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Hemispheric Equivalence in the Temporal Processing for
Somatosensory and Visual Stimuli: Age-Related Differences

by

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Abstract

Hemispheric asymmetries and age-related differences in judgements of simultaneity for tactile and visual stimuli were examined. The study was conducted in order (i) to determine whether both cerebral hemispheres are equally capable of processing fine temporal information, (ii) to determine whether there is an age-related differential hemispheric decline in judgements of simultaneity, (iii) to determine if simultaneity thresholds for tactile and visual stimuli increase with advanced age, and (iv) to examine the consistency of temporal judgements in two different modalities. Tactile stimulation to the middle and index fingers (bimanual and unimanual conditions) was delivered by mechanical tactile stimulators. Young and older adults were to judge whether two fingers were stimulated simultaneously. Light emitting diodes in a visual half-field display were employed to examine judgements of simultaneity for visual stimuli. Participants were to judge whether pairs of spatially separated diodes were illuminated simultaneously. Tactile and visual simultaneity thresholds were measured by using a modified parameter estimation by sequential testing (PEST) algorithm technique. The results suggest that both cerebral hemispheres are equally capable of making judgements of simultaneity to fine tactile and visual stimuli. The results further suggest that the hemispheric equivalence for judgements of simultaneity remains stable across adulthood. Relative to younger adults, older adults had significantly higher simultaneity thresholds for both the tactile and visual task. Older females had the highest simultaneity thresholds for both tasks, but this finding was statistically significant for the visual task only. These findings suggest that females may be more vulnerable to an age-related decline in judgments of

simultaneity. Finally, the overall findings indicate that both the hemispheric equivalence for judgements of simultaneity and the age-related increase in simultaneity thresholds occur in both the tactile and visual modality.

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Making Hemispheric Asymmetry Inferences



"By God, for a minute there it suddenly all made sense!"

Introduction

Temporal processing includes the ability to judge whether two events occurred simultaneously. For example, the ability to judge whether two planes will collide, or whether a vehicle merging onto a freeway will collide with another vehicle, are aspects of temporal processing (motion judgements). Judgements of whether two events occurred simultaneously can be inferred by the detection of apparent motion (Corballis, 1996; Geffen, Mason, Butterworth, McLean, & Clark, 1996; Hammond, 1982). Simultaneity is inferred when motion between sensory events is not detected. In contrast, when motion is detected, successiveness is typically inferred. The process of sequencing events is an activity that we engage in everyday. For example, words are produced and processed in a sequential manner for the production and comprehension of spoken language. Clearly, a deficit in this ability has the potential of disrupting our daily lives.

Several researchers have proposed a left hemispheric locus for the precise timing of events while others have proposed hemispheric equivalence for the ability to time events. There is evidence, especially with respect to the visual system, that temporal processing abilities tend to decline with advanced age. However, it is not known whether temporal processing abilities for somatosensory information decreases with age. Moreover, temporal processing among the aged from a lateralized perspective has yet to be examined.

It has been proposed that relative to the left hemisphere, information processing mediated by the right hemisphere declines with advanced age (Taylor, McDowd, & Hellige, 1991). One goal of the present research is to determine whether both cerebral hemispheres are equally capable of processing fine temporal information and whether this pattern holds for the elderly. The second goal of the present study is to determine whether older adults

demonstrate a decrement in processing fine somatosensory and visual temporal information. The term fine refers to the subtle difference in the time between the delivery of two stimuli (Hammond, 1982).

The introduction will provide a brief description of the typical structural and functional hemispheric asymmetries within the normal population including the controversial findings surrounding functional asymmetry with advanced age. The studies investigating temporal processing from both a lateralized perspective and an aging perspective will be reviewed.

Cerebral Asymmetries and Hemispheric Specialization

Structural and Functional Asymmetries

Specific structural or anatomical asymmetries of the left and right hemisphere have been documented. For instance, the left planum temporale is larger and the left Sylvian (lateral) fissure is longer than the right (Geschwind & Levitsky, 1968). It is believed that the left planum temporale, which constitutes the upper surface of the posterior temporal lobe and overlaps Wernicke's area, is related to the cerebral functional asymmetry of language skills. The size of the plenum temporale has also been associated with handedness which links brain structure with function (Steinmetz, Volkman, Jancke, & Freund, 1991). Steinmetz et al., (1991) reported that the significant degree of leftward asymmetry in the planum temporale, typically found among right-handers, was not as significant in left-handers.

It has been reported that the right hemisphere tends to be larger (Kertesz, Polk, Black, & Howell, 1990) and heavier than the left (Wada, Clarke, & Hamm, 1975). In addition, it has been documented that the right frontal lobe is longer and wider, while the left

occipital lobe is longer and wider (LeMay, 1977). The left occipital ventricular horn has been found to be longer than the right (McRae, Branch, & Milner, 1968).

Finally, it was reported that there is a greater amount of gray matter (cell bodies) than white matter (myelinated axons) in the left hemisphere (Gur, Parker, Hungerbuhler, Reivich, Obrist, Amernak, & Sackheim, 1980). Differences were more pronounced in the frontal and precentral regions which include areas that involve language and abstract reasoning (Gur et al., 1980). White matter consists of myelinated fibres (insulated by support cells), while gray matter consists of nonmyelinated fibres. The authors proposed that the left hemisphere processes or transfers information within regions, while the right hemisphere engages in considerable transfer across regions. This finding supports Semmes (1968) hypothesis that functions of the left hemisphere tend to be more focally represented, while right hemisphere functions tend to be more diffusely organized.

With the exception of the anatomical asymmetries reported for the planum temporale and the ratio of white to gray matter, the anatomical differences between the right-and-left hemispheres have been identified more frequently in right-handers than left-handers (Galaburda, LeMay, Kemper, & Geschwind, 1978). Handedness has also been associated with functional cerebral lateralization.

The term "functional cerebral lateralization" refers to the qualitative or quantitative differences in function of the left and right hemispheres (Geschwind & Galaburda, 1985). For example, Paul Broca has been highly recognized for his discovery that the brain was lateralized for language and that there was a relationship between this hemispheric specialization and handedness (Geschwind, 1984). The term hemispheric specialization means that one hemisphere of the brain is especially responsible for a specific cognitive

function (Efron, 1990). This does not mean that this particular hemisphere is exclusively responsible for processing the information, only that this particular hemisphere is more proficient, relative to the other hemisphere, with respect to information processing. Most researchers agree that hemispheric specialization is a matter of degree (relative) rather than an all-or-none (absolute) qualitative difference (Bouma, 1990).

The relationship between hemispheric specialization for language and handedness was substantiated by the sodium amytal test (a sedative drug injected into the carotid artery), devised by Juhn A. Wada (Springer & Deutsch, 1993). The drug temporarily interferes with the functioning of the hemisphere ipsilateral to the injected carotid artery. If the drug is injected to the hemisphere controlling speech, the individual generally remains speechless for a period of time (2 to 5 minutes). In contrast, speech is only disrupted for a few seconds if the drug is injected into the carotid artery of the nondominant hemisphere (Springer & Deutsch, 1993). It has been reported that over 95% of right-handers have speech localized in the left hemisphere, while the remainder of right-handers have speech localized in the right hemisphere. Approximately 70% of left-handers have speech localized in the left hemisphere, 15% have speech localized in the right hemisphere, and the remaining 15% exhibit no lateralization (see Springer & Deutsch, 1993). Although language has been the main emphasis of hemispheric specialization studies, different types of information processing have also been associated with cerebral lateralization. In an overwhelming majority of right-handed individuals and in a majority of left-handers, the left hemisphere tends to be specialized for verbal, sequential, and analytic processing, whereas the right hemisphere is specialized for nonverbal, spatial, and holistic processing (Springer & Deutsch, 1993).

Functional cerebral lateralization is typically investigated by using noninvasive techniques such as dichotic listening and visual half-field presentations. The dichotic listening procedure consists of spoken stimuli that are presented simultaneously to each ear through headphones for recall (see Springer & Deutsch, 1993). The information must be presented simultaneously since laterality effects only appear when there are competing inputs (Kimura, 1967). Thus, a right-ear advantage would indicate a left hemisphere advantage whereas a left-ear advantage indicates a right hemisphere advantage. The visual half-field method requires the individual to fixate on a central point while stimuli are presented tachistoscopically to the left-and-right visual fields. Since the visual system is completely crossed a stimulus presented in one visual field is represented in the contralateral hemisphere. Thus, better accuracy for stimuli presented in the right visual field would indicate a left hemisphere advantage.

