we acknowledge that haptic exploration was highly constrained in our experiment (participants could not take the stimuli in their hands to manipulate them, but only explore their surface with their dominant hand), and this could have biased our participants' responses (Ballesteros, Manga, & Reales, 1997) for the effect of exploration strategies over haptic encoding; see also Lederman and Klatzky (1993) for a review of haptic exploration strategies and associated property extraction.

Although we highlight the discrepancy between visual and haptic responses that emerged as local element size increased, we note that most of our results are suggestive of a similar developmental trajectory for global preferences in vision and haptics. This is supported by the strong correlation between global proportions in vision and haptics across individuals of different age (Figure 2D). It is also supported by our measure of visuo-haptic mismatch, which progressively decreased for participants of increasing age (Figure 4). Young children could show strong preferences for local or for global, but these were often inconsistent across modalities and highly variable across individuals—yet not due to random noise, given their high test-retest reliability across stimulus repetitions. We can only speculate on the factors that could contribute to this variability. Environment may favor visual over tactile exploration in some but not other individuals, and children might be particularly prone to change their perceptual styles based on experience, given the strong plasticity potential that is characteristic of this age range (Cantor, Osher, Berg, Steyer, & Rose, 2019, for a review) . However, our results suggest that even as young individuals manifest these very disparate tendencies, their development into adulthood eventually brings them to converge toward a common global preference, similar across sensory modalities.

Conclusions

Overall, our results show that global preference tends to increase with age in both vision and haptics. However, global responses are modulated by the size of the stimuli: whereas for stimuli with medium and small local elements the global responses tend to increase, for large local stimuli there is no change with age. Moreover, our study highlights discrepancies in local-global preference across sensory modalities: vision and haptics. These are both systematic (dependent on the size of local elements) and idiosyncratic (variable across participants). However, they are especially evident in the youngest participants and are reduced as global preference increases with age, suggesting a similar developmental path across modalities.

Keywords: local-global perception, local-global preference, individual differences, visual development, haptics development

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Corresponding author: Chiara Tortelli.
Email: chiara.tortelli@gmail.com.
Address: Department of Translational Research on New Technologies in Medicine and Surgery, University of Pisa, Pisa, Italy.

References

Agresti, A. (2003). *Categorical data analysis, 482*. Hoboken, NJ: John Wiley & Sons.

Akshoomoff, N. A., & Stiles, J. (1995a). Developmental trends in visuospatial analysis and planning: I. Copying a complex figure. *Neuropsychology, 9*(3), 364, https://doi.org/10.1037/0894-4105.9.3.364.

Akshoomoff, N. A., & Stiles, J. (1995b). Developmental trends in visuospatial analysis and planning: II. Memory for a complex figure. *Neuropsychology, 9*(3), 378, https://doi.org/10.1037/0894-4105.9.3.378.

Baisa, A., Mevorach, C., & Shalev, L. (2019). Can performance in Navon letters among people with autism be affected by saliency? Reexamination of the literature. *Review Journal of Autism and Developmental Disorders, 6*, 1–12, https://doi.org/10.1007/s40489-018-0150-8.

Ballesteros, S., & Manga, D. (1996). The effects of variation of an irrelevant dimension on same - different visual judgments. *Acta Psychologica, 92*(1), 1–16, https://doi.org/10.1016/0001-6918(95)00003-8.

Ballesteros, S., Manga, D., & Reales, J. M. (1997). Haptic discrimination ofbilateral symmetry in 2-dimensional and 3-dimensional unfamiliar displays. *Perception & Psychophysics, 59*(l), 37–50.

Ballesteros, S., Millar, S., & Reales, J. M. (1998). Symmetry in haptic and in visual shape perception. *Perception and Psychophysics, 60*(3), 389–404, https://doi.org/10.3758/BF03206862.

Behrmann, M., & Kimchi, R. (2003). What does visual agnosia tell us about perceptual organization and its relationship to object perception? *Journal of Experimental Psychology: Human Perception and Performance, 29*(1), 19–42, https://doi.org/10.1037/0096-1523.29.1.19.

