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# What Atypical Adults Can Teach Us about Development

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In my presidential address, I described the early trap I fell into of describing the super-baby capable of one after another adult perceptual ability, then how I discovered that two atypical populations of adults allowed me to study developmental *mechanisms*, namely, the role of early sensory input in sculpting the nervous system and the biological preparedness that constrains the experiential effects. Specifically, studies of adults who had dense central cataracts during childhood revealed that there are multiple critical periods during which visual input alters the potential of the nervous system for later refinement. Studies of adults with synesthesia generated novel hypotheses, subsequently supported experimentally, about the details of the biological preparedness that bias the child's early learning. Nevertheless, later studies indicated that considerable residual plasticity remains in adulthood.

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I spent my academic career at McMaster University in Hamilton, Ontario. I arrived there in 1973 already aware of the value of measuring babies' eye movements. The evidence was the several hundred boxes of punched computer cards I brought with me from Minneapolis, where I had done my Ph.D. at the University of Minnesota's Institute of Child Development. Like today, we measured babies' fixations by filming, every fraction of a second, the reflections off the infant's cornea of lights embedded in the stimulus so that we could measure their positions relative to the center of the pupil (Haith, 1969; Maurer, 1975). Those locations corresponded systematically to changes in the infant's fixation point. But, unlike today, the calculations were not automatic; instead, we tediously measured the xy coordinates of each light reflection and the center of the pupil, creating one punch card per film frame. Then, I wrote a computer program to quantify the distance of each of the reflections from the center of the pupil and to translate the distances into the location of the baby's fixation on the stimulus. The results of running the program generated a new box of 2,000 punch cards containing the results for 9 min of looking from one eye of one baby. The approach revealed that young infants fixate visual stimuli but that they look mainly at large, contrasty pieces of the external contour, whether they are shown triangles (Salapatek, 1968; Salapatek & Kessen, 1966), squares containing smaller squares (Salapatek, 1975), or faces (Haith, Bergman, & Moore, 1977). Only beginning about 2 months do infants scan more broadly and fixate internal features of objects, including faces (Hainline, 1978; Haith et al., 1977; Maurer & Salapatek, 1976).

This was valuable knowledge but not a good research strategy for an untenured assistant professor. So I was delighted when Les Cohen began promulgating a new tool for measuring infants' vision: the combination of habituation to criterion and infant-controlled trials (Cohen, 1969; see also Horowitz, Paden, Bhana, & Self, 1972). During an infant-controlled trial, a single stimulus remains on the screen for as long as the baby looks at it. Observers record that looking time. The stimulus is repeated until the looking time decreases to a predefined criterion of habituation. Then, a test is given that includes trials with the original stimulus and trials with a novel stimulus—importantly, with order counterbalanced and the observers blind to the identity of the stimulus on each trial. Longer looking at the novel than at the original stimulus signals that the babies can discriminate the two stimuli and remember the first stimulus well enough to recognize it, at least for a short time. Cohen's subsequent work showed that a habituation criterion of a 50% reduction in looking on three consecutive trials is more sensitive than more lenient criteria (e.g., a 30% reduction) (Pancratz & Cohen, 1970). In the late 1970s, I used this method to establish that 1-month-olds can discriminate orientation, an important finding signaling that the visual cortex must be functional by that age (Maurer & Martello, 1980); that 2-month-olds can discriminate among a schematic drawing of a face and various scrambled versions (Maurer & Barrera, 1981); and that 3-month-olds can recognize a photograph of the mothers' face (Barrera & Maurer, 1981a), as well as discriminate between unfamiliar female faces (Barrera & Maurer, 1981b) and between sad and happy facial expressions (Barrera & Maurer, 1981c). In some of these papers, I gloated that we had pushed the age when these skills can first be demonstrated to earlier points in development because of our use of more sensitive techniques. Tenure was secure. I anticipated many more studies of this type on perceptual skills known to be important in adults.