Hemispheric Asymmetries and Gender

Wada et al., (1975) reported that the right temporal cortex is larger in females relative to males. They also reported that when compared to adult males, the left plenum temporale of adult females tends to be larger. In addition, it has been reported that females have a larger splenial region of the corpus callosum when compared to males (deLacoste-Utamsing & Halloway, 1982). Since the splenium consists of fibers from the parietal and occipital regions for interhemispheric transfer (deLacoste, Kirkpatrick, & Ross, 1985), it is inferred that the greater number of fibers may result in better interhemispheric communication.

With respect to both verbal (usually mediated by left hemisphere) and spatial abilities (usually mediated by the right hemisphere), males are more lateralized than females

(Bryden, 1979; McGlone, 1980). However, the findings regarding gender differences in functional lateralization are equivocal. Many studies have failed to find reliable gender differences and it has been argued that many of these studies never get published (for review see Springer & Deutsch, 1993). However, when the results of the studies with diverse methodologies (neuroimaging, clinical studies, and behavioural studies) are considered collectively, the general conclusion is that males are more lateralized than females.

Hemispheric Asymmetries and Aging

Researchers have attempted to identify changes in brain structure and function in relation to age-related cognitive decline. The suggestion that the right hemisphere is more vulnerable to insult and the aging process relative to the left hemisphere has been proposed by several researchers (e.g., Boll, 1974; Goldstein & Shelly, 1981; Klisz, 1978; Meudell & Greenhalgh, 1987). For instance, Boll (1974) reported that patients with right hemisphere damage demonstrated ipsilateral and contralateral deficits in tactile performance, while patients with left hemisphere damage tended to display only contralateral deficits. These results also provide support to the view of Gur et al. (1980) that the right hemisphere processes involve more transfer across regions. One may argue that if the left hemisphere processes within regions while the right hemisphere engages in considerable transfer across regions, that the right hemisphere is more susceptible to disruptions that may occur in the brain since right hemisphere processing require more transfer than left hemisphere processing.

Carmon & Gombos (1970) demonstrated that ophthalmic artery pressures (arterial blood flow) were higher for the right hemisphere for most right-handed individuals, while the majority of left-handers showed greater ophthalmic pressures for the left hemisphere.

This report was interpreted as the right hemisphere being at greater risk for cerebrovascular incidents because of the greater blood flow in the right hemisphere (e.g., Meudell & Greenhalgh, 1987). However, Carmon and Gombos (1970) were unable to measure hemispheric blood flow directly and relied on blood pressure in both carotid arteries via the ophthalmic arteries. The authors did caution the reader that findings are limited since inferences were made about the hemispheric blood flow.

In a more recent study (Takada, et al., 1992) positron emission tomography (PET) was employed to measure the hemispheric cerebral blood flow (CBF) and the cerebral metabolic rate of oxygen (CMRO₂) of young and old adults during a resting state. The authors reported a significant decline for both CBF and CMRO₂ with advanced age. However, the CBF was only significant for the left superior temporal cortex. Interestingly, a significant linear correlation with age was found for the left hemisphere only in regard to CMRO₂. Takada et al. (1992) suggested that the physiological changes in the left hemisphere are related to the mild cognitive dysfunction or memory disturbance often demonstrated in the normal elderly population.

Gender differences in hemispheric structural asymmetries among the elderly are sparse. Gur et al., (1991) employed magnetic resonance imaging (MRI) to examine age and gender-related differences in brain atrophy (i.e., reduced brain weight) after correcting for body size. A significant negative correlation between age and brain volume was revealed. Relative to the left hemisphere, a significantly higher brain volume was found in the right hemisphere for both genders. The greatest amount of brain atrophy among males was in the left hemisphere, whereas brain atrophy for females was symmetrical. It was suggested by

Gur et al., (1991) that males are more susceptible than females to age-related changes in mental abilities that are controlled by the left hemisphere.

The research findings of hemispheric decline with advanced age tend to be inconsistent. To date, unequivocal findings have not been reported for left or right hemisphere differences in the development of neurofibrillary tangles and senile plaques (Meudell & Greenhalgh, 1987). In fact, some researchers (Rapp & Amaral, 1992) argue that aging does not mean inevitable cognitive decline for the left or right hemisphere due to individual variability.

The findings of the studies that have examined age-related functional cerebral asymmetries are also equivocal. In 1975 Brown and Jaffe hypothesized that there is a progressive language lateralization (left hemisphere) throughout the life span. Brown and Jaffe were the pioneers for the behavioral research relating to hemispheric decline with advanced age.

Right-Hemi Aging Hypothesis

Several researchers found that nonverbal scores (performance subtest) of the Wechsler Adult Intelligence Scale (WAIS) have a more rapid decline than verbal scores with increasing age (see Gaylord & Marsh, 1975; Schulz & Ewen, 1988). The performance subtest consists mainly of tasks involving visuospatial abilities (mediated by right hemisphere), while the verbal subtest consists mainly of language-related tasks (mediated by the left hemisphere). Thus, the decline in the performance scores has been associated with a decline in right hemisphere functioning. In fact, it has been noted that the pattern of scores for normal aged adults on the performance subtests (those requiring visuospatial abilities) is similar to that of patients who have right-hemisphere damage (Schaie & Schaie, 1977).

However, it has been argued that the Performance Subtests of the WAIS require more complex problem-solving abilities than do the Verbal Subtests (Botwinick, 1977). There is much evidence in the aging literature that the performance of aged adults is negatively affected by increases in task complexity, especially when the task loads working memory (e.g., Mack & Carlson, 1978; Salthouse, Mitchell, Skovronek, & Babcock, 1989; Wingfield, Stine, Lahar, & Aberdeen, 1988).

The differential decline in verbal and nonverbal abilities initiated the hypothesis that the right hemisphere ages more rapidly than the left hemisphere (Goldstein & Shelly, 1981) and to the right hemi-aging hypothesis (Taylor, McDowd, & Hellige, 1991). Taylor et al., (1991) defined the right hemi-aging hypothesis as "... a greater age-related decline in the right hemisphere information processing relative to the left hemisphere." However, the findings from dichotic listening and visual half-field studies are incongruent. Several studies provide evidence for the uniform aging of the hemispheres (Borod & Goodglass, 1980; Hoyer & Rybash, 1992), while other studies indicate that cognitive abilities controlled by the right hemisphere decline more rapidly with age relative to left hemisphere abilities (Goldstein & Shelly, 1981; Johnson, Cole, Bowers, Foiles, Nakaido, Patrick, & Woliver, 1979).

Several researchers have suggested that the inconsistent results are mainly due to task complexity (e.g., Obler, Woodward, & Albert, 1984; Tubi & Calev, 1989). That is, nonverbal testing material mediated by the right hemisphere tends to be more complex and novel when compared to the verbal testing material that is mediated by the left hemisphere. One of the challenges with lateralization studies is matching the tasks for complexity and familiarity. A lateralization study that employed the same testing material for both

hemispheres would provide valuable information in regard to the right hemi-aging hypothesis.

To date, attempts to correlate anatomical brain asymmetries and experimental behavioural data with hemispheric functional asymmetries have been generally unsuccessful. Moreover, attempts to link functional asymmetries to an age-related right hemispheric decline have also been unsuccessful.

Aside from the research conducted in visual temporal processing, most researchers investigating the temporal processing abilities of older adults have focused on memory for temporal information. The research on the memory for temporal information in the aged population was initiated by a claim that processing temporal information was an automatic process.

Temporal Processing (Memory)

Temporal memory includes the ability to recall the sequence of past (e.g., episodic) events (Kausler, 1994). This ability is an important aspect of daily living. For example, learning a new route involves the temporal ordering of environmental information for successful navigation (Allen, 1988). Similarly, understanding a conversation or reading a book requires the sequencing of words. At the extreme, deficits in the temporal processing of information may endanger lives. At a moderate level, decrements in the sequencing of information may interfere with one's daily activities. Not surprisingly, age-related deficits in the ability to process temporal information would place an older individual at a disadvantage with respect to many daily activities (e.g., driving a vehicle, understanding verbal concepts, navigating a route).

