

Development of object recognition in humans

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Abstract

Although the ability to perceive simple shapes emerges in infancy, the ability to recognize individual objects as well as adults do continues to develop through childhood into adolescence. Despite this slow development, recent neuroimaging studies have revealed that an area of the ventral visual cortex that responds selectively to the category of common objects is adult-like by 5-8 years of age. The challenge for future research will be to identify the specific visual skills involved in object recognition that continue to develop through childhood and adolescence, and the neural mechanisms underlying this protracted development.

Introduction and context

Adults have a remarkable ability to remember thousands of objects in great detail [1]. In addition to having an accurate visual memory of a particular object, adults have a flexible representation of objects that allows recognition of familiar objects under various viewing conditions (for example, lighting, viewpoint, color, retinal size) that change the retinal image. How such accurate and efficient recognition is accomplished is a question that has yet to be resolved [2], but new insights may be gained by examining how this ability develops with age. Consistent with the findings from the immense number of studies on face recognition and perception [3], the few studies examining non-face object perception and recognition reveal continuing improvement with age from young childhood into adulthood.

The antecedents of object recognition are evident in early infancy. For example, newborns preferentially orient towards visual stimuli with a face-like structure [4-6], which may provide an important diet of biased visual experience that supports later face (and perhaps object) recognition [7,8]. By 3-4 months of age infants can recognize three-dimensional shapes [9]. They also appear to have some understanding of shape parts - when familiarized with a compound object, infants show subsequent recognition of the component two-

dimensional shapes that went into forming the compound object [10]. This kind of form perception continues to improve rapidly along with more general visual abilities, such that by 6 years of age grating acuity and contrast sensitivity are adult-like [11], and by 9 years of age children are adult-like in perceiving global form in Glass patterns [12]. However, the perception (for example, classifying objects based on similarity) and recognition (for example, naming a familiar object) of more complex objects (for example, bicycles, teddy bears, abstract three-dimensional shapes) improves with age from young childhood to adolescence [13,14].

In particular, what appears to develop slowly are two important abilities involved in processing objects: the ability to differentiate exemplars within a particular object category (for example, two different cups), and the ability to recognize the same exemplar from multiple viewpoints that change the object's appearance quite dramatically (for example, a teapot seen from above looks quite different from the canonical side view). Describing the mechanisms underlying these abilities also provides the biggest challenge for studies of object recognition in the adult brain [2]. Developmental research with face stimuli has shown that children are particularly poor at processing the spatial relations among facial features [15]. This is arguably a critical

skill for object recognition more generally because two exemplars of the same category often differ primarily on the spatial relations among the object features, and because knowledge about the structural relations of salient features supports extrapolation to novel or unfamiliar views. Indeed, young children's similarity judgments about objects appear to rely more on the shape of salient features than on the spatial arrangement of those features [16,17], and sensitivity to the spatial arrangement of features continues to improve into adolescence [18,19]. However, it is unclear to what extent such age-effects reflect improvements in object perception *per se*, and/or more general visual abilities associated with form perception such as contour integration [20,21], and/or cognitive limitations in the ability to attend to and/or remember multiple features simultaneously [22,23]. Given that many aspects of perception and cognition improve with age, drawing conclusions about the development of object recognition *per se* is inherently difficult and requires appropriate control stimuli and tasks.

Major recent advances

In adults, efficient object recognition is supported, in part, through a division of labor, such that different classes of visual input are assigned to different underlying neural systems to mediate the representation of that object type [24]. For example, recent studies using functional magnetic resonance imaging (fMRI) have revealed category-specific activation in adult ventral visual cortex when viewing common objects, faces, buildings, and scrambled image patterns. This foundation of work is ideal for assessing potential developmental changes in the functional topography of ventral visual cortex. In adults, faces consistently activate a lateral portion of the posterior fusiform gyrus, called the fusiform face area [25], a lateral region in inferior occipital cortex called the occipital face area [26], and the superior temporal sulcus [27], whereas non-face objects primarily activate a region of the lateral occipital cortex (LOC) [28], and images of buildings and scenes activate a region of the parahippocampal gyrus called the parahippocampal place area [29]. Two recent neuroimaging studies have shown that children as young as 5-8 years of age demonstrate adult-like category-selectivity for objects in the LOC [30,31]. This finding is in striking contrast to the relatively slow development of the face-selective areas, which are smaller and vary greatly in location in young children and even in adolescents up to 16 years of age compared with adults [30,31]. However, it is unclear what early maturation of area LOC represents in terms of recognizing individual objects (as opposed to object categories) or the same object from various viewpoints, because the LOC is

defined simply as the area that shows greater blood-oxygen-level-dependent activation when viewing common objects relative to other classes of visual stimuli. Additionally, when observers are unexpectedly given an old-new recognition task to recall objects seen during the fMRI scan, recognition performance of common objects does not correlate with the size of LOC activation in children, adolescents, or adults (there was also no difference in recognition performance across the three age groups), even though recognition of faces correlated with right fusiform face area activation, and recognition of places correlated with left parahippocampal place area activation [30].