Berger, C., & Hatwell, Y. (1993). Dimensional and overall similarity classifications in haptics: A developmental study. *Cognitive Development, 8*(4), 495–516, https://doi.org/10.1016/S0885-2014(05)80006-1.

Berger, C., & Hatwell, Y. (1996). Developmental trends in haptic and visual free classifications: Influence of stimulus structure and exploration on decisional processes. *Journal of Experimental Child Psychology, 63*(3), 447–465, https://doi.org/10.1006/jecp.1996.0058.

Bleyenheuft, Y., Cols, C., Arnould, C., & Thonnard, J. L. (2006). Age-related changes in tactile spatial resolution from 6 to 16 years old. *Somatosensory and Motor Research, 23*(3–4), 83–87, https://doi.org/10.1080/08990220600816440.

Bleyenheuft, Y., Wilmotte, P., & Thonnard, J. L. (2010). Relationship between tactile spatial resolution and digital dexterity during childhood. *Somatosensory and Motor Research, 27*(1), 9–14, https://doi.org/10.3109/08990220903471831.

Bouhassoun, S., Poirel, N., Hamlin, N., & Doucet, G. E. (2022). The forest, the trees, and the leaves across adulthood: Age-related changes on a visual search task containing three-level hierarchical stimuli. *Attention, Perception, and Psychophysics, 84*(3), 1004–1015, https://doi.org/10.3758/s13414-021-02438-3.

Breitmeyer, B. G. (1992). Parallel processing in human vision: History, review, and critique. *Advances in Psychology, 86*, 37–78, https://doi.org/10.1016/S0166-4115(08)61349-7.

Burack, J. A., Enns, J. T., Iarocci, G., & Randolph, B. (2000). Age differences in visual search for compound patterns: long- versus short-range grouping. *Developmental Psychology, 36*(6), 731–740, https://doi.org/10.1037/0012-1649.36.6.731.

Cantor, P., Osher, D., Berg, J., Steyer, L., & Rose, T. (2019). Malleability, plasticity, and individuality: How children learn and develop in context1. *The science of learning and development*. (pp. 3–54). Abingdon, UK: Routledge, https://doi.org/10.1080/10888691.2017.1398649.

Chamberlain, R., Van der Hallen, R., Huygelier, H., Van de Cruys, S., & Wagemans, J. (2017). Local-global processing bias is not a unitary individual difference in visual processing. *Vision Research, 141*, 247–257, https://doi.org/10.1016/j.visres.2017.01.008.

Dukette, D., & Stiles, J. (1996). Children's analysis of hierarchical patterns: Evidence from a similarity judgment task. *Journal of Experimental Child Psychology, 63*(1), 103–140, https://doi.org/10.1006/jecp.1996.0044.

Dukette, D., & Stiles, J. (2001). The effects of stimulus density on children's analysis of hierarchical patterns. *Developmental Science, 4*(2), 233–251, https://doi.org/10.1111/1467-7687.00168.

Elkind, D., Koegler, R. R., Go, E., & Elkind, D. (1964). Studies in Perceptual Development: II. Part-Whole Perception. *Child Development, 35*(1), 81–90.

Enns, J. T., & Girgus, J. S. (1985). Developmental changes in selective and integrative visual attention. *Journal of Experimental Child Psychology, 40*(2), 319–337, https://doi.org/10.1016/0022-0965(85)90093-1.

Evers, K., Van der Hallen, R., Noens, I., & Wagemans, J. (2018). Perceptual Organization in Individuals With Autism Spectrum Disorder. *Child Development Perspectives, 12*(3), 177–182, https://doi.org/10.1111/cdep.12280.

Gerlach, C., & Krumborg, J. R. (2014). Same, same - but different: On the use of Navon derived measures of global/local processing in studies of face processing. *Acta Psychologica, 153*, 28–38, https://doi.org/10.1016/j.actpsy.2014.09.004.

