Chapter 5

General Discussion

5.1 Summary

It has been known for some time that adults take advantage of multisensory redundancy in spatial localization tasks, as evidenced by shorter head and/or eye movement latencies to bimodally specified co-localized targets than to unimodally specified ones, as are the deleterious effects of spatial or temporally disparity. What has not been known until now, however, is when in development multisensory facilitation of localization behavior emerges. This work represents the first to examine the development of spatial localization behavior in infancy across such a broad age range, to compare localization of auditory-only, visual-only, and spatially and/or temporally congruent or incongruent audiovisual targets, and to compare infants responses to such targets directly with those of adults. Overall, the results of this present research indicates that response latencies to all types of targets generally decrease over the first year of life. In addition, the results show that response latencies are generally fastest to congruent audiovisual targets, and somewhat slower to unimodal or discrepant targets, with the differences between unimodal and incongruent target latencies highly dependent on the age of subjects, the degree of disparity, and relational differences in position or order.

5.1.1 Study 1: Congruent Audiovisual Stimuli

5.1.1.1 Audiovisual Integration

Adults presented with a spatially and temporally congruent audiovisual target at ±25° or ±45° along the horizontal plane have a significantly improved response latency in orienting toward the target than a visual-only or auditory-only target at the same location. This response is sufficiently faster than can be explained through statistical facilitation alone, as evidenced by a violation of the most liberal upper boundary of the Race Model. Infants under eight months of age intermittently showed significantly faster response latencies to audiovisual targets at either eccentricity, but failed to show any reliable violation of the Race Model, suggesting that after birth and over the first eight months of life, their response latencies are dominated by the faster of the two sensory systems—most often vision—and any significant gain in speed is due to statistical facilitation. However, infants between the ages of eight and ten months showed a limited indication of adult-style non-linear audiovisual integration, with a violation of the Race Model for audiovisual targets at 25° but only borderline at 45°, and their response latencies were still significantly longer than adult performance to identical stimuli, indicating that significant maturation is still required.

5.1.1.2 Asymmetrical Development of Auditory Response

The relative response latency to a unimodal target can be modified by changes to it's intensity; low-intensity targets being generally more difficult to orient toward than higher intensity targets. The relative intensities of the auditory and visual targets used in this study (white noise at 55–65 dB and a vertical line of three red LEDs) produced comparable response latencies in adult subjects, but produced unequal response times in older infants (4–10 months) when targets were at 25°. Where response latencies to visual-only targets at both eccentricities and auditory-only targets at 45° shared a common developmental profile of improved response latency with age, the auditory-only response at 25° remained flat, showing no improvement in speed with age. One possible explanation for this asymmetrical developmental profile between auditory-only targets is a slower maturation rate for the neural network required for binaural processing (necessary for targets within the parafoveal region: ±40° of center) compared with that for monaural processing (sufficient for peripheral targets: $> 40°$).

5.1.2 Study 2: Spatially Incongruent Audiovisual Stimuli

5.1.2.1 Spatial Disparity and Age

Adults presented with a spatially incongruent auditory and visual stimulus had significantly longer response latencies compared to a congruent audiovisual target for disparities ranging from 20° to 90° with the steepest change in latency at the smallest disparity, and then a more gradual increase in latency for the larger disparities ($\geq 50°$). In the youngest infants (2–4 months), only very large spatial disparities produced a significantly slower response latency, though there was a general increasing trend with increased displacement. Older infants (6–10 months) also showed a significantly slowed response for only the larger disparities, but the increasing trend for increased displacement was present and all response latencies were shifted closer to or greater than a visual-only latency. The shape of the disparity curve was much more broad in all infants than found in adults, though improvements in tuning were apparent between 6–8 and 8–10 month olds. Infants between four and six months showed a unique response latency profile to spatial disparity: When the visual target was at 25°, only the 20° disparity condition was significantly different from the audiovisual (it was uniquely faster), and when the visual target was at 45°, there was no change in response latency with spatial disparity—infants in this age group were insensitive to all spatial disparities tested. Infants throughout the age range tested showed a steady increase in their sensitivity to spatial disparity, approaching but not yet reaching that found in adult subjects.

