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Neonatal Synesthesia: A Reevaluation

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In *The World of the Newborn*, Charles and Daphne Maurer (1988) proposed that the normal newborn is synesthetic. They argued that “the newborn does not keep sensations separate from one another, but rather “mixes sights, sounds, feelings, and smells into a sensual bouillabaisse” in which “sights have sounds, feelings have tastes,” and smells can make the baby feel dizzy (p. 51). In later publications, D. Maurer and Mondloch provided additional evidence for this hypothesis (Maurer, 1993; Maurer & Mondloch, 1996) and distinguished strong and weak forms of it (Maurer & Mondloch, 1996). The purpose of this chapter is to review the basis for the original hypothesis and to reevaluate it in light of the evidence since 1996 on the neural basis of synesthesia, on developmental plasticity, and on cross-modal interactions in nonsynesthetic adults and children.

The Original Hypothesis

The hypothesis grew out of paradoxical evidence of U-shaped development of cross-modal perception: Babies demonstrated successful linking of information across sensory modalities near birth, failed at similar tasks later in infancy, and then appeared to gradually learn cross-modal links in the second half of the first year of life. For example, 1-month-olds who saw a patch of white light repeatedly for 20 trials showed evidence of habituation to that light and to a sound at a level identified by adults as best matching the intensity of the light. When another group was shown a more intense light, evidence of habituation shifted to a more intense sound (Lewkowicz & Turkewitz, 1980). Evidence of the young infant’s ability to link auditory and visual information extends beyond intensity matching to synchrony—the

synchrony of sound to the visual impact of a dropped object (Bahrick, 2001) and the synchrony of a spoken passage to lip movements of a stranger's face (Pickens et al., 1994). There is also evidence of links between touch and vision: After a familiarization period during which they mouthed a hard pacifier, 1-month-olds preferred to look at a novel, soft, deforming pacifier (and vice versa) (Gibson & Walker, 1984), and after tactual habituation to one object (e.g., a six-pointed star or a plain square), 2- to 3-month-olds demonstrated a similar preference to look at the novel shape (e.g., a six-pointed flower or a square with a central hole) (Steri, 1987). Apparent imitation of tongue protrusion also suggests integration between vision (e.g., the sight of a model sticking out his or her tongue or of any looming visual stimulus, Jacobson, 1979) and proprioception (i.e., the feeling of sticking out the tongue or of making similar movements with other appendages; Gardner & Gardner, 1970). (Note that some interpretations of the phenomenon do not involve cross-modal integration (e.g., the baby "reaches" with the tongue toward an interesting visual stimulus; Jones, 1996).

Despite such evidence of cross-modal integration near birth, there are surprising failures at later ages and evidence of the baby's subsequently learning to integrate differentiated senses. The most striking evidence comes from three studies that used the same procedure at different ages and found success at younger ages followed by failure later in infancy. For example, Pickens et al. (1994) found that 5- to 6-month-old full-term infants looked randomly at the adult reciting the passage they were hearing when that was paired with an adult reciting a different passage, while younger (3- to 4-month-old) and older (7- to 8-month-old) infants looked preferentially at the adult reciting the matching passage. Similarly, unlike younger infants (Steri, 1987), 4- to 5-month-olds fail to look differentially at two objects after tactile habituation to one of them (Steri & Pêcheux, 1986). The frequency with which babies stick out their tongue in response to a visual model also decreases systematically after the first month (Abravanel & Sigafos, 1984; Fontaine, 1984; Heimann, Nelson & Schaller, 1989) and gradually reemerges later in infancy as the baby appears to learn the connection between movements of his or her own face and those of a visual model (e.g., Piaget, 1952).

Adultlike Synesthesia at Birth

We proposed that the apparent cross-modal integration in early infancy results from synesthetic perception. In one form of the hypothesis (which we originally called the "strong form"), young infants resemble synesthetic adults in whom stimulation of one sensory modality evokes a percept not only in that modality (such as hearing the presented sound or seeing the achromatic letter) but also a specific percept in a second modality (or along a second dimension, such as color). Thus, when the baby is habituated to an

auditory stimulus, he or she simultaneously perceives and is habituated to the corresponding visual stimulus. This hypothesis is consistent with what is known about the brain basis of synesthesia and neural development during infancy. Colored word hearing (synesthesia in which specific sounds or letters evoke colored percepts) appears to be based on unusual connections between cortical areas. In such synesthetes, hearing words evokes evidence of neural activity not only in the auditory cortex but also in extrastriate visual cortex (Gray, Williams, Nunn & Baron-Cohen, 1997; Nunn et al., 2002), in a number of higher visual areas (Paulesu et al., 1995) and, in one study, even in the primary visual cortex (Aleman, Rutten, Sitskoorn, Dautzenberg & Ramsey, 2001). (Alternatively, such connections may exist in all adult brains but may be released from inhibition in synesthetes; Grossenbacher & Lovelace, 2001). In contrast, the synesthesia of one gustatory synesthete was correlated with cortical suppression. Synesthesia increased with cortical depressants like ethanol and amyl nitrate and decreased with cortical stimulants like amphetamines, nicotine, and caffeine. A PET scan confirmed a decrease in cortical blood flow through the parietal, frontal, and temporal cortices while the subject reported the synesthetic induction of tactile feeling (e.g., cold glass columns) by odorants (Cytowic, 1989). There is also evidence for suppression of some areas of sensory visual cortex during colored word hearing (Paulesu et al., 1995) and a pattern of event-related potentials during the induction of colored graphemes that is consistent with suppression of activity in the frontal cortex (Schiltz et al., 1999). Cytowic (1989) speculated that synesthesia is mediated by the limbic system, a speculation consistent with evidence that lesions of the monkey's amygdala abolish cross-modal matching between vision and touch while not interfering with matching within either modality (Murray & Mishkin, 1985). Thus, synesthesia might arise either from unusual connections between cortical areas or from cortical suppression.

There is ample anatomical evidence that young organisms have transient connections between cortical areas that will subsequently be pruned (DeHay, Bullier & Kennedy, 1984; DeHay, Kennedy & Bullier, 1988; Huttenlocher, 1994; Kennedy, Bullier & DeHay, 1989) and that the cortex of the human newborn is hardly functioning, as evidenced by anatomical immaturities, low levels of blood flow, and failure at behavioral marker tasks (reviewed in Atkinson & Braddick, 2003; Braddick, Atkinson & Hood, 1996; de Haan & Johnson, 2003). Moreover, there is anatomical evidence that the limbic system develops relatively early (reviewed in Benes, 1994) and behavioral evidence that it may be functional at birth (Pascalis & de Schonen, 1994). Thus, the newborn might have synesthetic perceptions because some of the transient connections are functional and/or because the limbic system is functioning with little specific input from the cortex. According to this form of the hypothesis, a stimulus such as a tone induces more than one percept for

the baby—one in the inducing modality (hearing the tone) and one or more in other modalities (e.g., seeing a red color or tasting a sweet substance induced by the tone). In the strongest form of the hypothesis, unlike synesthetic adults, the baby is unable to differentiate real from synesthetically induced percepts (e.g., seeing a red object versus “seeing” a red-inducing tone; tasting sweet milk versus “tasting” a sweet-inducing tone). Of course, because of cortical immaturity, none of the baby’s percepts is as richly differentiated as those of adults: red will not look as saturated and sweet will not taste as complex.