Thinking about the likely role of exposure, we went on to test 3-month-olds' ability to discriminate between the faces of unfamiliar males and to recognize the face of the father. The results were positive, paralleling the findings we had already published about the mother's face (Barrera & Maurer, 1981a). I confidently wrote up the results and submitted them to *Child Development*, the journal that had published most of the previous work. The paper was rejected! One reviewer's comments were piercing: *she has shown babies can recognize the mother's face; now she wants to publish the same story for the father's face; what's next: grandmother, uncle, and the family dog?* I was stunned. But on further reflection I realized that the reviewer had a point. My research strategy had been essentially antidevelopmental: I was showing that the super baby is able to demonstrate important adult capabilities at earlier and earlier ages. Doing so is indeed important as a starting point but it does not elucidate developmental mechanisms, how these abilities change with age and experience or how they are mediated at different ages. To do so—to illuminate development—requires a different approach. I found a way by turning to two atypical populations.

The first atypical population is children who suffered a period of visual deprivation because they were born with dense central cataracts in both eyes that block patterned input to the retina until the cataracts were removed surgically and the child fit with compensatory contact lenses. We studied a cohort of such children from the moment they could first see: the day of contact lens fitting after the eyes had healed from the surgery. To do so, we used preferential looking acuity: the smallest stripes eliciting longer looking than a plain gray matched in luminance (Lewis & Maurer, 1986). When the babies who were born with cataracts could first see, their acuity was like that of a normal newborn, regardless of whether the treatment was near birth or as late as 9 months of age (Maurer, Lewis, Brent, & Levin, 1999). That finding indicates that in the child with normal eyes, the rapid improvement in visual acuity over the first year (Mayer et al., 1995) is driven by visual input. But the system was not dormant during the deprivation: the acuity of the cataract-reversal patients improved after just 1 h of visual input, to the level of the typical 6-week-olds (Maurer et al., 1999). It continued to improve at a faster-than-normal rate, so that by the first birthday, patients' acuity was normal (Lewis, Maurer, & Brent, 1995). In other words, the system is experience-expectant, getting ready to respond rapidly to visual input once it is received. The clinicians relaxed, thinking they had achieved an effective intervention. Unfortunately, our longitudinal approach revealed a sleeper effect (Maurer, Mondloch, & Lewis, 2007): about age 2, the acuity of cataract-reversal patients stopped improving while that of children with normal eyes continued to improve slowly until about age 7, with a twofold improvement after age 2 (Lewis et al., 1995). That pattern indicates that early visual input is critical for setting up the neural architecture for later improvements. In its absence, for as little as the first 2 months of life, deficits emerge later, presumably because the necessary neural substrate is missing.

Our studies of children who had similar visual deprivation because of dense, central bilateral cataracts—but with a postnatal onset—revealed that a short period of visual deprivation any time during the first 7 years of life causes an acuity deficit, but the later the onset of the deprivation, the smaller the deficit (Lewis & Maurer, 2009). The implication is that during the entire 7-year period during which acuity improves in the child with normal eyes, visual input is necessary to drive the changes. Even when the onset of visual deprivation was after age 7—after the age when acuity is adult-like, and hence, the neural substrate is presumably mature—acuity deficits emerged when the onset was before age 10. The implication is that in the child with normal eyes, visual input is essential to consolidate or crystallize the connections between ages 7 and 10. After the age of 10, the critical period for damage is over: a period of visual deprivation no longer diminishes visual acuity.

It was tempting to think we had discovered the one and only critical period for visual development. Fortunately, we went on to test other visual capabilities, including ones requiring integration of local elements into global percepts, processes that, unlike acuity, depend on extrastriate cortical areas. One example is global motion: the ability to look at many vectors of local motion, moving in multiple directions, yet perceive the overall direction of drift. We do this whenever we look at a flock of moving birds or a crowd leaving a stadium. In the laboratory, sensitivity to global motion can be tested with random dot kinematograms in which dots move in multiple random directions except for a percentage of dots all moving coherently in the same direction (Newsome & Pare, 1988). To prevent a solution based on following a single dot, each dot has a limited lifetime, being reborn frequently in new positions. A measure of sensitivity to the global direction of motion can be calculated as the smallest percentage of dots that need to be moving coherently for the observer to determine that direction at a specified level of accuracy, such as 71%. The exact threshold depends on the parameters of the dots (their velocity, displacement, etc.).