5.1.2.2 Relative Importance of Position in Visual Field

Differences were also found depending on the relative position of the visual and auditory stimuli in the visual field. Visual targets more centrally located were less susceptible to the interference of spatial disparity, witnessed by a generally flat response to increasing disparity for the youngest infants (2–6 months), and a slightly more tuned u-shaped response in older infants (6–10 months); visual targets at 45° developed a more narrow response curve to increasing spatial disparity. Even in adults, the larger disparities (50°–70°) produced response latencies 30% slower than AV_0, compared to the 40% slower latency at large disparities (70°–90°) for a visual target at 45°. There were also differences in latency depending on whether the visual stimulus was in a central or peripheral position. A disparity of 20° slowed the response latency more when the visual target was in the periphery than in the parafoveal region for all infants, as did a disparity of 70° in most infant groups (not for 4–6 month olds, and borderline in 8–10 month olds), but for neither in adults.

5.1.3 Study 3: Temporally Incongruent Audiovisual Stimuli

5.1.3.1 Temporal Disparity and Age

Adults and infants presented with an asynchronous auditory and visual stimulus had significantly slower response latencies than a synchronous stimulus. Infants and adults showed the same general profile of response latency as a function of increasing temporal disparity, but with differences due to age in the degree of slowing produced by the disparity. When the visual component was presented first, infants responded with a consistently flat, slowed response latency but when the auditory was first, there was an open-ended increase in latency with increasing disparity. In infants, the smallest percent change in response latency with disparity was found in the youngest age group (2–4 months). The magnitude of response depression increased with age until peaking with a maximum degree of interference in 6–8 month olds, before decreasing again for the oldest infants (8–10 months).

5.1.3.2 Sensory Maturity

Infants' differential response profile to temporal disparities depending on the modality of the leading stimulus is consistent with the respective performance capabilities for auditory versus visual spatial localization at 25°. Infants between the ages of two and ten months of age had previously been found to have a more difficult time orienting toward auditory than visual unimodal targets in this region (Study 1), as evidenced by their much longer mean response latencies and shallower cumulative distribution curve. Taking into account this difference in capabilities, infants responding to the leading stimulus onset would be much more likely to have initiated a response to a visual stimulus than an auditory one for the majority of temporal disparity conditions used.

5.2 Implications

5.2.1 Consistency of Interpretation

In all three studies, infants, in general, had a faster mean response latency toward a spatially and temporally congruent audiovisual stimulus than when spatially or temporally incongruent. The magnitude of the increase in latency was dependent on the degree of disparity and the relative position (spatial) or order (temporal) of the auditory and visual components, as well as the age of the infants. In the youngest infants, the degradation in response was more generalized for both spatial and temporal disparities, with response latencies no slower than found for unimodal-only targets and a greater degree of insensitivity to the absolute magnitude of disparity. The middle ages (4–6 and 6–8 months) represent periods where the magnitude of the interference by the disparities showed the greatest increase—as measured by the difference from the relevant unimodal latency—and frequently began to show advances toward adult-style tuning. Within these middle ages, 4–6 month olds usually had more of the generalized flat profile than 6–8 month olds, with additional fine-tuning occurring in the oldest infants (8–10 months). In place of the flattened profile younger infants showed, in most instances, toward spatial and temporal disparities, the absolute magnitude of the spatial or temporal disparity grew more critical in older infants, with the oldest infants beginning to show a closer affinity with adults' orienting response. However, although the changes occuring with age tended to approach the profile of responses found in adults for identical stimulus presentation, responses were not yet at an adult level, indicating that maturation of the auditory and visual sensory systems and integrative mechanisms must still undergo further maturation beyond the first ten months of age. There were also differences between the developmental timelines for spatial and temporal disparity. In the temporal disparity study (Study 3), the general shape of the plots of infants' response latencies to increasing disparity were much closer in appearance to adults' than in the spatial disparity study (Study 2). One interpretation of these results is that this represents another example of the well-supported developmental principles of heterogeneity and heterochrony, which state that there are not one but several distinct neural mechanisms underlying multisensory integration and that they each develop along a different timecourse with distinct developmental onsets (D. J. Lewkowicz, 2002). If the above results are an indication that the interference provided by temporal disparity is further along developmentally than that of spatial disparity, it is not surprising considering the relative onsets of other temporal properties. For example, the ability to detect synchrony—an amodal multisensory property like the detection of spatial and temporal disparity—occurs at a very early age (by at least 4 weeks of age) and is thought to be one of the first, and most critical, amodal multisensory integration mechanisms to emerge, given that the only way to detect synchrony (unlike other amodal properties that are redundant) is through the abstraction of information from more than one sensory input (Bahrick, 1987, 1992, 1994; Bahrick & Lickliter, 2000). Synchrony detection is believed to provide the first crucial framework for perceiving unity across different modalities, and so the developmental jump from detecting synchrony to the inhibition of asynchrony may be shorter (and hence better developed within our age ranges) than the inhibition of spatial disparity.