A Special Neonatal Form of Synesthesia

Another form of the hypothesis (which we originally called “weak form”; Maurer & Mondloch, 1996) is that, largely because of an immature cortex, the baby does not differentiate stimuli from different modalities, but rather responds to the total amount of energy, summed across all modalities. The baby is aware of changes in the pattern of energy and recognizes some patterns that were experienced before, but is unaware of which modality produced the pattern. As a result, the baby will appear to detect cross-modal correspondences when stimuli from different modalities produce common patterns of energy change. When presented with a human voice, the baby may experience a pattern of changing oscillations and recognize their similarity to patterns experienced before from the same voice. Although aware of the oscillations, the baby does not yet perceive them as sound per se. As a result the baby may not differentiate between the pattern of oscillations created by the voice and by a stimulus from another modality—a bouncing ball or rhythmic stroking that creates the same frequency of oscillations. Additional evidence for this form of the hypothesis is that the newborn’s visual preferences and sleeping patterns are related to total amount of stimulation, with equivalent effects of increasing stimulation within one modality and adding a moderate level of stimulation from another modality (e.g., Brackbill, 1970, 1971, 1973, 1975; Gardner, Lewkowicz, Rose & Karmel, 1986; Greenberg & Blue, 1977; Lewkowicz, 1991; Lewkowicz & Turkewitz, 1981; Turkewitz, Gardner, & Lewkowicz, 1984).

This form of the hypothesis resembles Zelazo’s (1996) claim that the young infant has only first-level minimal consciousness in which the baby perceives objects but is unaware of whether he or she is seeing or feeling them. Newborns’ perception may be analogous to the mandatory fusion of information from different visual cues that occurs in adults’ perception of depth (Hillis, Ernst, Banks & Landy, 2002). Adults can perceive the slant of an object based on the changes in the texture on its surface or from binocular disparity and perceive it more accurately when those cues are consistent. However,

when those cues are made inconsistent in the laboratory, adults’ patterns of errors indicate that they cannot access information from the separate visual cues: they appear to perceive slant but not the visual cues specifying that slant. In adults, no such mandatory fusion occurs between visual and tactile cues to depth: performance is better if the cues are consistent, but it does not deteriorate if the cues are inconsistent, a pattern indicating fused cross-modal perception without loss of information from each modality. Unlike adults, a similar mandatory fusion may occur across modalities for infants, such that they perceive an object but lose access to information about the modality supplying the information.

Unlike synesthetic adults who experience two percepts—one in the inducing modality and a second in the synesthetic modality—the baby may experience just one percept for a given pattern of energy change, a percept that is the same whether the pattern is heard, seen, or tasted. Alternatively, the baby may experience different percepts when the energy change is heard rather than seen or tasted but may be less aware than adults of the modality of input and much more sensitive than adults to similarities across modalities in the pattern of energy change. This enhanced sensitivity will diminish as transient connections are pruned and as a more specialized cortex exerts more control. Thereafter the baby learns to interrelate differentiated senses, but remnants of the synesthesia persist in cross-modal influences (see “Synesthetic Correspondences in Children and Adults”).

In the next section we explore evidence for transient connections between cortical areas during infancy. Such evidence comes from three sources: experimental studies with animals in which the sensory input to cortical regions is altered “natural” experiments involving deaf and blind humans, and neuroimaging and behavioral studies involving infants.

Evidence for Transient Connections during Infancy

Cortical Plasticity

Recent evidence on cross-modal plasticity suggests that the immature cortex is less specialized than it will be later in development. Altering the input to primary sensory cortices early in life is sufficient to change the nature of their specialization. The most striking examples come from studies in which retinal axons in the ferret are induced to replace the normal auditory innervation of the medial geniculate nucleus (MGN), where they establish an orderly visuospatial map. Neurons in the auditory cortex, to which the MGN projects, become sensitive to visual orientation, direction of motion, and velocity and mediate visual percepts (reviewed in Sur & Leamey, 2001).

These results suggest that the specialization of primary sensory cortex is largely determined by the nature of the inputs it receives. Studies in cats indicate that the mere absence of the normal sensory input (e.g., because of enucleation of the eyes at birth) is sufficient to induce responses to auditory stimuli in the primary visual cortex (Yaka, Yinon & Wollberg, 1999; reviewed in Bavelier & Neville, 2002). These effects are thought to reflect the stabilization of transient connections and/or the unmasking of silent inputs that would normally not be revealed or might even be inhibited (reviewed in Rauschecker, 1995; Bavelier & Neville, 2002). During normal development, these connections would be diminished through Hebbian competition in which the more frequent activation by input from the "correct" sensory modality increases the strength of the "correct" synaptic connections. Because such competitive effects have been demonstrated to operate within the visual modality over periods as short as 1 hr, they are unlikely to arise from the formation of new synaptic connections. Rather, they are likely to reflect competitive influences on preexisting connections (reviewed in Rauschecker, 1995). There is evidence of such competitive interactions in one fMRI study of synesthetes with colored hearing: in the control group, seeing colors activated an extrastriate visual cortical area called V4 in both hemispheres; in the synesthetes, hearing words activated that area in the left hemisphere and seeing colors did so only in the right hemisphere, as if the auditory input had captured V4 in the left hemisphere through Hebbian competition to the detriment of the normal visual input (Nunn et al., 2002).

Blind Adults

Human studies confirm that when the normal sensory input is missing (because of blindness or deafness), the primary visual and auditory cortices can become responsive to other sensory inputs. Neuroimaging studies using PET and fMRI have documented that, in adults blind from an early age, reading Braille activates the visual cortex, including much of extrastriate visual cortex and, in most studies, the primary visual cortex (Burton et al., 2002; Melzer et al., 2001; Sadato et al., 1998, but see Büchel, Price, Frackowiak & Friston, 1998). For example, in one study, while blind subjects read Braille, the increase in the fMRI signal over the baseline resting period was only 2% less from the primary visual cortex than it was from the sensorimotor cortex (Melzer et al., 2001). Because tactile input from feeling the Braille characters would be routed only to the hemisphere contralateral to the hand, yet the activation of visual cortex by Braille was bilateral, the reorganization is likely to reflect changes in cortical connections rather than in subcortical inputs to the visual cortex (Sadato et al., 1996). The functional importance of the visual cortical activity is indicated by the disruptive effect of transcranial magnetic stimulation placed so as to temporarily deactivate the visual cortex.