In our setup, adults with normal eyes have thresholds of less than 10%, that is, over 90% of the dots can move in random directions yet the observers can detect the direction of movement of the coherently moving dots. Adults treated as infants for bilateral congenital cataracts can do the task, but they require 40–50% of the dots to be moving coherently in order to do so accurately. In other words, their thresholds are 4–5 times worse than normal (Ellemberg, Lewis, Maurer, Brar, & Brent, 2002; Hadad, Maurer, & Lewis, 2012). This is surprising because sensitivity to the direction of motion only emerges postnatally around 3 months of age (Braddick, Birtles, Wattam-Bell, & Atkinson, 2005) and then takes many years to become adult-like (Hadad, Maurer, & Lewis, 2011). Yet adult patients whose deprivation had ended before 3 months of age showed a deficit as large as those whose deprivation ended later. This is another example of a sleeper effect: visual deprivation during the first few months, before the first signs of sensitivity emerge, alters the neural architecture necessary for later refinement. In other words, visual input during the first few months in the child with normal eyes is setting up the cortical architecture for later acute sensitivity to global motion.

Adults for whom the deprivation began postnatally, as early as 8 months of age, had completely normal thresholds for global motion, despite having abnormal acuity as expected (Ellemberg et al., 2002). Thus, the critical period for damage to global motion is very short. Combined, the data indicate that early visual input is necessary for both low-level and high-level visual capabilities, but that the duration of the critical period for damage (10 years for acuity; <8 months for global motion) cannot be predicted from the age of emergence of a visual function (by birth for acuity; 3 months for global motion) nor from the duration of its developmental trajectory (7 years for acuity; with some parameters, as long as 12 years for global motion).

Some aspects of visual development are not damaged by early visual deprivation, either because there was no damage or because complete recovery is possible by adulthood (Mondloch, Lewis, Levin, & Maurer, 2013). Thus, adults treated for bilateral congenital cataracts are (nearly) normal at distinguishing a face from a scrambled image (Mondloch et al., 2013), at discriminating among basic shapes and among faces differing in the shape of facial features (Maurer, Lewis, & Brent, 1989; Mondloch, Robbins, & Maurer, 2010), at discriminating facial expressions (Gao, Maurer, & Nishimura, 2013), and at decoding biological motion in point light walkers (Hadad et al., 2012). These skills may be undamaged because they can be mediated by the low spatial frequencies for which the cataract-reversal patients have normal sensitivity (Ellemberg, Lewis, Maurer, Lui, & Brent, 1999). Interestingly, all of the intact skills are present in rudimentary form at birth, that is, the neural substrate was able to develop before visual input.

Combined, our studies of cataract-reversal patients indicate that newborn babies are biologically prepared to learn to see: they emerge from the womb already able to distinguish faces from scrambled images (although this may be based on basic properties such as top-heaviness, positive contrast, and spatial congruity [Cassia, Valenza, Simion, & Leo, 2008; Farroni, Menon, & Johnson, 2006; Simion, Valenza, Cassia, Turati, & Umilta, 2002], discern some basic shapes (Fantz, 1965), and recognize the patterns of movement made by biological organisms (Simion, Regolin, & Bulf, 2008)). These abilities guide the initial scanning of newborn infants and are preserved (or are able to recover) despite early visual deprivation. Other visual abilities, even though they may first be manifest postnatally, arise because early visual input sculpts the brain to allow their later emergence. When it is absent, sleeper effects are evident later. How long early visual input is critical depends on the particular visual ability and cannot be predicted by its developmental trajectory.

The second atypical population—adults with synesthesia—allowed me to learn more about the biological preparedness. *Synesthesia* is derived from the Greek routes *syn* (union) and a*esthis* (sensation). It comes in at least 63 forms, but the common denominator is that an external stimulus evokes both the expected percept (e.g., hearing a C sharp) and an additional percept, often in a different sensory modality (e.g., perceiving vermillion triangles or tasting oranges that are not quite ripe) (Ramachandran & Hubbard, 2003). It occurs in 4–5% of the population, equally in males and females and is consistent over time (Simner & Logie, 2007; Simner et al., 2006). Synesthetes' reports that the extra percepts occur automatically are backed up by Stroop-like interference and fMRI patterns of activation. If the synesthete reports that C sharp evokes vermillion, he/she takes longer to name a yellow patch accompanied by the playing of a C sharp compared to naming a vermillion patch or a neutral condition without sound (Nikolić, Lichti, & Singer, 2007). Such synesthetes also demonstrate activation of color area V4 while listening to music (Hubbard, Arman, Ramachandran, & Boynton, 2005). Synesthetes also report that they have had it all their lives and that it tends to run in their family

(Day, 2005; Rich, Bradshaw, & Mattingley, 2005). They are fond of their extra percepts, which enliven their perceptual worlds and aid them in memory tasks and some basic discriminations (Banissy, Walsh, & Ward, 2009; Yaro & Ward, 2007).