5.2.2 Visual Dominance

Humans, like other primates, are strongly visual creatures and infants are no different, even considering the immature state of the visual system at birth and it's gradual maturation. In all three studies, it was also apparent the dominant role vision tended to play in both congruent and incongruent conditions. In the spatially and temporally congruent study (Study 1), visual-only response latencies were shorter compared to auditory-only latencies with frequently little to no difference between the visual and audiovisual response latencies. Even the one age group where non-linear audiovisual integration was found (8–10 months), the violation of the Race Model occurred in the parafoveal region where vision is the strongest. Visual dominance also played a key role in both disparity studies. In Study 2, the orienting response was frequently less sensitive to the deleterious effects of spatial disparity when the visual component was centrally located than when it was peripherally located. In Study 3, when the visual target preceded the onset of the auditory target, latencies were again depressed less (for all disparity values) than when the auditory target preceded the visual, even though audition is generally thought (and found) to be the stronger modality in distinguishing temporal relations.

5.2.3 Probability Summation versus Neural Summation: Predictions

When the original psychophysical studies examining the facilitory effect of spatial and temporal congruency on task performance and response latencies were being performed, theories fell into one of two broad camps: improved responses were either reflective of some neural mechanism (neural summation) or an artifact due to statistical facilitation (probability summation). Out of that original debate has come the standard for verifying the presence of non-linear neural summation, namely looking for a Race Model violation. If faster response latencies to an audiovisual event were the end result of a contest between two independent, non-integrated sensory systems, than the upper boundary of possible response latencies would be constrained by the sum of the cumulative distributions of both. If the sensory systems are not completely independent, that boundary condition would be lower still. Adult studies have long been finding such violations in adults' localization of audiovisual targets (Miller, 1982; Hughes et al., 1994), but before this work it was unclear if infants also possessed the same or similar multisensory mechanisms. While there has also been a large degree of research into the behavioral and physiological effects of spatial and temporal disparity in adults, very little has been accomplished towards testing the result of these disparities against the Race Model, let alone the developmental consequences. One spatial localization study—using similar stimuli to ours (white noise and a 3 mm amber LED)—examined the degree of spatial disparity that could be tolerated while still producing a violation of the Race Model (Harrington & Peck, 1998). They found that adults are quite tolerant to even large spatial disparities, with vigorous violations found for all three of their subjects for disparities up to 22.5–30°, and then a gradual reduction in the magnitude of the violation for increasing disparity. Considering the small violation found at only one eccentricity (25°) for 8–10 month olds and that spatial disparities greater than 20° produced latencies approaching or exceeding that seen for unimodal targets, it seems likely that while 20° *might* be tolerated in these older infants, any additional increase in disparity would probably show a quick drop off in the violation. Given that even the shortest temporal disparities (150 ms preceding a visual leading target) were found to be significantly longer than the synchronous condition, 8–10 month olds are probably even less tolerant of temporal disparities.

5.2.4 Stepping Stone for Future Work

Although this work was not intended to be the definitive source for multisensory facilitation and inhibition in infants, the broad age range explored has provided a spotlight on particular ages for focusing future studies. Among them would be a closer examination the development of binaural versus monaural process, of the multisensory integration in the age range beyond 10 months to find when multisensory integration finishes developing, an extension of the spatial disparity study to include finer degrees of disparity for the same versus opposing hemifields, or shorter and longer temporal disparities at more eccentric positions.