Adults blind from an early age reported that Braille dots did not make sense, that some were missing, and that extraneous phantom dots appeared, and their error rates increased significantly (Cohen et al., 1997; Cohen et al., 1999). No such disruption occurred when TMS deactivated other cortical areas. Additional evidence that the visual cortex plays a functional role in the ability to read Braille comes from a congenitally blind woman who lost that ability suddenly when she suffered a bilateral occipital stroke at age 63, despite intact peripheral sensitivity (Hamilton, Keenan, Catala & Pascual-Leone, 2000).

The visual cortex of congenitally blind persons is also responsive to sound. In a recent fMRI study (Röder, Sock, Bien, Neville & Rösler, 2002), spoken sentences activated left auditory cortical areas in both sighted and blind subjects, but in blind subjects, spoken sentences also activated primary and extrastriate visual areas, with a pattern that was related to syntactic and semantic difficulty: The harder the task, the greater the activation of visual cortex. Researchers using magnetoencephalography and event-related potentials (ERPs) have also noted that responses to oddball stimuli (an infrequent auditory frequency or location or incongruent word) are recorded from electrodes over the visual cortex only from people blind from an early age (Kujala et al., 1995; Leclerc, Saint-Amour, Lavoie, Lassonde & Lepore, 2000; Liotti, Ryder & Waldoff, 1998; Röder, Rösler & Neville, 2000; Röder et al., 1999), although not while the subjects are reading Braille (Kujala et al., 1995), as would be expected from the evidence presented above that the visual cortex plays an active role in decoding Braille. Overall, the evoked responses are more sharply tuned to variations in the auditory stimulus in blind subjects than in sighted subjects, and, correspondingly, blind subjects localize peripheral auditory sounds more precisely (Leclerc et al., 2000; Lessard, Paré, Lepove & Lassonde, 1998; Röder et al., 1999). The pattern of lateralization is also unusual, with more bilateral responses to language than in sighted adults (Röder et al., 2000, 2002), as is true in young infants, a pattern suggesting that transient connections for language in the right hemisphere have become stabilized.

The increased activation in visual cortex revealed by PET and fMRI when congenitally blind subjects process tactile or auditory information contrasts with decreased activation in some of these same areas in normally sighted subjects doing the same tasks (Sadato et al., 1998; Weeks et al., 2000). Although the decreased activation in normally sighted subjects could reflect merely a shift of attention away from vision when processing information from other modalities, the pattern is consistent with models postulating that synesthetic visual percepts reflect the activation of intercortical connections that are normally suppressed (e.g., Grossenbacher & Lovelace, 2001). Visual stimuli deactivate the auditory cortex (and vice versa), but only when presented alone (Laurienti et al., 2002). When a multimodal stimulus is

presented, activation levels in the visual (or auditory) cortex are equivalent to the level of activation seen when only a visual (or auditory) stimulus is presented. That interpretation—that many intracortical connections are present but suppressed in the adult brain—is also consistent with evidence that the visual cortex of the blind is active during Braille reading, even when the onset of blindness was as late as 13 years of age, and there are some, albeit smaller, changes when the onset of blindness was even later (e.g., Burton et al., 2002; Cohen et al., 1999) or when normally sighted adults learn to be better at discriminating Braille characters during 5 days of training while blindfolded (Kauffman, Théoret & Pascual-Leone, 2002). In any event, studies of congenitally blind persons document that the visual cortex, including the primary visual cortex, can be made to respond to auditory and tactile input. The evidence from TMS, stroke patients, and animal models suggest that the responses in visual cortex contribute to somatosensory and auditory percepts.

Deaf Adults

Similar effects to those found for blind subjects have been documented for the congenitally deaf. Visual presentation of moving dots or sign language activates auditory cortical areas, including primary auditory cortex, based on position emission tomography (PET) and functional magnetic resonance imaging (fMRI) measurements (Finney, Fine & Dobkins, 2001; Nishimura et al., 1999, 2000; see Neville, 1995, for ERP evidence), and so does vibrotactile stimulation produced by resonances in a tube the subject is holding (Levänen, Jousmääki & Hari, 1998). Combined with the evidence from congenitally blind persons, these studies suggest that the transient connections between cortical areas present in early infancy are modified postnatally by the type of input received. Input arriving from the “wrong” modality can stabilize the connection if the “right” input is missing, presumably through Hebbian competition, and/or such input can prevent normal inhibitory mechanisms from developing.

Neuroimaging Studies with Infants

Evidence using neuroimaging techniques with infants indicates that the transient connections may be functional and supports at least a special form of neonatal synesthesia. There is evidence for the influence of auditory input on the infants’ somatosensory and visual cortices and for the influence of visual input on the infants’ auditory cortex. For example, stimulation of the wrist elicits a somatosensory evoked response in both newborns and adults, but only in newborns is its magnitude enhanced when wrist stimulation is accompanied by white noise (Wolff, Matsumiya, Abrohms, van Velzer & Lombroso, 1974). Spoken language elicits large ERP responses over

temporal regions in both adults and infants, but only in infants does it also elicit a large response over visual cortex (Neville, 1995), much as it does in blind adults (Leclerc et al., 2000; Liotti et al., 1998; Röder et al., 2000). fMRI studies show that spoken words also elicit activity over both temporal and visual cortices in synesthetes (e.g., Aleman et al., 2001; Nunn et al., 2002; Paulesu et al., 1995). Finally, at 2 months of age, PET activation in response to faces, relative to illuminated diodes, includes areas that will be differentially activated by faces in adults: an area within the right inferior temporal gyrus that is homologous to the adult fusiform face area and bilateral activation of inferior occipital cortex (Tzourio-Mazoyer et al., 2002; but see Dehaene-Lambertz, Dehaene & Hertz-Pannier, 2002). In addition, in infants faces activate the left inferior frontal and superior temporal gyri—areas that later become associated with language. Collectively, these results suggest less specificity of cortical areas during early infancy. Specificity increases during the first three years of life. For example, by 36 months the ERP response over the visual cortex in response to spoken language has declined to adultlike levels (Neville, 1995).