In 1979, Hasher and Zacks proposed that processing temporal information is an automatic process that is "age insensitive." They defined automatic processing as a process that does not place demands on processing resources since it does not require awareness or intention (i.e., conscious effort). Many researchers questioned Hasher and Zacks' proposal and began investigating age-related differences in the cognitive processes that had been identified as automatic (Salthouse, 1991).

The majority of the research focused on memory for temporal information by including intentional and incidental (i.e., unintentional) conditions. In an intentional condition, participants are informed that their memory for relevant information will be tested. No information regarding the testing requirements is revealed to participants in the incidental condition. If temporal processing is truly an automatic process, then no age effects should be found in the incidental condition. In general, results suggest that temporal processing is not an automatic process. Moreover, age differences are present in both the incidental and intentional conditions (e.g., Kausler, Lichty, & Davis, 1985; Kausler, Salthouse & Sauls, 1988; McCormack, 1981).

Experiments examining temporal processing proficiency typically employ word stimuli (Kausler, 1994). Subsequent to word presentation, participants are asked to recall the sequence of the words. Alternatively, a test may present pairs of words where participants indicate which word of each pair appeared more recently in the list. McCormack (1981) reported a significant age-related decrement in performance. Although, Perlmutter, Metzger, Nezworski, and Miller (1981) found age differences, the differences were not statistically significant.

Zacks (1982) presented categories of instances to young and older adults (categories such as types of flowers and types of metals). Participants were required to "keep track" of the categorical instances. The presentations were interrupted at random points and participants were asked to name the most recent item of a particular category that was presented (e.g., "What was the last flower you saw?"). Zacks (1982) reported that the performance of the elderly was impaired when compared to that of young adults.

Kausler, Salthouse, and Saults (1988) had young, middle age, and older adults reconstruct the order of a list of previously studied words. A correlation coefficient between the true order and reconstructed order of words was calculated for each subject. Results of the intentional condition (i.e., participants were advised that they would be tested) revealed a significant decrement that was apparent at middle age and continued into late adulthood with little change. Not surprisingly, several other researchers (Kausler, Lichty, & Davis, 1985; Kausler & Philips, 1988; Waugh & Barr, 1982) have reported significant age-related deficits in tasks requiring memory for temporal information.

The evidence does not support Hasher and Zacks' (1979) claim that temporal processing is an age insensitive automatic process. In fact, the research findings indicate that an age-related decline in the memory for temporal information is evident by middle-age (Kausler, Salthouse, & Saults, 1988). Given that these studies have investigated the memory for temporal information, it is difficult to determine whether the decrement in performance can be attributed to decrements in memory, deficits in sequencing abilities, or a combination of both. It is well documented that older adults demonstrate impaired performance on memory tasks such as the recall of lists of unrelated words, the recall of pictures, working memory tasks, and memory for spatial location (Craik, 1994). With the

exception of the visual system, little is known about whether older adults are impaired in judging the timing of information when memory demands are minimal.

Temporal Processing: Clinical Studies

Much research on temporal processing has been conducted in areas such as dyslexia, dysphasia, learning disabilities, amnesia, and disorders of the central nervous system. In fact, deficits in temporal processing have been implicated in many diseases such as Korsakoff's syndrome (Koeppel, et al., 1995; Mayes, MacDonald, Pickering, & Fairburn, 1991; Shimamura, 1990), and Parkinson's (Harrington, Haaland, & Hermanowicz, 1998).

It has been suggested that impaired performance in temporal processing is related to some atrophy (e.g., neuronal loss) of the frontal lobes that occurs with normal aging (e.g., Kausler, 1994; Parkin, Walter, & Hunkin, 1995). Evidence from computed tomography (CT) brain scans indicate that over 80% of individuals with Korsakoff's amnesia show frontal lobe atrophy (Kolb & Whishaw, 1985). Korsakoff amnesics have displayed deficits in temporal processing and in executing plans (Mayes, et al., 1991; Shimamura, 1990). It is believed that both of these information processes are mediated by the frontal lobe (Shimamura, 1990). Research also indicates that non-Korsakoff amnesic patients with frontal lobe lesions tend to be impaired in their ability to sequence words and order events (Shimamura, Janowsky & Squire, 1990). As well, Parkinsonian patients with frontal lobe dysfunction have demonstrated deficits in tasks involving temporal sequencing (Vriezen & Moscovitch, 1992). Milner (1974; cited in Moscovitch & Winocur, 1992) reported that the frontal lobes and hippocampus (medial temporal region) appear to be involved in judgements of temporal ordering.

Recently, Parkin, Walter, and Hunkin (1995) examined the relationship between normal aging, frontal lobe function, and memory for temporal information. Frontal lobe functioning was assessed by several tasks such as the Wisconsin Card Sorting Test (WCST) and Word Fluency Tests. The authors reported that younger adults outperformed older adults in the memory for temporal ordering. Correlations were calculated on measures of the temporal ordering memory task and frontal lobe performance. Although the correlations of the young group were not significant, the correlation between temporal discrimination abilities and frontal lobe performance of older adults was similar to that of individuals with frontal lobe damage.

The results of Parkin et al. (1995) indicate frontal lobe involvement in temporal processing. However, impaired performance on the WCST is not necessarily indicative of frontal lobe dysfunction. Several researchers have reported no differences in WCST performance between patients with frontal lobe damage and patients with damage to other lobes (Anderson, Damasio, Jones, & Tranel, 1991; Grafman, Jonas, & Salazar, 1990). In addition, Canavan, Passingham, Marsden, Quinn, Wyke, and Polkey (1989) reported that patients with frontal lobe lesions and patients who had undergone right temporal lobectomies were both impaired in motor sequencing abilities when compared to an early Parkinsonian group or a left temporal lobectomy group. Yet, Petrides and Milner (1982) found that patients with temporal lobe lesions, regardless of which side of the brain, were not impaired in tasks that required them to organize information and carryout a sequenced response provided that there was not extensive damage to the hippocampus. They also reported that patients with left frontal lobe damage were impaired in both verbal and

nonverbal sequencing tasks, while patients with right frontal lobe lesions demonstrated impairment for nonverbal sequencing tasks only.

To infer brain function from structural brain damage may be misleading since the effects of brain damage are rarely localized to a specific region. Moreover, the cognitive effects of brain damage are typically not confined to only one type of ability. The data at this time are not sufficient to implicate a specific lobe that is solely responsible for mediating temporal processing. Furthermore, it has yet to be established whether there is even a hemispheric locus for the timing of events.

Hemispheric Temporal Sequencing

Early studies (e.g., Efron, 1963a, 1963b) demonstrated that individuals with left hemisphere (left hemisphere) brain damage (mildly aphasic) were more impaired on tasks requiring the temporal ordering of physical stimuli, relative to right hemisphere damaged patients (nonaphasics). Aphasia tends to result from left hemisphere lesions and refers to an ability loss in the production of speech or writing, or defects in comprehending written or spoken language (Kolb & Whishaw, 1980). This finding led several researchers to conclude that the dominant hemisphere for speech (usually the left hemisphere) may be crucial for making temporal judgements (Swisher & Hirsh, 1972). Several researchers have posited that the existence of specialized mechanisms within the left hemisphere for temporal processing may represent evolutionary precursors to lateralized speech perception and language functions (Calvin, 1990; Fitch, Brown, O'Connor, & Tallal, 1993). Given that the ability to understand language involves the sequencing of spoken words, while the production of coherent sentences involves the proper sequencing of words, the left hemisphere is viewed as a serial processor (Efron, 1990). In addition, the left hemisphere

has been implicated in sequential motor control (Bryden, 1990). The notion that the left hemisphere may be responsible for making temporal judgements initiated the investigation of temporal processing abilities within the auditory, tactile, and visual modalities.