In adults, progress has been made to identify the functional properties of the LOC using fMR-adaptation paradigms [32]. Repeated presentations of the same object image suppress LOC activation relative to sequential presentations of different objects. To the extent that this suppression effect is maintained even as changes are made to a particular object (for example, size, position, viewpoint), rather than 'released', the LOC is said to be invariant to such image properties [28,32]. Previous studies with adults showed that the LOC is invariant to changes in object size and position, but not viewpoint [28,32,33]. Whether such adaptation effects will be observed in children and adolescents remains to be tested. Findings from such studies may reveal limitations in the neural basis of invariant object representations in children, which would be consistent with the behavioral evidence of delayed object perception.

Future directions

In summary, the behavioral research suggests that the ability to recognize objects continues to develop from childhood into adolescence, and results from developmental fMRI studies reveal that area LOC shows robust category selectivity for common objects in children as young as 5-8 years of age. Nothing is currently known about developmental changes in the neural substrate supporting the formation of integrated invariant representations of individual objects, or faces for that matter. The challenge for future studies then, is to combine fine-grained behavioral measurements with neuroimaging techniques so that we can begin to understand how such representations and their neural foundation emerge developmentally.

Currently, there is a clear lack of behavioral research in young children (age 2-6 years) and adolescents (age 12-16 years) with appropriate control tasks to determine their ability to recognize objects despite concomitant immaturities in general visual abilities, attention, and

memory. Recently, paradigms utilizing adaptation after-effects have been used successfully with face stimuli [34] and may also be useful in examining the underlying mental representation of common objects. In addition, studies that use naturalistic stimuli, such as videos of objects from multiple views within a scene, may be important for future developmental research.

There is also very little known about the neural mechanisms underlying object recognition in infants and young children. The existing studies have been conducted in the context of understanding memory development and have primarily evaluated infants' and children's abilities to distinguish familiar from unfamiliar stimuli. These studies suggest that brain activity, as measured by event-related potentials, evoked by visual processing of faces and common objects, develops greatly during the first year of life [35]. Infants' event-related potentials (ERPs) can also reliably discriminate a highly familiar (for example, infant's mother's face or infant's favorite toy) versus a novel exemplar (for example, an unfamiliar female face or toy) by 18 months of age [36]. Therefore, electroencephalography may be a particularly useful method for examining the neural correlates of object recognition in infants and young children. Future studies should investigate how well infants discriminate and recognize entirely novel exemplars within an object category.

Another potentially exciting avenue for future research is to examine dorsal stream contributions to the development of object recognition. There is some suggestion that action perception may aid in young children's object recognition [37]. Consistent with the notion that action may influence perception, fMR-adaptation has been used to reveal the existence of object representations in the dorsal stream of adults [33]. If areas in the dorsal stream that are relevant for object recognition mature earlier than the ventral stream, as has been suggested [38], then the interactions between the dorsal and ventral streams may play a large role in bootstrapping the acquisition of invariant object representations.

The key for future research will be studies that correlate neural activity, as measured by fMRI, ERP, or even magnetoencephalography, with behavioral performance in the same infants/children to elucidate the development of visual mechanisms subserving object recognition. Findings from these investigations will provide a foundation of knowledge about one of the most essential questions in the cognitive and neural sciences, namely, how accurate and efficient object recognition is accomplished. Such work will also provide a benchmark for assessing deviations in many neurodevelopmental

disorders that affect visuoperceptual processing, like autism and Williams syndrome. In addition, identifying the neural regions supporting behavioral development of object recognition will direct targeted investigations of the neural code underlying adult object recognition, which could, in turn, provide important insights for implementing machine vision. Critical to the goal of developing a comprehensive theory of the emergence and instantiation of sophisticated object recognition abilities is to ensure consistency and transparency of methods and stimuli so that results may be comparable across different samples and age ranges.

Abbreviations

ERP, event-related potential; fMRI, functional magnetic resonance imaging; LOC, lateral occipital cortex.

Competing interests

The authors declare that they have no competing interests.

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