Gerlach, C., Marstrand, L., Habekost, T., & Gade, A. (2005). A case of impaired shape integration: Implications for models of visual object processing. *Visual Cognition, 12*(8), 1409–1443, https://doi.org/10.1080/13506280444000751.

Gerlach, C., & Poirel, N. (2017). Navon's classical paradigm concerning local and global processing relates systematically to visual object classification performance. *Scientific Reports, 8*(1), 1–9, https://doi.org/10.1038/s41598-017-18664-5.

Gerlach, C., & Poirel, N. (2020). Who's got the global advantage? Visual field differences in processing of global and local shape. *Cognition, 195*(June 2019), 104131, https://doi.org/10.1016/j.cognition.2019.104131.

Gerlach, C., & Starrfelt, R. (2018). Delayed processing of global shape information is associated with weaker top-down effects in developmental prosopagnosia. *Cognitive Neuropsychology, 35*(8), 471–478, https://doi.org/10.1080/02643294.2018.1519505.

Goodenough, D. R. (1976). The role of individual differences in field dependence as a factor in learning and memory. *Psychological Bulletin, 83*(4), 675–694, https://doi.org/10.1037/0033-2909.83.4.675.

Harrison, T. B., & Stiles, J. (2009). Hierarchical forms processing in adults and children. *Journal of Experimental Child Psychology, 103*(2), 222–240, https://doi.org/10.1016/j.jecp.2008.09.004.

Hegdé, J. (2008). Time course of visual perception: Coarse-to-fine processing and beyond.

Progress in Neurobiology, 84(4), 405–439, https://doi.org/10.1016/j.pneurobio.2007.09.001.

Horlin, C., Black, M., Falkmer, M., & Falkmer, T. (2016). Proficiency of individuals with autism spectrum disorder at disembedding figures: A systematic review. *Developmental Neurorehabilitation, 19*(1), 54–63, https://doi.org/10.3109/17518423.2014.888102.

Kimchi, R. (1992). Primacy of wholistic processing and global/local paradigm: A critical review. *Psychological Bulletin, 112*(1), 24–38, https://doi.org/10.1037/0033-2909.112.1.24.

Kimchi, R. (2006). Relative dominance of holistic and component properties in the perceptual organization of visual objects. In M. A Peterson, & G Rhodes (Eds), *Perception of faces, objects, and scenes: Analytic and holistic processes* (pp. 235–263). Oxford: Oxford University Press, https://doi.org/10.1093/acprof:oso/9780195313659.003.0010.

Kimchi, R. (2015). The perception of hierarchical structure. In J Wagemans (Ed.), *Oxford handbook of perceptual organization* (pp. 129–149). Oxford: Oxford University Press.

Kimchi, R., Batsheva, H., Behrmann, M., & Palmer, E. S. (2005). Hemispheric processing of global form, local form, and texture. *Psychological Science, 76*(2), 133–147, https://doi.org/10.1016/0001-6918(91)90042-X.

Kimchi, R., Hadad, B., Behrmann, M., & Palmer, S. E. (2005). Microgenesis and ontogenesis of perceptual organization: Evidence from global and local processing of hierarchical patterns. *Psychological Science, 16*(4), 282–290, https://doi.org/10.1111/j.0956-7976.2005.01529.x.

Kimchi, R., & Palmer, S. E. (1982). Form and texture in hierarchically constructed patterns. *Journal of Experimental Psychology: Human Perception and Performance, 8*(4), 521–535, https://doi.org/10.1037/0096-1523.8.4.521.

Köhler, W. (1971). Human perception. In *The selected papers of Wolfgang Köhler* (pp. 142–167). New York: Liveright.

Kovács, I. (2000). Human development of perceptual organization. *Vision Research, 40*(10–12), 1301–1310, https://doi.org/10.1016/S0042-6989(00)00055-9.

Kovács, I., Kozma, P., Fehér, Á., & Benedek, G. (1999). Late maturation of visual spatial integration in humans. *Proceedings of the National Academy of Sciences of the United States of America, 96*(21), 12204–12209, https://doi.org/10.1073/pnas.96.21.12204.