Many studies employing dichotic listening have demonstrated a right ear advantage when verbal stimuli are presented simultaneously to both ears (see Springer & Deutsch, 1993). It has been suggested that the right ear advantage for verbal material is a result of the right ear having direct access (via the contralateral pathways) to the left hemisphere which is specialized for language abilities (Kimura, 1967; Tallal, Miller, & Fitch, 1993). However, the findings from studies that have examined auditory temporal processing indicate that the right ear advantage is not a result of verbal analysis “per se,” but rather a result of temporal analysis. A typical study using this procedure to examine temporal processing may involve binaurally presented verbal and nonverbal stimuli. The presentation of the stimuli would be separated by different intervals. Participants indicate the order in which the stimuli were presented.

Several researchers (e.g., Efron, 1963c; Papcun, Krashen, Terbeek, Remington, & Harshman, 1974; Schwartz & Tallal, 1980) have posited that the left hemisphere is specialized for processing information that rapidly changes in a temporal manner. Lackner and Teuber (1973) found that war veterans who sustained left hemisphere penetrating wounds were impaired in resolving two auditory clicks that were presented in close time to one another dichotically. Tallal and Newcombe (1978) also tested war veterans with left hemisphere damage and reported a high correlation between the degree of language comprehension and temporal processing abilities for both verbal and nonverbal stimuli. In addition, Swisher and Hirsh (1972) reported that patients with left, but not

right hemispheric damage were impaired in making judgements of fine temporal auditory and visual stimuli.

However, more recently, Efron and his colleagues demonstrated that deficits in processing temporal auditory stimuli were not restricted to left hemisphere damage. Sherwin and Efron (1981) found significantly elevated thresholds in temporal ordering abilities for both left-and- right hemisphere damaged patients. They argued that deficits in temporal processing following damage to the right hemisphere may have been underestimated. Given that temporal processing deficits have been exhibited by both left- and right- brain damaged individuals, it is doubtful that the left hemisphere mediates temporal judgements exclusively (Geffen, et al., 1996).

Although only a few studies have investigated hemispheric specialization for the processing of temporal information, when compared to language and spatial information (Mills & Rollman, 1980), these studies have mainly focused on the temporal processing of tactile and visual information. The choice of these two modalities relative to the auditory modality, may be due to the crossed pathways of the somatosensory and visual system.

Tactile Processing

The processing of tactile temporal information involves the transmission of somatic sensory information from the skin to the thalamus and then to the somatosensory cortex (Figure 1) for interpretation.

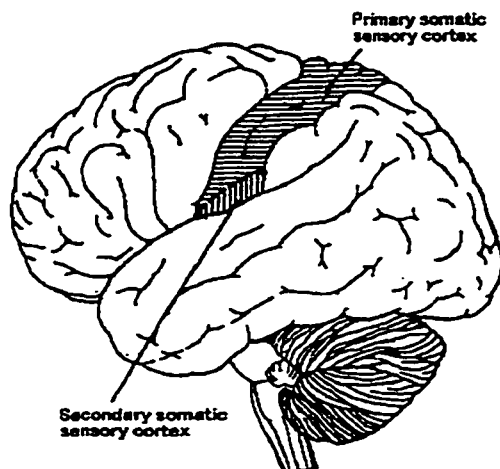


Figure 1: Lateral view (left hemisphere) illustrating the location of the somatosensory cortex.

Mechanoreceptors and Somatosensory Neural Pathways

The glabrous (hairless) skin is sensitive to touch and is most sensitive in the fingertips (Martin, 1991). Two types of mechanoreceptors in the superficial glabrous skin are the rapidly adapting Meissner's corpuscles and the slowly adapting Merkel's receptors. Rapidly adapting receptors respond at the onset, but not to the duration of the stimulus. In contrast, slowly responding receptors respond to a continuous or persistent stimulus.

Subcutaneous tissue contains the rapidly adapting Pacinian corpuscles and the slowly adapting Ruffini's corpuscles. The Meissner's corpuscles are sensitive to touch and vibration, the Merkel's receptors and Ruffini's corpuscles are sensitive to light touch and pressure, the Pacinian corpuscles are sensitive to deep pressure and vibration, and the free nerve endings respond to pain and pressure (Schneider & Tarshis, 1995).

Somatosensory information from the skin surface is projected to the contralateral postcentral gyrus in the anterior region of the parietal lobe that is contralateral to the site of

skin stimulation (Martin, 1991). The dorsal column-medial lemniscal pathway and the anterolateral pathway are the two main somatosensory pathways. The dorsal column-medial lemniscal system (Figure 2) mediates tactile stimulation (i.e., touch and vibration) and limb proprioception, while the anterolateral system mediates pain and temperature information.

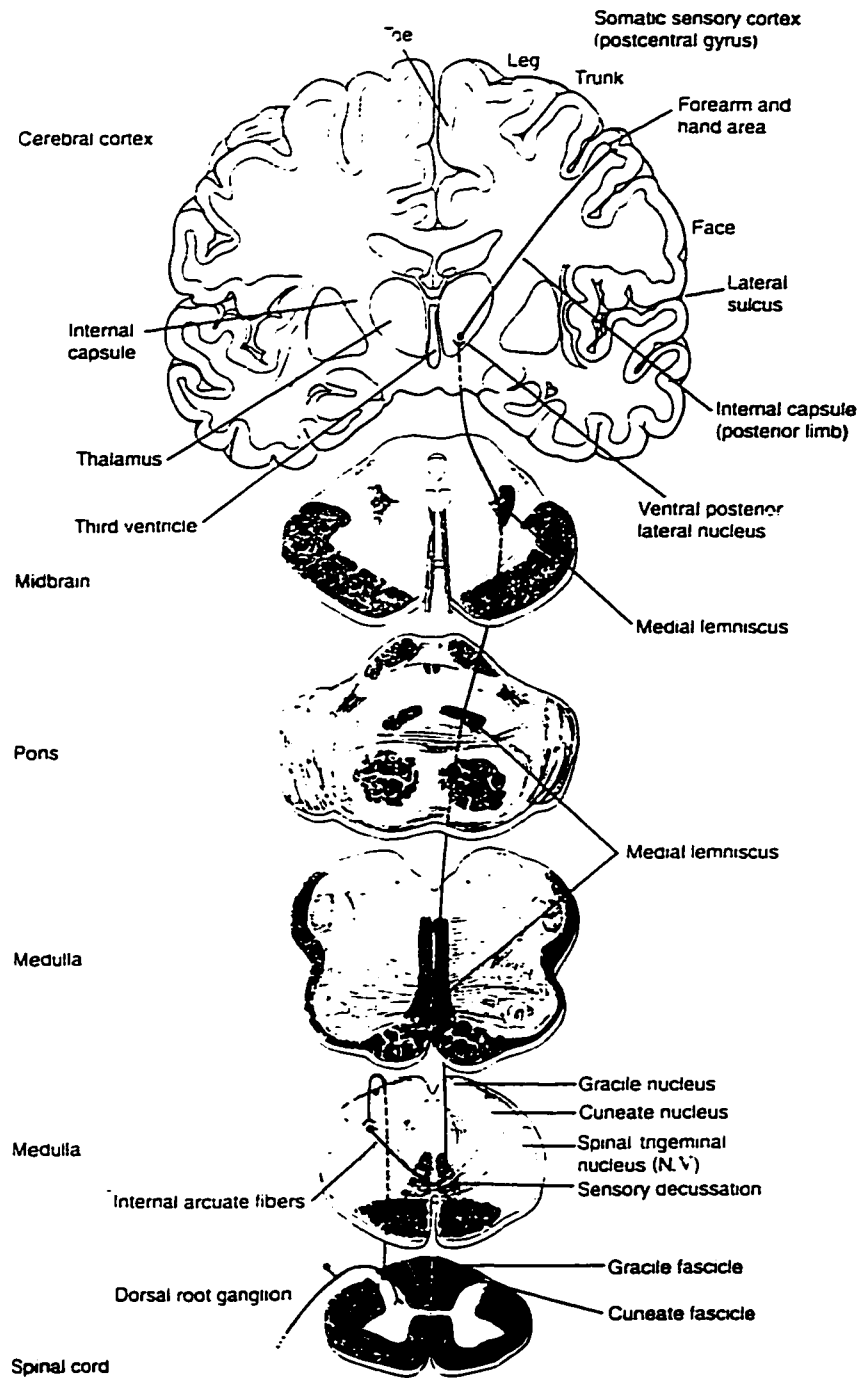


Figure 2: The general organization of the dorsal column-medial lemniscal system.