Behavioral Evidence

Recent behavioral studies that explore cross-modal correspondences during infancy are also consistent with the hypothesis that senses are not separate from one another in newborns. Molina and Jouen (2001) measured the frequency with which newborns squeezed smooth and granular objects and found that they squeezed smooth stimuli more frequently than granular stimuli. During the test period, the newborns were presented with the same tactile stimulus and a visual stimulus. The visual stimulus either matched (e.g., smooth–smooth) or did not match (e.g., smooth–granular) the tactile stimulus. Frequency of squeezing did not change when a matching visual stimulus was presented. However, frequency of squeezing increased when the granular tactile stimulus was accompanied by the smooth visual stimulus and decreased when the smooth tactile stimulus was accompanied by the granular visual stimulus. Molina and Jouen concluded that newborns are able “to compare texture density information across modalities” (p. 123). It is our contention that these results indicate a merging of the senses; newborns’ handling of the tactile stimulus varies with the overall pattern of energy rather than with the texture of the tactile stimulus per se. Thus, the smooth–smooth and granular–granular combinations simply supply reflections of the same pattern of energy experienced in the first part of the study. The combined pattern of energy evoked by the smooth tactile–granular visual combination represents an increase in energy over smooth tactile alone and evokes the same frequency of squeezing as a granular texture. The combination of granular texture with a smooth visual pattern represents

a reduction in energy in the synesthetic compound and hence yields the increased frequency of squeezing evoked by a smooth texture alone. Indeed, similar changes in frequency of squeezing might be observed if the tactile stimulus were accompanied by a pulsating versus a continuous tone.

Newborns do show evidence of learning some cross-modal correspondences that are not arbitrary—learning that is consistent with the neonatal synesthesia hypothesis because it may be based on similar patterns of neural firing in two sensory areas that are not yet differentiated. For example, after being habituated to a single toy that was both collocated and synchronous with a sound, newborns' looking time increased (i.e., they showed a novelty response) when the toy was presented on the opposite side of the midline from the sound (Morrongiello, Fenwick & Chance, 1998). Furthermore, after habituation to two objects, only one of which was collocated with sound, newborns looked longer when the sound was located with the other toy. Likewise, Bahrick (2001) showed that 4-week-old infants are sensitive to synchrony: they dishabituate when they see an asynchronous auditory-visual event after being habituated to a synchronous event. By 7 weeks of age, infants also show sensitivity to composition—another amodal relationship. After being habituated to a single object that was synchronous with a single-impact sound and to a cluster of objects that was synchronous with a multiple-impact sound, 7-week-olds looked longer when the sound-object pairings were reversed. Sensitivity to amodal correspondences may be based on shared patterns of neural stimulation (e.g., timing, spatial representation, proportion of fibres activated, Cytowic, 2002; Marks, 1987) and facilitate the infant's learning of more arbitrary relations (Bahrick, 2001). Sensitivity to arbitrary sound-object pairings (e.g., shape-pitch) emerges much later (Bahrick, 1994; Fernandez & Bahrick, 1994; see also Reardon & Bushnell, 1988).

Synesthetic Correspondences in Children and Adults

Although young children and adults with normal perception do not experience visual percepts in response to auditory stimuli, under a variety of conditions they appear to experience cross-modal interactions that parallel those experienced by synesthetes. This is evident in tasks involving sensory matching, perceptual judgments, and language.

Sensory Matching

Nonsynesthetic adults match higher-pitched tones with smaller, brighter lights (Marks, Hammael & Bornstein, 1987) and the lighter of two gray

squares (Marks, 1974). They also match louder tones with brighter lights (Marks et al., 1987) and with larger objects (Smith & Sera, 1992). Some of these cross-modal correspondences can be attributed to intensity matching. This explanation can be invoked whenever subjects are asked to match stimuli that vary along dimensions we describe in more-end terms (i.e., "prothetic" dimensions), such as size, loudness, and brightness (Smith & Sera, 1992; Stevens, 1957): "big," "loud," and "bright" are more than "small," "quiet," and "dim," respectively. Thus, a match of the bigger of two objects or the brighter of two lights to the louder of two sounds could be based on intensity matching. However, intensity matching cannot be invoked if one of the dimensions is "metathetic" and cannot be described in more-end terms. Although "loud" is more than "quiet," and "bright" is more than "dim," adults do not describe either achromatic color (surface lightness) or pitch in more-end terms. Dark gray, for example, is not more than light gray, and "treble tones" are not more than bass tones." Thus, although adults match "large" with "bright" (Marks et al., 1987), they do not match "large" with either dark or light gray (Smith & Sera, 1992). Thus, the correspondences that both synesthetes and nonsynesthetic adults report between pitch and surface lightness and between pitch and size cannot be attributed to intensity matching.

Some correspondences may be learned (e.g., larger objects do make louder sounds than smaller objects when dropped, and smaller musical instruments, such as a violin, do make higher-frequency sounds than larger musical instruments, such as a cello). These learned correspondences are slow to develop. Unlike adults, two-year-olds do not match size and loudness; it is not until 3 years of age that children match the larger of two objects with the louder sound (Smith & Sera, 1992). Likewise, the correspondence between pitch and size is not adultlike in young children. Although adults match a higher pitch with a smaller light in a perceptual matching task, 9-year-olds do not; nor do they understand cross-modal metaphors involving pitch and size (Marks et al., 1987; but see below for evidence of pitch-size matching in 3-year-olds when tested with a more child-friendly procedure).

Other correspondences are not learned through experience. It is hard to imagine a learned basis for the correspondence between surface lightness and pitch—lighter objects do not make higher-pitched sounds in the real world. We hypothesize that unlearned correspondences that cannot be based on intensity matching are remnants of neonatal synesthesia. Consequently, they ought to be present throughout development. We have tested correspondences between pitch and both size and surface lightness in young children (Mondloch & Maurer, in press). We showed 30- to 36-month-olds a movie of two balls bouncing in synchrony with each other and with a central sound that varied in frequency. The balls differed in size and/or surface lightness. Each child was asked to point to the ball that was making the sound. Based on previous research (Marks et al., 1987), we predicted that the pitch-size

correspondence, which may be learned, would be either absent or weak. In contrast, if the correspondence between pitch and surface lightness reported by both synesthetes and nonsynesthetes is a remnant of neonatal synesthesia, then young children ought to associate the lighter ball with the higher-pitched sound. In experiment 1, the balls differed in both size and surface lightness. Eleven of the twelve children said that the smaller, white ball was making the higher-pitched sound or that the larger, gray ball was making the lower-pitched sound ($p < .01$). In experiment 2 both balls were the same size, but they differed in surface lightness. Every child ($n = 12$) said that the white ball was making the higher-pitched sound. In experiment 3, both balls were white, but they differed in size. Only 9 of the 12 children matched the smaller ball with the higher-pitched sound ($p = .07$). We tested an additional 12 children; 10 of these children matched in the expected direction ($p < .05$).