Krakowski, C. S., Borst, G., Vidal, J., Houdé, O., & Poirel, N. (2018). Children inhibit global information when the forest is dense and local information when the forest is sparse. *Journal of Experimental Child Psychology, 173*, 155–167, https://doi.org/10.1016/j.jecp.2018.03.020.

Krakowski, C. S., Poirel, N., Vidal, J., Roëll, M., Pineau, A., & Borst, G. et al. (2016). The forest, the trees, and the leaves: Differences of processing across development. *Developmental Psychology, 52*(8), 1262–1272, https://doi.org/10.1037/dev0000138.

Lakatos, S., & Marks, L. E. (1999). Haptic form perception: Relative salience of local and global features. *Perception and Psychophysics, 61*(5), 895–908, https://doi.org/10.3758/BF03206904.

Large, M. E., & McMullen, P. A. (2006). Hierarchical attention in discriminating objects at different levels of specificity. *Perception and Psychophysics, 68*(5), 845–860, https://doi.org/10.3758/BF03193706.

Lawson, R. (2007). Local global processing biases fail to influence face, object, and word recognition. *Visual Cognition, 15*(6), 710–740, https://doi.org/10.1080/13506280601112519.

Lederman, S. J., & Klatzky, R. L. (1987). Hand Movements: A Window into Haptic Object Recognition. *Cognitive Psychology, 19*, 342–368.

Lederman, S. J., & Klatzky, R. L. (1993). Extracting object properties through haptic exploration. *Acta Psychologica, 84*(1), 29–40, https://doi.org/10.1016/0001-6918(93)90070-8.

Lewis, T. L., & Maurer, D. (2005). Multiple sensitive periods in human visual development: Evidence from visually deprived children. *Developmental Psychobiology: The Journal of the International Society for Developmental Psychobiology*, *46*(3), 163–183, https://doi.org/10.1002/dev.20055.

Liu, T. T., & Behrmann, M. (2014). Impaired holistic processing of left-right composite faces in congenital prosopagnosia. *Frontiers in Human Neuroscience, 8*(SEP), 1–11, https://doi.org/10.3389/fnhum.2014.00750.

Macé, M. J. M., Joubert, O. R., Nespoulous, J. L., & Fabre-Thorpe, M. (2009). The time-course of visual categorizations: You spot the animal faster than the bird. *PLoS ONE, 4*(6), e5927, https://doi.org/10.1371/journal.pone.0005927.

Martin, M. (1979). Local and global processing: The role of sparsity. *Memory & Cognition, 7*(6), 476–484, https://doi.org/10.3758/BF03198264.

Michael, G. A., Lété, B., & Ducrot, S. (2013). Trajectories of attentional development: An exploration with the master activation map model. *Developmental Psychology, 49*(4), 615–631, https://doi.org/10.1037/a0028410.

Milne, E., & Szczerbinski, M. (2009). Global and local perceptual style, field-independence, and central coherence: An attempt at concept validation. *Advances in Cognitive Psychology, 5*, 1, https://doi.org/10.2478/v10053-008-0062-8.

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, https://doi.org/10.1016/S0022-0965(02)00161-3.

Navon, D. (1977). Forest before trees: The precedence of global features in visual perception. *Cognitive Psychology, 9*(3), 353–383, https://doi.org/10.1016/0010-0285(77)90012-3.

Oliva, A., & Torralba, A. (2006). Chapter 2 Building the gist of a scene: the role of global image features in recognition. *Progress in Brain Research, 155*, 23–36, https://doi.org/10.1016/S0079-6123(06)55002-2.

Peters, R. M., & Goldreich, D. (2013). Tactile spatial acuity in childhood: Effects of age and fingertip size. *PLoS ONE, 8*(12), e84650, https://doi.org/10.1371/journal.pone.0084650.