Both Merkel's and Meissner's corpuscles have small receptive fields and are capable of resolving fine spatial differences. In contrast, the Pacinian and Ruffini's corpuscles have large receptive fields and resolve coarse spatial differences. It has been suggested that Merkel's receptors best encode the spatial characteristics of stimuli (slowly adapting receptors) while the rapidly adapting Pacinian receptors provide temporal information for tactile stimulation (Martin, 1991). It is well documented that the Pacinian corpuscles are most sensitive to high-frequency stimuli with a peak sensitivity in the region of 200 to 300 Hz, while the Meissner's corpuscles are most sensitive to low-frequency stimuli (25 Hz) (Gescheider, Bolanowski, & Verrillo, 1989; Gescheider, Valetutti, Padula, & Verrillo, 1992; Vandoren, Gescheider, & Verrillo, 1990).

When a mechanical force (i.e., skin stimulation) stretches the pressure-sensitive region of the receptor, the pores of the mechanoreceptor open and sodium ions enter the cell. The influx of the positively charged sodium ions causes depolarization and if the depolarization is sufficient, an action potential is produced. Somatosensory information from the various types of receptors is conveyed to the spinal cord by the peripheral nerves. When the peripheral nerve fibers enter the spinal cord through the dorsal roots, the afferent fibers join together to form the spinal nerves. The region of skin that is innervated by a dorsal root (i.e., spinal nerve) is referred to as a dermatome. With respect to the hands, innervation of the index and middle finger is within the same dermatome (see Figure 3), while the thumb and two remaining fingers have two separate dermatomes (Martin & Jessell, 1991).

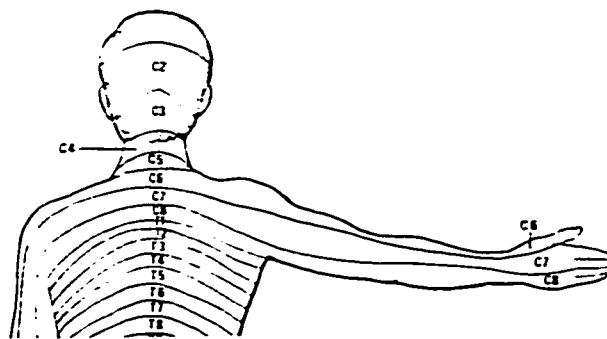


Figure 3: Dorsal view of the dermatomes for the upper portion of the body (C, cervical, T, thoracic).

The spinal cord consists of the central gray area (cell bodies) that has butterfly-shaped dorsal horns and a surrounding white matter area (myelinated axons). The dorsal columns of the dorsal column-medial lemniscal system, which consist of axons, are located medial to the dorsal horns. These columns relay tactile sensory information to the caudal medulla which is the point at which crossover occurs. Sensory information is then projected to the thalamus via the medial lemniscus (a brainstem pathway) and then to the anterior parietal lobe (somatosensory cortex).

The primary somatosensory cortex (S-I) and the secondary somatosensory cortex (S-II) are the two main somatosensory cortical regions (see Figure 1). The S-I region is situated on the postcentral gyrus and receives sensory information from the contralateral body. The S-II region primarily receives information from the S-I region. Thus, projections from the S-I region are necessary for the perceptual function of S-II (Martin & Jessell, 1991).

The coding of tactile stimulation occurs in the somatosensory cortex and is ruled by place arrangement. Impulses that are related to the type of stimulation are relayed to different regions of the somatosensory cortex by separate neurons (Schneider & Tarshis, 1995). The amount of cortex devoted to a particular body region is proportionate to its sensitivity. For example, a larger amount of cortex is devoted to the sensory input of the fingertips relative to the palm of the hand. The intensity of the stimulus is conveyed by the number of impulses firing in a unit of time in different cortical regions. Thus, information regarding the type and the amount of pressure of a stimulus is coded by the activation of the region of cortex that represents the specific skin surface and by the number of impulses conveyed to that region.

Age-Related Changes

Age-related changes in the mechanical properties of the skin have been documented. The amount of elastin and collagen in elderly skin is decreased so that there is a loss of elastic recovery and skin indentation is prolonged (Marks, 1983). Changes in the number and morphology of the Pacinian and Meissner mechanoreceptors have also been documented (for a review see Kenshalo, 1986). Briefly, the Meissner corpuscles decrease considerably in numbers and change in their shape (i.e., the capsule itself becomes enlarged and coiled and its shape becomes irregular). Besides the decrease in the density of the Pacinian corpuscles with age, there are morphological changes in the corpuscles that do remain. For instance, the body of the Pacinian corpuscle becomes long and twisted (Kenshalo, 1986). Merkel and Ruffini receptors show little change in density and morphology with advanced age.

Changes in the afferent fibers that are associated with advanced age have also been identified (Kenshalo, 1986). For example, the distance between the nodes of Ranvier of the myelinated axons is abnormally shorter among the healthy (disease-free) elderly when compared to young adults. It is believed that this anomaly is due to segmental demyelination and remyelination or to degeneration and subsequent regeneration of peripheral nerve fibers (Kenshalo, 1986). Not surprisingly, slower neural conduction among the elderly has been reported by several researchers (e.g., Desmedt & Cheron, 1980; Selkoe, 1992) and the decrease in speed and efficiency is attributed to alteration of myelin (i.e., age-related changes in the lipid composition of the myelin) (Selkoe, 1992). Finally, Kenshalo (1986) reported a loss of spinal root ganglion cells (up to 36%) between 10 to 70 years of age.

The findings indicate that the mechanical properties of the skin and neural processing within the somatosensory system undergo age-related changes. It is difficult to separate the sensory neural functioning from the earlier functioning of the peripheral properties since the organization of the somatosensory is sequential. Therefore, age-related changes in both the mechanical skin properties and neural processing efficiency must be considered when examining tactile temporal processing judgements.

Temporal Tactile Processing

The few studies investigating tactile temporal processing among older adults have focused on tactile sensitivity relative to judgements of simultaneity. Furthermore, no study to date has investigated judgements of simultaneity in an aged population from a lateralized perspective. Nevertheless, the results of vibrotactile studies that have examined the tactile

temporal acuity of older adults suggest that there is a decrease in sensitivity to tactile stimuli with advanced age.

VanDoran, Gescheider, and Verillo (1990) reported an age-related decline in the ability of adults to detect temporal gaps of ongoing vibrations that were delivered to the right thenar eminence (i.e., the bulge of muscles in the palm at the base of the thumb). In addition, Gescheider et al., (1992) reported that when compared to younger adults, older adults showed an impairment in detecting high frequency vibrations to the thenar eminence. These researchers examined the thresholds of the Pacinian receptors by employing high frequency vibrations (250 Hz) with stimulation durations of 500 to 976 ms. An age-related increase in tactile sensitivity thresholds to fingertip stimulation has also been reported by several researchers (e.g., Axelrod, Thompson, & Cohen, 1968; Kenshalo, 1986; Thornbury, & Mistretta, 1981; Stevens, 1992; Stevens & Patterson, 1995; Woodward, 1993).

Not surprisingly, there is a great deal of evidence indicating an age-related decline in somatosensory sensitivity to tactile stimulation that appears to be associated with age-related changes in the mechanical properties of the skin. However, little is known as to whether the age-related decrements in the processing of tactile temporal information can be attributed to other age-related factors (neuronal loss and shrinkage, decline in the number of synapses, loss of myelin) that have a profound effect on neural transmission (Ivy, MacLeod, Petit, & Markus, 1992).

In order to determine whether the age-related increase in temporal thresholds can be attributed to changes in the mechanical properties of the skin or to changes that may occur in the nervous system itself, Woodward (1993) examined the skin compliance and tactile discrimination thresholds of adults (ranging in age from 18 to 84 years). Woodward's

stimuli consisted of a two-point wheel and a gap wheel. The two-point wheel consisted of four pairs of pins that were spatially separated (ranging from 0.0 to 3.5 mm) in order to determine the minimum space necessary between the two stimulating pins for the perception of two distinct events. The gap wheel was designed to assess thresholds by delivering a stimulus that had two smooth surfaces that were separated by spaces. The two-point wheel produced significantly more skin indentation than the gap wheel. Thus, the stimulus wheels were designed to measure individual skin compliance (the mean indentation produced by 8 presentations of each wheel with a prescribed force). Participants were to indicate when they perceived that the gap/pin spacing occurred.