Thus, when a child-friendly procedure is used, children as young as 30–36 months tend to match higher-pitched sounds with smaller objects, perhaps as a result of learning. However, this correspondence may be weaker than that between pitch and surface lightness. Because both pitch and surface lightness are metathetic, the pitch–surface lightness correspondence cannot be attributed to intensity matching. Furthermore, pitch and surface lightness are not reliably related in the real world, so this correspondence cannot be attributed to learning. Rather, our results support the hypothesis that some cross-modal correspondences have their origin in neonatal synesthesia.

Cross-modal influences on perceptual judgments. Adults' perceptual judgments are influenced by seemingly irrelevant input from other sensory modalities, with a pattern of correspondences similar to those reported by synesthetic adults. For example, adults are more accurate at identifying the odor of solutions that have the appropriate color (e.g., red–cherry) than an inappropriate color (e.g., red–lemon; Zellner, Bartoli & Eckard, 1991). In addition, they report that odors presented in colored solutions smell stronger than odors presented in colorless solutions (Zellner & Kautz, 1990), and the more saturated the color, the stronger the effect, regardless of whether the color is appropriate; red mint smells stronger than pink mint. Similarly, adults' discrimination of visual stimuli is influenced by auditory distractors: their performance is better if there is a synesthetic match (bright light/high pitch) than if the match is opposite (Marks, 1987; Melara, 1989). We contend that such cross-modal influences in adults arise from remnants of neonatal synesthesia.

Language

Additional evidence of natural correspondences in nonsynesthetic adults abounds in human language, as evidenced by the preponderance of cross-modal metaphors, such as “soft light” and “loud colours.” Not only do adults

match brighter lights with louder tones, they also rate sunlight as louder than moonlight (Marks et al., 1987). Furthermore, metaphors in which a visual noun is modified by an auditory word (e.g., “a loud tie”) are much more common both in English and German literature than are metaphors in which an auditory noun is modified by a visual word (e.g., “bright thunder”; Day, 1996)—a pattern that parallels synesthesia.

Systematic investigations of the role of language in cross-modal correspondences have demonstrated that words denoting loudness, brightness, pitch, and surface lightness act in much the same way as sensory stimuli that vary on these dimensions. Adults rate “bright coughs” as louder than “dim coughs,” and “loud sunlight” as brighter than “quiet sunlight” (Marks, 1982), just as they match brighter lights with louder tones (Marks et al., 1987). Likewise, they rate “bright” sneezes as higher pitched than “dim” sneezes and violins as brighter than thunder (Marks, 1982), just as they match higher pitched tones with lighter and brighter visual stimuli (Marks, 1974; Marks et al., 1987). Not only are sensory dimensions that adults match in laboratory studies mirrored in metaphors, but sensory dimensions that adults fail to match in laboratory tasks are not related metaphorically. Dark squares are not consistently matched with louder/quieter tones (Marks, 1974) and dark piano notes are not rated as much louder than bright piano notes (Marks, 1982).

Ramachandran and Hubbard (2001) suggest that synesthetic correspondences between sensory dimensions have not simply facilitated the production and understanding of cross-modal metaphors, but may have “boot-strapped” the very evolution of language. Adults rate angular nonsense figures as more aggressive, more tense, stronger, and noisier than rounded shapes (Marks, 1996); they also are more likely to label angular shapes “takete” or “kiki” and rounded shapes “maluma” or “bouba”—perhaps because there is a correspondence between the visual percept, the phonemic inflections, and the movement of the tongue on the palate that results from the same cortical connections among contiguous cortical areas that underlie synesthesia (Ramachandran & Hubbard, 2001). Ramachandran and Hubbard also point out that the movements made to produce words conveying large objects frequently involve widening the vocal tract (e.g., large, huge), whereas words describing small objects often involve narrowing the vocal tracts (e.g., teeny, tiny). This tendency may be the result of natural constraints on sensory and motor maps, which are in turn linked in nonarbitrary ways to an object's appearance. Additional evidence reviewed by Ramachandran and Hubbard consists of mirror neurons (neurons that fire not only when a complex manual task is performed but also when a monkey watches a conspecific perform a complex task), and synkinesia (cross-activation of motor maps; e.g., the tendency to point both lips and fingers when referring to someone else).

Although cross-modal correspondences may have boot-strapped the evolution of language, Martino and Marks (1999) argue that language now plays a central role in mediating cross-modal correspondences in adults. According to their model, information from multiple sources (e.g., vision, audition, touch) “converges on a shared, abstract, semantic representation” (p. 921; see also Martino & Marks, 2001). When asked to classify stimuli (e.g., nonsense figures as angular/rounded; tones as high/low pitched), adults perform better when the stimulus is accompanied by a stimulus from another modality that is congruent, rather than incongruent (Marks, 1987). For example, adults’ reaction time is faster when classifying tones as high/low pitched if the lower pitched tone is accompanied by a black square or a word printed in black ink, and if the higher pitched tone is accompanied by a white square or a word printed in white ink. That semantic codes may come to mediate these effects is evident in two findings: (1) Similar results are obtained when adjectives (e.g., SHARP, DULL, BLUNT) are accompanied by congruent (e.g., SHARP by a higher tone) versus incongruent (e.g., DULL by a higher tone) stimuli (Walker & Smith, 1984), and (2) the presentation of words (e.g., WHITE, DAY) influences the strength of the congruency effect between sensory stimuli (e.g., pitch–lightness; Martino & Marks, 1999). For example, adults classify a high-pitched tone faster if presented with the words WHITE or DAY printed in white ink than if presented with the words BLACK or NIGHT printed in white ink.

The interplay between language and perception is illustrated in a study conducted by Smith and Sera (1992) in which preschoolers (2–5 years) and undergraduate students were asked to match stimuli varying in size, loudness, or surface lightness to a perceptual or verbal model that represented an extreme value on one of the other dimensions. For example, after being presented with a large mouse or the word BIG, children would be asked which of two mice—one emitting a quiet noise, one a louder noise—was most like the model stimulus. Two-year-olds did not match “loud” with “big”; loudness–size matching became consistent by 3 years of age, just when children showed comprehension of the four relevant adjectives: big, little, loud, quiet. Thus, verbal comprehension may play a role in perceptual organization of polar dimensions. In contrast, only 2-year-olds matched darker gray with the bigger of two objects (i.e., indicated that the larger of two mice was most like the dark gray model mouse). Comprehension of the four relevant adjectives (dark, light, big, little) resulted in perceptual disorganization such that older children failed to match these two dimensions consistently. Individual adults were consistent; however, some matched dark gray with “big” and others matched dark gray with “little.” Thus, cross-modal perception represents a complex interplay between language and the physiological response to sensory stimuli.