Adults with synesthesia are interesting to a developmental psychologist because their cortical wiring appears to preserve a more infantile state: with more exuberant connections, presumed to be the result of less experience-dependent pruning, and less feedback inhibition, both of which lead to sensory cortical and parietal areas which are less specialized. Support for this hypothesis comes from evidence in adults with synesthesia of increased gray and white matter in adults, of more short and less long-range resting state connectivity, and of fewer inhibitory interactions (Dovern et al., 2012; Hänggi, Wotruba, & Jäncke, 2011; Hubbard, Brang, & Ramachandran, 2011; Neufeld et al., 2012; Rothen & Terhune, 2012; Rouw & Scholte, 2007; van Leeuwen, den Ouden, & Hagoort, 2011; Volberg, Karmann, Birkner, & Greenlee, 2013). The implication is that the perception of the young child and the adult with synesthesia will have some similarities. Thus, synesthesia can be used as a source of novel hypotheses about young children and vice versa (Spector & Maurer, 2009).

As predicted, common patterns of extra percepts in adults with synesthesia can be demonstrated in young children. For example, a common form of synesthesia is to perceive black letters in color. Although the exact colors evoked by each letter tend to be idiosyncratic in adults with colored grapheme synesthesia, for some letters they agree on the color for a given letter more often than expected by chance (Day, 2005; Rich et al., 2005; Simner et al., 2005). For those same letters, similar color-letter associations are found in adults without synesthesia. Some of these shared associations appear to be rooted in learning to read: for Anglophone synesthetes B tends to be Blue; Y to be yellow, V to be violet, G to be green, and R to be red. A tends to be red, perhaps because we learn as children that A is for apple and apples are red. Other shared associations are difficult to explain based on literacy: Cs are yellow, Is and Os are white, Xs and Zs are black. Ferrinne Spector and I predicted that the associations explained by literacy would emerge after the child learns to read, but that the others might be intrinsic to the wiring of the nervous system, to the specific interconnections between visual form and visual color areas. As predicted, a “find the hidden letter” game revealed that toddlers—who do not yet know how to read and barely know a few letters of the alphabet—searched for I and O in the white side of a black-and-white box, X and Z on its black side, and C on the yellow side of a yellow-and-blue box (Spector & Maurer, 2008, 2011). It’s hard to fathom how these connections might be learned. Rather, they appear to reflect intrinsic brain organization that affects the natural associations of toddlers, the cross-modal matches of adults, and the actual synesthetic percepts of adults with colored grapheme synesthesia. In contrast, toddlers were random in searching for A and G in a red-and-green box and for B and Y in a blue-and-yellow box. These associations emerged only in 7- to 9-year-old children who had begun to learn to read and they remained as cross-modal associations in the nonsynesthetic adults we tested, as they do in Anglophone adults with colored grapheme synesthesia. They clearly reflect learning.

Adults with synesthesia also provide new insights about young children's cross-modal perception. Although the specific colors elicited by distinct pitches varies across synesthetes, those colors increase systematically in lightness with increases in pitch (Ward, Huckstep, & Tsakanikos, 2006). The same association is apparent in adults without synesthesia asked to make color associations to variations in pitch. There is no obvious basis for this association in learning: black mice squeak as sharply as white mice and the roar of a polar bear does not depend on whether it is black or white. Our analysis suggested that this might be another natural correspondence reflecting intrinsic interconnectivity of tonotopically organized auditory cortical areas and color areas of the visual stream. As predicted, toddlers—who do not yet know metaphors like *dark notes*—indicated that a darker ball was making a lower pitched sound when it bounced and that a lighter colored ball was emitting the higher pitched sound (Mondloch & Maurer, 2004).