Woodward (1993) reasoned that if the age-related changes in the mechanical properties of the skin contributed significantly to the increase in the tactile thresholds of the elderly, then skin compliance, relative to age, should be a significant predictor for tactile sensitivity. Her regression findings showed that age was the only significant predictor of tactile discrimination thresholds. Thresholds increased for both the two-point and gap detection tasks as age increased. As well, skin compliance was not correlated with discrimination thresholds. In fact, age was the only variable that significantly correlated with tactile sensitivity. Interestingly, gender and skin compliance were correlated. Males skin compliance measures were significantly lower than those of females reflecting the notion that male hands tend to be less compliant. Woodward argued that the relationship between increasing tactile thresholds and age is not attributable to changes in the compliance of the skin, but rather to other factors that are associated with advanced age. Woodward proposed that age-related changes in the nervous system (e.g., neuronal loss and shrinkage, decline in the number of synapses, loss of myelin) that affect the speed, quantity,

and quality of information processing may be responsible for the age-related changes in fine tactile discrimination abilities.

Other researchers have corroborated the gender difference in skin compliance reported by Woodward (1993). Gescheider, Bolanowski, Hall, Hoffman, and Verillo (1994) reported that females demonstrated greater sensitivity than males in detecting vibrotactile stimuli. If a decline in skin compliance contributes significantly to the increase in tactile sensitivity thresholds, then one would expect males to have higher tactile discrimination thresholds than females. However, this gender difference did not emerge in Woodward's (1993) study.

Results of the previous studies indicate that somatosensory sensitivity decreases as a function of age. It is believed that the age-related decrease in tactile sensitivity is attributed to changes that occur in the mechanical properties of the skin with advanced age (e.g., Gescheider et al., 1992; Van Doren et al., 1990). Although Woodward (1993) reported an age-related decline in tactile discrimination thresholds after controlling for skin compliance, additional research examining age differences in the perception of the timing of fine tactile information, relative to tactile sensitivity is required.

Hemispheric Temporal Tactile Processing

In 1925, Klemm (as cited in Efron, 1963a) found that the reaction time to a foot stimulus was 25 to 30 ms slower than a stimulus administered to the forehead. He concluded that this increase in reaction time was due to the longer sensory pathway from the foot. In 1962, Halliday and Mingay (as cited in Efron, 1963a) conducted a similar experiment. However, they measured cortical evoked potentials rather than reaction time. They demonstrated that the evoked potentials for toe stimulation occurred approximately 20

ms later than the evoked potentials for finger stimulation. In order for the two stimuli to be perceived as simultaneous, the stimulus to the toe had to be administered approximately 9 to 17 ms prior to stimulating the index finger. The authors concluded that the judgement of simultaneity occurs when two sensory messages reach the central nervous system at about the same time.

Efron (1963a) employed this method to test the hypothesis that temporal discriminations were processed by the hemisphere dominant for speech. That is, within the left hemisphere for the majority of the right-handed population (Springer & Deutsch, 1993). Efron argued that sensory messages received by the nondominant hemisphere (right hemisphere) must be transferred to the left hemisphere via the corpus callosum (Figure 4).

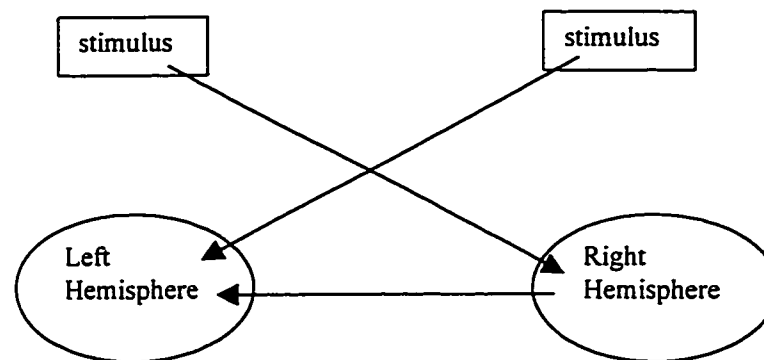


Figure 4: Efron's model displaying a left hemisphere locus for making temporal judgements and the transfer of information from right- to- left hemisphere.

To test his hypothesis, Efron's somatosensory stimuli consisted of mild electric shocks which were delivered to the right and left index fingers. Given that the sensory pathways are almost completely crossed, (Martin, & Jessell, 1991), stimuli delivered to the

left side of the body will project to the right hemisphere, whereas right-sided stimuli will project to the left hemisphere.

When each hemisphere receives a sensory message and a comparison or judgement must be made regarding these two messages (e.g., temporal), the information must be integrated in one place (Swisher & Hirsh, 1972). Since interhemispheric transfer of information requires time, Efron reasoned that in order for the information to be perceived as simultaneous, the left-sided stimulus must be administered a few milliseconds before the right-sided stimulus. This situation is reversed if the individual is right hemisphere dominant.

Efron (1963a) tested 40 normal participants (20 right-handed, 20 left-handed). Each session began with the pair of stimuli separated by 100 ms. Initially, the left-sided stimulus preceded the stimulus of the right side. Participants were told to report the order of the two stimuli (left before right, right before left, or simultaneous) within each condition. Stimuli were delivered and repeated every two seconds until a response was given. The stimuli were separated by step intervals of 5 ms until the participant responded with a judgement of simultaneous. The same procedure was followed again except the right-sided stimulus was delivered before the left. Two descending series were each repeated 10 times within each modality.

Efron reported a delay of 2-6 ms for stimuli administered to the left side of the body (right hemisphere) for right-handers. Efron's results demonstrated a left hemisphere advantage since the left side of the body had to be stimulated prior to the right side in order for the individual to report simultaneity. The reverse held true for a few left-handers. The differential results regarding handedness are congruent with the research findings that

indicate that some left-handers may be right hemisphere dominant, while other left-handed individuals do not exhibit lateralization (Springer & Deutsch, 1993). The results of the right-handers support the view that the left hemisphere is specialized for temporal judgements (i.e., Halliday & Mingay, 1962).

An important question to ask is whether the 2-6 ms delay represented interhemispheric transfer or the differential slowing that occurred in the sensory pathways (e.g., between the skin of the left index finger and the somatosensory cortex). Efron argued that it is very unlikely that delays occur in the sensory pathways. This would imply that right-handed persons have slower left-sided sensory pathways, relative to their right side. Halliday and Mingay (1962) also considered this possibility and examined the latency of the cortical evoked potentials of the right and left index fingers. They found no difference in latency between the left and right sides.

Efron's (1963a) findings indicating a left hemispheric locus for temporal judgements were later supported by Hammond (1981). Hammond investigated the ability of individuals to detect whether a train of six electrical pulses, which were delivered to the left and right hand, appeared at regular intervals. Hammond found that the left hemisphere was better than the right hemisphere for detecting fine irregularities in the train of pulses.

In a more recent study, Clark and Geffen (1990) investigated judgements of simultaneity for tactile stimuli. However, unlike the previous studies, Clark and Geffen included both unilateral and bilateral conditions. A pair of stimuli presented unilaterally, was projected to one hemisphere only (opposite to the side of the body that is stimulated), while bilaterally presented stimulus pairs involved both hemispheres. Clark and Geffen

(1990) investigated whether both cerebral hemispheres are equally capable of temporal discrimination judgements by including stimulation in unilateral situations.

Clark and Geffen questioned Efron's conclusion that the left hemisphere is specialized for making temporal judgements. They argued that confounds in the methodology may have been responsible for his results. Clark and Geffen (1990) believed that a right-sided bias in the orientation of attention may have occurred in the previous research. They argued that participants' hands should be placed along the body midline during stimulation in order to avoid an attentional bias. They also argued that the responses of "right first" when the stimuli were actually administered simultaneously may be explained by priming effects. That is, given that the responses were verbal, the left hemisphere may have been primed to right-sided stimuli. These two confounds were addressed in their study.