Summary

Our current knowledge of infant behavior, cortical plasticity, cross-modal matching, language, and synesthesia suggests that connections—either direct (e.g., Ramachandran & Hubbard, 2001) or indirect (e.g., Cytowic, 2002)—between brain regions typically associated with distinct modalities may underlie each of these phenomena and thus that knowledge of any one topic can inform us about the others. According to the neonatal synesthesia model, newborns fail to differentiate input from different senses—either because of connections between cortical areas that are pruned or inhibited later in development or because of the multimodal limbic system being more mature than the cortex. Because of more widespread cortical activation and/or multimodal limbic activity, newborns nevertheless sometimes behave as if they are able to relate input between distinct modalities. The remnants of this unspecialized cortex are most clearly evident in synesthetic adults who experience, for example, visual percepts in response to sound and in adults with abnormal sensory experiences, such as the congenitally blind or deaf who have unusual patterns of activation in cortical areas deprived of typical input. However, remnants also are observed in normal children and adults in their ability to match dimensions from different modalities (e.g., pitch and size) and in the prevalence of cross-modal metaphors (e.g., ‘loud colours’) in everyday speech. Fostering cross-talk among researchers from these distinct fields should facilitate our understanding of the normal development of cross-modal perception and language as well as our understanding of the roots of synesthesia.

References

- Abravanel, E., & Sigafos, A.D. (1984). Exploring the presence of imitation during early infancy. *Child Development*, 55, 381–392.
- Aleman A., Rutten G.J., Sitskoorn M.M., Dautzenberg G., & Ramsey N.E. (2001). Activation of striate cortex in the absence of visual stimulation: An fMRI study of synesthesia. *Neuroreport*, 12, 2827–2830.
- Atkinson, J., & Braddick, O. (2003). Neurobiological models of normal and abnormal visual development. In M de Haan & M. Johnson (Eds.), *The cognitive neuroscience of development* (pp. 43–71). East Sussex: Psychology Press.
- Bahrick, L. (1994). The development of infants’ sensitivity to arbitrary inter-modal relations. *Ecological Psychology*, 6, 111–123.
- Bahrick, L. (2001). Increasing specificity in perceptual development: Infants’ detection of nested levels of multimodal stimulation. *Journal of Experimental Child Psychology*, 79, 253–270.
- Bavelier, D., & Neville, H. (2002). Cross-modal plasticity: Where and how? *Nature Reviews Neuroscience*, 3, 443–452.

- Benes, F. (1994). Development of the corticolimbic system. In G. Dawson & K. Fischer (Eds.), *Human behavior and the developing brain* (pp. 176–206). New York: Guilford.
- Brackbill, Y. (1970). Acoustic variation and arousal level in infants. *Psychophysiology*, *6*, 517–525.
- Brackbill, Y. (1971). Cumulative effects of continuous stimulation on arousal level in infants. *Child Development*, *42*, 17–26.
- Brackbill, Y. (1973). Continuous stimulation and arousal level: Stability of the effect over time. *Child Development*, *44*, 43–46.
- Brackbill, Y. (1975). Continuous stimulation and arousal level in infancy: Effects of stimulus intensity and stress. *Child Development*, *46*, 364–369.
- Braddick, O., Atkinson, J., & Hood, B. (1996). Striate cortex, extrastriate cortex, and colliculus: Some new approaches. In F. Vital-Durand, J. Atkinson, & O. Braddick (Eds.), *Infant vision* (pp. 203–220). Oxford: Oxford University Press.
- Büchel, C., Price, C., Frackowiak, R., & Friston, K. (1998). Different activation patterns in the visual cortex of late and congenitally blind subject. *Brain*, *121*, 409–411.
- Burton, H., Snyder, A., Conturo, T., Akbudak, E., Ollinger, J., & Raichle, M. (2002). Adaptive changes in early and late blind: a fMRI study of Braille reading. *Journal of Neurophysiology*, *87*, 589–607.
- Cohen, L.G., Celnik, P., Pascual-Leone, A., Corwell, B., Faiz, L., Dambrosia, J., Honda, M., Sadato, N., Gerloff, C., Catalá, M., & Hallett, M. (1997). Functional relevance of cross-modal plasticity in blind humans. *Nature*, *389*, 180–183.
- Cohen, L., Weeks, R., Sadato, N., Celnik, P., Ishii, K., & Hallett, M. (1999). Period of susceptibility for cross-modal plasticity in the blind. *Annals of Neurology*, *45*, 451–460.
- Cytowic, R.E. (1989). *Synesthesia: A union of the senses*. New York: Springer Verlag.
- Cytowic, R.E. (2002). *Synesthesia: A union of the senses*. (2nd edition). New York: MIT Press.
- Day, S. (1996). Synaesthesia and synaesthetic metaphor. *Psyche: An Interdisciplinary Journal of Research on Consciousness*, *2*. Available at <http://psyche.cs.monash.edu.au/v2/psyche-2-32-day.html>
- de Haan, M., & Johnson, M. (2003). Mechanisms and theories of brain development. In M. de Haan & M. Johnson (Eds.), *The Cognitive Neuroscience of Development* (pp. 1–18). East Sussex: Psychology Press.
- Dehaene-Lambertz, G., Dehaene, S., & Hertz-Pannier, L. (2002). Functional neuroimaging of speech perception in infants. *Science*, *298*, 2013–2015.
- DeHay, C., Bullier, J., & Kennedy, H. (1984). Transient projections from the frontoparietal and temporal cortex to areas 17, 18, and 19 in the kitten. *Experimental Brain Research*, *57*, 208–212.
- DeHay, C., Kennedy, H., & Bullier, J. (1988). Characterization of transient cortical projections from auditory, somatosensory and motor cortices to visual areas 17, 18, and 19 in the kitten. *Journal of Comparative Neurology*, *230*, 576–592.
- Fernandez, M., & Bahrick, L.E. (1994). Infants' sensitivity to arbitrary object-odor pairings. *Infant Behavior and Development*, *21*, 745–760.
- Finney, E., Fine, I., & Dobkins, K. (2001). Visual stimuli activate auditory cortex in the deaf. *Nature Neuroscience*, *4*, 1171–1173.
- Fontaine, R. (1984). Imitative skills between birth and six months. *Infant Behavior and Development*, *7*, 323–333.
- Gardner, J., & Gardner, H. (1970). A note on selective imitation by a six-week old human infant. *Child Development*, *41*, 1209–1213.
- Gardner, J., Lewkowicz, D., Rose, S., & Karmel, B. (1986). Effects of visual and auditory stimulation on subsequent visual preferences in neonates. *International Journal of Behavioural Development*, *9*, 251–263.
- Gibson, E.J., & Walker, A.S. (1984). Development of knowledge of visual-tactile affordances of substance. *Child Development*, *55*, 453–460.
- Gray, J., Williams, S., Nunn, J., & Baron-Cohen, S. (1997). Possible implications of synaesthesia for the hard question of consciousness. In S. Baron-Cohen & J. Harrison (Eds.), *Synaesthesia: Classic and contemporary readings* (pp. 173–181). Oxford: Blackwell.
- Greenberg, D.J., & Blue, S.Z. (1977). The visual preference technique in infancy: Effect of number of stimuli presented upon experimental outcome. *Child Development*, *48*, 131–137.
- Grossenbacher, P., & Lovelace, G. (2001). Mechanisms of synesthesia: Cognitive and physiological constraints. *Trends in Cognitive Sciences*, *5*, 36–41.
- Hamilton, R., Keenan, J., Catala, M., & Pascual-Leone, A. (2000). Alexia for Braille following bilateral occipital stroke in an early blind woman. *Neuroreport*, *11*, 37–240.
- Heimann, M., Nelson, K.E., & Schaller, J. (1989). Neonatal imitation of tongue protrusion and mouth opening: Methodological aspects and evidence of early individual differences. *Scandinavian Journal of Psychology*, *30*, 90–101.
- Hillis, J.M., Ernst, M.O., Banks, M.S., & Landy, M.S. (2002). Combining sensory information: Mandatory fusion within, but not between, senses. *Science*, *298*, 1627–1630.
- Huttenlocher, P. (1994). Synaptogenesis in human cerebral cortex. In G. Dawson & K. Fischer (Eds.), *Human behaviour and the developing brain* (pp. 137–152). New York: Guilford.
- Jacobson, S.W. (1979). Matching behavior in the young infant. *Child Development*, *50*, 425–430.
- Jones, S. (1996). Imitation or exploration? Young infants' matching of adults' oral gestures. *Child Development*, *67*, 1952–1969.
- Kauffman, T., Théoret, H., & Pascual-Leone, A. (2002). Braille character discrimination in blindfolded human subjects. *NeuroReport*, *13*, 571–574.
- Kennedy, H., Bullier, J., & DeHay, C. (1989). Transient projection from the superior temporal sulcus to area 17 in the newborn macaque monkey. *Proceedings of the New York Academy of Sciences*, *86*, 8093–8097.
- Kujala, T., Huotilainen, M., Sinkkonen, J., Ahonen, A., Alho, K., Hämäläinen, M., Ilmoniemi, R., Kajola, M., Knuutila, J., Lavikainen, J., Salonen, O., Simola, J., Standertskjöld Nordenstam, C.G., Tiihinen, H., Tissari, S., & Näätänen, R.