Peters, R. M., Hackeman, E., & Goldreich, D. (2009). Diminutive digits discern delicate details: Fingertip size and the sex difference in tactile spatial acuity. *Journal of Neuroscience, 29*(50), 15756–15761, https://doi.org/10.1523/JNEUROSCI.3684-09.2009.

Poirel, N., Krakowski, C. S., Sayah, S., Pineau, A., Houdé, O., & Borst, G. (2014). Do you want to see the tree? Ignore the forest: Inhibitory control during local processing: A negative priming study of local-global processing. *Experimental Psychology, 61*(3), 205–214, https://doi.org/10.1027/1618-3169/a000240.

Poirel, N., Mellet, E., Houdé, O., & Pineau, A. (2008). First came the trees, then the forest: developmental changes during childhood in the processing of visual local-global patterns according to the meaningfulness of the stimuli. *Developmental Psychology, 44*(1), 245–253, https://doi.org/10.1037/0012-1649.44.1.245.

Poirel, N., Simon, G., Cassotti, M., Leroux, G., Perchey, G., Lanoë, C., . . . Houdé, O. (2011). The shift from local to global visual processing in 6-year-old children is associated with grey matter loss. *PLoS ONE, 6*(6), 1–5, https://doi.org/10.1371/journal.pone.0020879.

Poncet, M., & Fabre-Thorpe, M. (2014). Stimulus duration and diversity do not reverse the advantage for superordinate-level representations: The animal is seen before the bird. *European Journal of Neuroscience, 39*(9), 1508–1516, https://doi.org/10.1111/ejn.12513.

Sanocki, T. (1993). Time course of object identification: Evidence for a global-to-local contingency. *Journal of Experimental Psychology: Human Perception and Performance, 19*(4), 878–898, https://doi.org/10.1037/0096-1523.19.4.878.

Schellingerhout, R., Smitsman, A. W., & Cox, R. F. A. (2005). Evolving patterns of haptic exploration in visually impaired infants. *Infant Behavior and Development, 28*(3), 360–388, https://doi.org/10.1016/j.infbeh.2005.05.007.

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

Schyns, P. G., & Oliva, A. (1994). From blobs to boundary edges: Evidence for Time- and Spatial-Scale-Dependent Scene Recognition. *Psychological Science, 5*(4), 195–200, https://doi.org/10.1111/j.1467-9280.1994.tb00500.x.

Stevens, J. C., & Choo, K. K. (1996). Spatial acuity of the body surface over the life span. *Somatosensory & Motor Research, 13*(2), 153–166, https://doi.org/10.3109/08990229609051403.

Stone, J. (2013). *Parallel processing in the visual system: the classification of retinal ganglion cells and its impact on the neurobiology of vision.* Berlin: Springer Science & Business Media.

Titchener, E. B. (1902). *Experimental psychology of the thought-processes*. New York: Macmillan Company.

Wagemans, J., Feldman, J., Gepshtein, S., Kimchi, R., Pomerantz, J. R., & Van der Helm, P. A. et al. (2012). A century of Gestalt psychology in visual perception: II. Conceptual and theoretical foundations. *Psychological Bulletin, 138*(6), 1218, https://doi.org/10.1037/a0029334.

Wertheimer, M. (1923). Laws of organization in perceptual forms. In W. D. Ellis (Ed.), *A source book of Gestalt psychology* (pp. 71–88). London: Routledge and Kegan Paul.

Wetzels, R., & Wagenmakers, E. J. (2012). A default Bayesian hypothesis test for correlations and partial correlations. *Psychonomic Bulletin and Review, 19*(6), 1057–1064, https://doi.org/10.3758/s13423-012-0295-x.

Wu, C.-T., Crouzet, S. M., Thorpe, S. J., & Fabre-Thorpe, M. (2014). At 120 msec you can spot the animal but you don't yet know it's a dog. *Journal of Cognitive Neuroscience, 27*, 141–149, https://doi.org/10.1162/jocn.

Wundt, W. (1894). Grundzuge der Physiologischen Psychologie. *The American Journal of Psychology, 6* (2), 298–299, https://doi.org/10.2307/1410982.