Based on the evidence for the preservation of a more infantile, or less specialized, brain in synesthesia, one also can make predictions in the other direction, namely, that synesthetic perception will resemble in some respects the less specialized perception of the young infants. We have explored this possibility by studying the phenomenon of perceptual narrowing, one of the consequences of experience-dependent pruning in the typically developing child. Perceptual narrowing describes the phenomenon that infants around 3–6 months are equally good at discriminating among native stimuli to which they are exposed as among non-native stimuli they never experience, but toward the end of the first year, they fail the same task with non-native contrasts, while showing maintained or improved discrimination of the native contrasts (Maurer & Werker, 2014). For example, Caucasian 6-month-olds are as good at discriminating among Asian faces as among Caucasian faces but 3 months later, they fail the test with Asian faces while continuing to pass the test with their native ethnicity (Kelly et al., 2007). Similarly, (Caucasian) 6-month-old infants are as good at discriminating among monkey faces as they are among (Caucasian) human faces but at 9 months, they fail the test for monkey faces while continuing to show evidence of discriminating among human faces (Pascalis, de Haan, & Nelson, 2002; Pascalis et al., 2005). A parallel process occurs for speech sounds: 6-month-old infants can discriminate as well between two non-native speech sounds, such as the Hindi dental and retroflex /ta/ for English-learning infants, as they can two native sounds such as /ra/ and /la/. (Werker & Tees, 1984). By 12 months of age, English-learning infants, unlike Hindi-learning infants, fail to show evidence of continued discrimination of the Hindi /ta/ contrast. Given the less specialized brains of adults with synesthesia, we predicted that they may have undergone less perceptual narrowing. In a recent study that prediction proved correct: adults with synesthesia were better than controls at discriminating between monkey faces and at discriminating a non-native Hindi dental versus retroflex /da/.

These examples illustrate how we have used the atypical percepts of adults with synesthesia to generate novel hypotheses about biological preparedness, here manifest as natural correspondence between attributes that are unrelated to the statistical regularities the child encounters in the environment (Maurer, Gibson, & Spector, 2012, 2013). In turn, this approach has allowed us to gain new insights about adults with synesthesia, based on our knowledge of the developmental mechanisms that lead to specialized sensory cortical areas. By adulthood those areas are largely confined to processing one sensory modality and can no longer be altered by sensory deprivation, that is, all known critical periods for damage have ended. As a consequence, we usually assume they are no longer plastic and hence that it is too late for any effective sensory rehabilitation. To evaluate that tenet, we recently attempted to improve the vision of adults who had been treated for bilateral congenital cataracts in whom we had documented a large number of seemingly permanent visual deficits.

The rehabilitative treatment we chose was to have them play an action video game, Medal of Honor, for 10 h a week over 4 weeks. We chose that approach because the game combines vision for action (moving a joystick to shoot off a gun) from a first person perspective, is titrated to the player's level of performance, requires monitoring the central and peripheral visual fields simultaneously, is highly motivating, and is known to enhance dopamine and hence perhaps makes the brain more changeable. Playing it for 10–40 h also enhances many aspects of vision even in those with normal eyes (Green & Bavelier, 2006, 2007; Li, Polat, Makous, & Bavelier, 2009). Our sample included seven adults, aged 19–31, who had been treated for bilateral congenital cataracts at 3–10 months of age (Jeon, Lewis, & Maurer, 2012). They completed a full day of pretests, demonstrating deficits in acuity (range 20/50 to 20/100 in the worse eye), spatial and temporal contrast sensitivity, sensitivity to global motion, discrimination of faces, peripheral vision, and stereopsis, as we had expected from our previous research. After 40 h of game play, the post-tests indicated improvements in acuity, sensitivity to high spatial frequencies and low temporal frequencies, sensitivity to global motion, and discrimination of upright but not inverted faces. There were no changes in stereopsis or peripheral vision. Like recent work with strabismic and anisometropic amblyopes (Baroncelli, Maffei, & Sale, 2011; Bavelier, Levi, Li, Dan, & Hensch, 2010; Clavagnier, Thompson, & Hess, 2013; Levi & Li, 2009; Li, Ngo, Nguyen, & Levi, 2011; Li et al., 2013), these results illustrate that despite the importance of early visual input for sculpting the brain, the adult brain is still malleable. Future research is needed to discern whether the improvements arise from rewiring sensory cortical areas so that external stimuli elicit clearer signals and/or from modifying higher cortical areas so that an unchanged noisy signal can better attract attention. In other words, does training serve to tune in the station on an old-fashioned radio or to teach us to hear the announcer despite the static? Whatever the answer, the results imply that the adult brain, although highly specialized through intrinsic connections and early sensory experience, nevertheless can be modified.

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