- (1995). Visual cortex activation in blind humans during sound discrimination. *Neuroscience Letters*, 183, 143–146.
- Laurienti, P., Burdette, J., Wallace, M., Yen, Y.E., Field, A., & Stein, B. (2002). Deactivation of sensory-specific cortex by cross-modal stimuli. *Journal of Cognitive Neuroscience*, 14, 420–429.
- Leclerc, C., Saint-Amour, D., Lavoie, M., Lassonde, M., & Lepore, F. (2000). Brain functional reorganization in early blind humans revealed by auditory event-related potentials. *Neuroreport*, 11, 545–550.
- Lessard, N., Paré, M., Lepore, F. & Lassonde, M. (1998). Early-blind human subjects localize sound sources better than sighted subjects. *Nature*, 395, 278–280.
- Levänen, S., Jousmääki, V., & Hari, R. (1998). Vibration-induced auditory-cortex activation in a congenitally deaf adult. *Current Biology*, 8, 869–872.
- Lewkowicz, D.J. (1991). Development of intersensory functions in human infancy: Auditory/visual interactions. In M.J. Weiss & P.R. Zelazo (Eds.), *Newborn attention* (pp. 308–338). Norwood, NJ: Ablex.
- Lewkowicz, D., & Turkewitz, G. (1980). Cross-modal equivalence in early infancy: Auditory-visual intensity matching. *Developmental Psychology*, 16, 597–607.
- Lewkowicz, D.J., & Turkewitz, G. (1981). Intersensory interaction in newborns: Modification of visual preferences following exposure to sound. *Child Development*, 52, 827–832.
- Liotti, M., Ryder, K., & Woldoff, M. (1998). Auditory attention in the congenitally blind: Where, when, and what gets recognized. *Neuroreport*, 9, 1007–1012.
- Marks, L.E. (1974). On associations of light and sound: The mediation of brightness, pitch, and loudness. *American Journal of Psychology*, 87, 173–188.
- Marks, L.E. (1982). Bright sneezes and dark coughs, loud sunlight and soft moonlight. *Journal of Experimental Psychology: Human Perception and Performance*, 8, 177–193.
- Marks, L. (1987). Auditory-visual interactions in speeded discrimination. *Journal of Experimental Psychology: Human Perception and Performance*, 13, 384–394.
- Marks, L.E. (1996). On perceptual metaphors. *Metaphor and Symbolic Activity*, 11, 39–66.
- Marks, L., Hammel, R., & Bornstein, M. (1987). Perceiving similarity and comprehending metaphor. *Monographs of the Society for Research in Child Development*, 52, (serial no. 215).
- Martino, G., & Marks, L.E. (1999). Perceptual and linguistic interactions in speeded classification: Tests of the semantic coding hypothesis. *Perception*, 28, 903–923.
- Martino, G., & Marks, L.E. (2001). Synesthesia: Strong and weak. *Current Directions in Psychological Science*, 10, 61–65.
- Maurer, D. (1993). Neonatal synesthesia: Implications for the processing of speech and faces. In B. Boysson-Bardies, S. de Schonen, P. Juszyk, P. McNeilage, & J. Morton (Eds.), *Developmental neurocognition: Speech and face processing in the first year of life* (pp. 109–124). Dordrecht: Kluwer.
- Maurer, D., & Maurer, C. (1988). *The world of the newborn*. New York: Basic Books.
- Maurer, D., & Mondloch, C. (1996, October). Synesthesia: A stage of normal infancy? In S. Masin (Ed.), *Proceedings of the 12th meeting of the International Society for Psychophysics* (pp. 107–112), Padua.
- Melara, R.D. (1989). Dimensional interactions between color and pitch. *Journal of Experimental Psychology: Human Perception and Performance*, 15, 69–79.
- Melzer, P., Morgan, V., Pickens, D., Price, R., Wall, R., & Ebner, F. (2001). Cortical activation during Braille reading is influenced by early visual experience in subjects with severe visual disability: A correlational fMRI study. *Human Brain Mapping*, 87, 589–607.
- Molina, M., & Jouen, E. (2001). Modulation of manual activity by vision in human newborns. *Development Psychobiology*, 38, 123–132.
- Mondloch, C., & Maurer, D. (in press). Do small balls squeak? Pitch-object correspondence in young children. *Cognitive, Affective, & Behavioral Neuroscience*.
- Morrongiello, B., Fenwick, K.D., & Chance, G. (1998). Cross-modal learning in newborn infants: Inferences about properties of auditory-visual events. *Infant Behaviour & Development*, 21, 543–554.
- Murray, E.A., & Mishkin, M. (1985). Amygdalectomy impairs crossmodal association in monkeys. *Science*, 228, 604–606.
- Neville, H. (1995). Developmental specificity in neurocognitive development in humans. In M. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 219–231). Cambridge, MA: Bradford.
- Nishimura, H., Doi, K., Iwuki, T., Hashikawa, K., Nishimura, T., & Kubo, T. (2000). Sign language activated the auditory cortex of a congenitally deaf subject revealed by positron emission tomography. In C. Kim, S. Chang, & D. Lim (Eds.), *Updates in cochlear implantation. Advances in otorhinolaryngology*, Vol. 57 (pp. 60–62). Basel: Karger.
- Nishimura, H., Hashikawa, K., Doi, K., Iwaki, T., Watanabe, Y., Kusuoka, H., Nishimura, T., & Kubo, T. (1999). Sign language 'heard' in the auditory cortex. *Nature*, 367, 116.
- Nunn, J.A., Gregory, L.J., Brammer, M., Williams, S., Parslow, D., Morgan, M., Morris, R., Bullmore, E., Baron-Cohen, S., & Gray, J. (2002). Functional magnetic resonance imaging of synesthesia: Activation of V4/V8 by spoken words. *Nature Neuroscience*, 5, 371–375.
- Pascalis, O., & de Schonen, S. (1994). Recognition memory in 3–4 day old human neonates. *Neuroreport*, 5, 1721–1724.
- Paulesu, E., Harrison, J., Baron-Cohen, S., Watson, J., Goldstein, L., Heather, J., Frackowiak, R., & Frith, C. (1995). The physiology of coloured-hearing: A PET activation study of colour-word synesthesia. *Brain*, 118, 661–676.
- Piaget, J. (1952). *The origins of intelligence in children*. New York: International University Press.
- Pickens, J., Field, T., Nawrocki, T., Martinez, A., Soutollo, D., & Gonzalez, J. (1994). Full-term and preterm infants' perception of face-voice synchrony. *Infant Behavior and Development*, 17, 447–455.
- Ramachandran, V.S., & Hubbard, E.M. (2001). Synaesthesia - A window into perception, thought and language. *Journal of Consciousness Studies*, 8, 3–34.