Participants' fingers rested on the mechanical tactile stimulators that were placed in a line that extended forward 90 degrees from the vertical body (see Figure 5). Both index fingers were stimulated in the bilateral condition. In the unilateral conditions (i.e., within left-hand, within right-hand), index and middle fingers were stimulated. Stimulation to the tips of these two fingers on one hand projects to the contralateral somatosensory cortex via the same bundle of nerve fibers (Martin, 1981; Schneider & Tarshis, 1995). Consequently, this procedure prevents differences in arrival time of the sensory messages to the cortex that may occur if different sensory pathways are involved.



Figure 5: Participant's fingers resting on the mechanical tactile stimulators that were placed in a line that extended forward 90 degrees from the vertical body (i.e., midline).

To examine priming effects, both verbal and motor output responses were included in the bilateral and unilateral conditions. Participants' feet were placed on a bipedal mechanism that was connected to a computer for recording purposes.

Participants were required to respond whether a pair of stimuli were delivered simultaneously (YES response) or not (NO response). Each trial began with a pair of stimuli separated by an interval (i.e., SOA - the time between the onset of the first stimulus and the onset of the second stimulus) at which a NO response (verbal or motor) was confidently established for each participant during a previous practice trial.

For the unilateral conditions (within-left hand, within-right hand), no significant differences were reported in thresholds in either of the two conditions. Clark and Geffen argued that if the left hemisphere was superior to the right hemisphere in making temporal judgements, the threshold for right hand stimulation (left hemisphere) should be lower than

the threshold for left hand stimulation (right hemisphere). Clark and Geffen's results suggest that both hemispheres are equally efficient in making temporal judgements.

Clark and Geffen reported no significant differences in simultaneity thresholds for the bilateral condition. Thus, thresholds were similar regardless of which hand was stimulated first. Finally, they reported no significant differences in any condition for the mode of response (verbal vs. motor). As such, it appears that verbal responses do not prime the left hemisphere in this type of task.

Similar results supporting the notion that both hemispheres are equally capable of processing temporal tactile information have since been provided by several researchers (i.e., Geffen, Mason, Butterworth, McLean, & Clark, 1996). These findings appear to contradict those reported by Efron (1963a, 1963b). Clark and Geffen (1990) attribute the lack of a left hemisphere advantage for temporal judgements to (i) the right-ward attentional bias, which was controlled for in their study by having the hands placed at body midline, and (ii) the increased sensitivity of the testing equipment.

Summary

It is clear that further research is required for assessing the abilities of the cerebral hemispheres to process temporal tactile information. The findings reported by Clark and Geffen (1990) and Geffen et al., (1996) suggest that both hemispheres may be equally proficient in making temporal judgements. In contrast to Efron's (1963a, 1963b) findings, the results of other researchers (Clark & Geffen, 1990; Geffen et al., 1996) indicate that a left-sided stimulus does not need to precede the right-sided stimulus in order for the perception of simultaneity to occur. Unfortunately, Efron did not include unilateral stimulations which may have provided additional information for the

comparison of simultaneity thresholds. Although Efron's results indicated a left hemisphere advantage for temporal judgements, the presence of equal thresholds in the unilateral situations would have raised questions regarding the findings observed in the bilateral conditions. The results of Clark and Geffen (1990) and Geffen et al., (1996) certainly indicate that both cerebral hemispheres are equally capable of making temporal tactile judgements. Nevertheless, given that few studies have investigated interhemispheric judgements of simultaneity for tactile information, a definitive conclusion regarding the locus of temporal judgements would be premature.

Visual Processing

Temporal processing in the visual system involves phototransduction and the transmission of electrical signals to the visual cortex for interpretation.

Optical Components and Visual Neural Pathways

Visual processing includes the refraction of light from objects so that the light is brought into focus on the retina and then transduced into neural impulses (Fozard, 1990). Light enters the cornea and lens, where it is refracted, and then travels through the vitreous humor before it reaches the retina. However, the light must first pass through the transparent (unmyelinated) outer layers of retinal neurons in order to be absorbed by the photoreceptors (i.e., rods and cones).

Visual images are undistorted at the fovea where there are no cell bodies to interfere with the image. Nasal to the fovea is the optic disc where the nerve fibers exit the retina. The photoreceptors, cones and rods, within the retina transduce the refracted light into neural impulses. Cones respond to day vision, mediate color, provide good spatial and temporal resolution, and respond to rapid changes in visual image. Not surprisingly, cones

are concentrated in the fovea area where visual images are less distorted. In contrast, rods respond to night vision or poor illumination conditions, do not mediate color, and have poor visual acuity capabilities.

Once light reaches the retina and is transduced into electrical signals by the photoreceptors, it is then transferred to the ganglion cells via the bipolar cells. The axons of the ganglion cells form the optic nerve and it is at this point that the ganglion cells are myelinated (Tessier-Lavigne, 1991). The optic nerve leaves the retina at the optic disc and projects to the visual cortex.

When both eyes are fixated on a central point in the visual field, the left hemifield projects to the nasal hemiretina (region that is medial to the fovea) of the left eye and the temporal hemiretina (region that is lateral of the fovea) of the right eye. Thus, the right hemifield projects to the nasal hemiretina of the right eye and the temporal hemiretina of the left eye. Neurons of the optic nerve from the nasal portions of the retina cross at the optic chiasm to the contralateral hemisphere (Figure 6), while the neurons from the temporal region do not cross (Mason & Kandel, 1991).

Some axons of the optic nerve project to the superior colliculus (midbrain) where they form synapses with neurons that control oculomotor functions (Mason & Kandel, 1991). However, most of the axons project to the lateral geniculate nucleus in the thalamus and form synapses with the neurons that project to the calcarine fissure of the occipital lobe. Images in the right hemifield project to the lateral geniculate nucleus, superior colliculus and primary visual cortex in the left hemisphere, while images in the right hemifield project to the lateral geniculate nucleus, superior colliculus and primary visual cortex of the left

hemisphere. In short, visual information is represented in the hemisphere that is contralateral to the visual field.

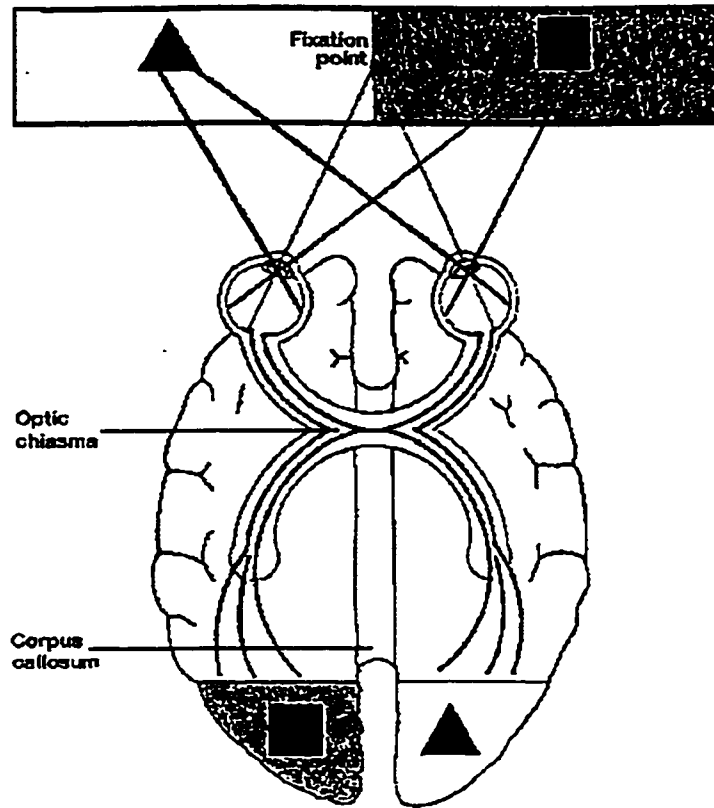


Figure 6: Illustration of the crossed visual system: Stimuli presented in one visual field is projected to the contralateral hemisphere.