- Rauschecker, J. (1995). Compensatory plasticity and sensory substitution in the cerebral cortex. *Trends in Neuroscience*, 18, 36–43.
- Reardon, P., & Bushnell, E. W. (1988). Infants' sensitivity to arbitrary pairings of color and taste. *Infant Behavior and Development*, 11, 245–250.
- Röder, B., Rösler, E., & Neville, H. (2000). Event-related potentials during auditory language processing in congenitally blind and sighted people. *Neuropsychologia*, 38, 1482–1502.
- Röder, B., Sock, O., Bien, S., Neville, H., & Rösler, E. (2002). Speech processing activates visual cortex in congenitally blind humans. *European Journal of Neuroscience*, 16, 930–936.
- Röder, B., Teder-Sälejärvi, W., Sterr, A., Rösler, E., Hillyard, S., & Neville, H. (1999). Improved auditory spatial tuning in blind humans. *Nature*, 400, 162–166.
- Sadato, N., Pascual-Leone, A., Grafman, J., Deiber, M.-P., Ibañez, V., & Hallett, M. (1998). Neural networks for Braille reading by the blind. *Brain*, 121, 1213–1229.
- Sadato, N., Pascual-Leone, A., Grafman, J., Ibañez, V., Deiber, M., Dold, G., & Hallett, M. (1996). Activation of the primary visual cortex by Braille reading in blind subjects. *Nature*, 380, 526–528.
- Schiltz, K., Trocha, K., Wieringa, B.M., Emrich, H.M., Johannes, S., & Münte, T. (1999). Neurophysiological aspects of synesthetic experience. *Journal of Neuropsychiatry and Clinical Neurosciences*, 11, 58–65.
- Smith, L. B., & Sera, M.D. (1992). A developmental analysis of the polar structure of dimensions. *Cognitive Psychology*, 24, 99–142.
- Steri, A. (1987). Tactile discrimination of shape and intermodal transfer in 2- to 3-month-old infants. *British Journal of Developmental Psychology*, 5, 213–220.
- Steri, A., & Pêcheux, M.G. (1986). Vision-to-touch and touch-to-vision transfer of form in 5-month-old infants. *British Journal of Developmental Psychology*, 4, 161–167.
- Stevens, S.S. (1957). On the psychophysical law. *Psychological Review*, 64, 153–181.
- Sur, M., & Leamey, C. (2001). Development and plasticity of cortical areas and networks. *Nature Reviews Neuroscience*, 2, 251–262.
- Turkewitz, G., Gardner, J., & Lewkowicz, D.J. (1984). Sensory/perceptual functioning during early infancy: The implications of a quantitative basis for responding. In G. Greenberg & E. Tobach (Eds.), *Behavioral evolution and integrative levels* (pp. 167–195). Hillsdale, NJ: Erlbaum.
- Tzourio-Mazoyer, N., de Schonen, S., Crivello, E., Reutter, B., Aujard, Y., & Mazoyer, B. (2002). Neural correlates of woman face processing by 2-month-old infants. *NeuroImage*, 15, 454–461.
- Walker, P., & Smith, S. (1984). Stroop interference based on the synaesthetic qualities of auditory pitch. *Perception*, 13, 75–81.
- Weeks, R., Horwitz, B., Aziz-Sultan, A., Tian, B., Wessinger, C., Cohen, L., Hallett, M., & Rauschecker, J. (2000). *Journal of Neuroscience*, 20, 2664–2672.
- Wolff, P., Matsumiya, Y., Abrohms, I.E., van Velzer, C., & Lombroso, C.T. (1974). The effect of white noise on the somatosensory evoked responses in sleeping newborn infants. *Electroencephalography and Clinical Neurophysiology*, 37, 269–274.
- Yaka, R., Yinon, U., & Wollberg, Z. (1999). Auditory activation of cortical visual areas in cats after early visual deprivation. *European Journal of Neuroscience*, 11, 1301–1312.
- Zelazo, P.D. (1996). Towards a characterization of minimal consciousness. *New Ideas in Psychology*, 14, 63–80.
- Zellner, D.A., Bartoli, A.M., & Eckard, R. (1991). Influence of color on odor identification and liking ratings. *American Journal of Psychology*, 104, 547–561.
- Zellner, D.A., & Kautz, M.A. (1990). Color affects perceived odor intensity. *Journal of Experimental Psychology: Human Perception and Performance*, 16, 391–397.