The lateral geniculate nucleus consists of several layers which represent the magno- and parvocellular pathways that project to the visual cortex (Mason & Kandel, 1991). The two pathways process different types of visual input. For instance, the magnocellular pathways have high temporal resolution (movement) and low spatial resolution, while the parvocellular pathways process detail on form, color, and have high spatial resolution. Thus, information regarding the features of a stimulus (e.g., color, form, shape) and orientation are coded and conveyed for interpretation.

Age-Related Changes

Several age-related changes in the visual system have been identified and are reviewed by Kline & Scialfa (1996). The cornea thickens and becomes yellow with age (Weale, 1982), however, the effects on normal functioning appear to be limited (Kline & Scialfa, 1996). In addition to thickening and becoming yellow, the lens hardens so that its ability to focus (accommodate) decreases with advanced age (Kashima, Trus, Unser, Edwards, & Datiles, 1993). Although the decrease in pupil size reduces the amount of retinal illumination (Loewenfeld, 1979), the effects appear to be most evident in low-illumination situations (Winn, Whitaker, Elliot, & Phillips, 1994).

With respect to photoreceptors, an age-related loss in cone density in the far periphery has been noted, however the loss of foveal cones appears to be minimal (Curcio, & Millican, Allen, & Kalina 1993; Gao, & Hollyfield, 1992). A loss in rod density (i.e., 30% decline) near the central retina (i.e., macula) has also been noted (Curcio et al., 1993). The loss in rods however, does not appear to have adverse visual effects since the remaining rods are able to maintain the capture of photons at a constant rate (Kline & Scialfa, 1996). Finally, a decline in the number of retinal ganglion cell axons has also been reported (Jonas, Schmidt, Muller-Bergh, Schlotzer-Schrehardt, & Naumann, 1992).

The findings indicate that the optical components and neural functioning within the visual system undergo age-related changes. As with the somatosensory system, it is difficult to separate neural functioning from peripheral functioning since the organization of the visual system is sequential. However, there is evidence that neural functioning contributes to some of the age-related visual deficits in temporal resolution. That is, age-

related deficits are not significantly reduced when young and older adults are equated with respect to visual ability (Elliott, Whitaker, & Thompson, 1989; Johnson, Adams, & Lewis, 1989). These findings suggest that the loss in temporal resolution with age may be associated with neural decline. Nonetheless, age-related changes associated with the optical components and neural processing proficiency must be considered when examining temporal visual processing.

Temporal Visual Processing

Early studies reported that older adults had lower (poorer) fusion thresholds than younger adults for detecting the point at which a flickering light no longer appears to be flickering (i.e., critical flicker frequency) (Coppinger, 1955; McFarland, Warren, & Karris, 1958). Research findings generally indicate that temporal visual resolution decreases with advanced age. However, the nature of visual temporal deficits in normal adults has been debated for at least three decades (Brannan, 1992). That is, it is difficult to determine the degree to which the age-related decline in temporal visual processing is attributed to the functioning of the optical components or to neural functioning.

Schieber and Kline (1982) examined discrimination abilities for successive and simultaneous stimuli among young and older adults. Participants were to indicate which stimulus (circle or square) was presented first after the stimuli were visually presented either successively (different intervals) or simultaneously. In comparison to the young adults, older adults required longer intervals to correctly discriminate the order of the two stimuli.

Kline and Schieber (1982) suggested that some of the age-related reduction in visual sequencing (temporal resolution) could be partially explained by the yellowing of the lens and a reduction in pupillary diameter which reduces the amount of light that falls on the

retina. However, it has also been suggested that neural changes may contribute to the age-related decline in temporal resolution (Elliott, Whitaker, & MacVeigh, 1990).

It was suggested that the age-related deficit in visual temporal judgements is due to an age-related increase in stimulus persistence (Kline & Schieber, 1982; Lynk, Kline, & Culham, 1994). That is, given the age-related changes in the nervous system (e.g., neuronal loss and shrinkage, decline in the number of synapses, loss of myelin), there is an overall slowing of the aging nervous system such that more time is required for older adults to recover from a visual stimulus. If the time interval between two visual stimuli is insufficient, an "optical blur" may occur (Lynk et al., 1994).

An age-related decline has also been noted in temporal resolution of color. Kline, Ikeda, and Schieber (1982) presented green and red circles on a screen. The flashes of these two circles were separated by different intervals so that the two colors would be integrated to produce the color yellow. Kline et al., (1982) found that older participants integrated red and green significantly more often than younger adults at longer intervals. These findings support the stimulus-persistence hypothesis in that the trace for the flashed red and green stimuli took longer to decay for the older adults, relative to the younger adults. Changing the luminance levels had no effect on visual persistence. The investigators suggested that at least some of the age differences in visual persistence can be attributed to neural functioning, relative to photoreceptor activity.

Researchers have attempted to separate optical functioning from neural functioning by simulating the typical optical age-related changes in young participants. For instance, Elliott, Whitaker, and Thompson, (1989) investigated the effects of retinal illuminance by fitting young participants with neutral density filters. Thus, one method used to separate

optical function from neural function is to simulate the age-related optical changes through the use of lenses (induce optical blur) and neutral density filters (reduce the amount of retinal luminance).

It has been postulated that the age differences in temporal resolution may be due to changes within the visual neural system. The reported age-related decline in temporal visual processing appears to be a robust finding within the aging literature (Brannan, 1992). Although it is yet to be determined just how much of the age-related decline in temporal visual processing is attributed to optical changes or to neural functioning, it appears that neural processing does contribute to this age-related decline.

The methods used to study adult age differences in temporal visual processing have yet to examine this area from a lateralized perspective. It is not known whether older adults exhibit hemispheric asymmetry in processing temporal visual information. This type of information will greatly enhance our understanding of the deficits in temporal processing in the aged population. That is, it is not known whether there is an age-related differential hemispheric decline in temporal visual processing (i.e., a right hemispheric decline).

Hemispheric Temporal Visual Processing: Clinical Studies

Efron (1963c) examined temporal visual processing abilities in aphasics. Efron (1963c) compared temporal judgements of simultaneity between moderate aphasics (left hemisphere strokes) and right hemisphere brain damaged individuals (non-aphasics). Participants were to report whether a red or green light was flashed first. The flashes of light were displayed on a screen and separated by intervals of 0 to 600 ms. Interestingly, the group of aphasics required significantly longer interstimulus intervals relative to the non-aphasics to determine the temporal order of the lights (e.g., 400 - 600 ms). However, some

participants with lesions in comparable regions of the right hemisphere also demonstrated difficulties in temporal judgements when compared to normals, although these deficits were not as severe as those of aphasic individuals. Efron (1963c) suggested that aphasia should not be viewed solely as a language disorder, but rather as a consequence of a temporal sequencing disorder. These findings (Efron, 1963c) initiated the investigation of temporal analysis from a hemispheric perspective (Efron, 1990).

Goldman, Lodge, Hammer, Semmes, & Mishkin (1968) found that patients with left temporal lobectomies were significantly impaired in detecting flickering light from continuous light (critical flicker frequency). However, Goldman et al., (1968) also reported that patients with right temporal lobectomies demonstrated an impairment, but to a lesser degree. In contrast, Eals (1987) employed an apparent motion task and found a right hemisphere advantage for normal adults. Participants were required to make directional judgements to an array of dots that was presented unilaterally in rapid succession so that motion could be inferred.

Patients with commissurotomy (a surgical procedure in which the corpus callosum is cut in order to prevent the interhemispheric spread of epileptic seizures) have demonstrated that they are able to perceive apparent motion when stimuli are presented bilaterally. Given that these patients (split-brain individuals) were able to respond to bilateral presentations, the perception of apparent motion must be mediated by subcortical interhemispheric pathways (Corballis et al., 1998). Although this finding has been reported by several researchers (e.g., Naikar & Corballis, 1996; Ramachandran, Cronin-Golomb, & Myers, 1986), it remains unclear whether split-brain patients can make simultaneous and successive

judgements with above chance accuracy when the presented stimuli are separated by intervals shorter than 100 ms (Corballis et al., 1998).

Corballis et al., (1998) examined temporal judgements of a right-handed 42 year old split-brain patient, L.B., who underwent section of the corpus callosum at the age of 12, and a left-handed 20 year old, R.B., who was born with callosal agenesis (i.e., absence of the corpus callosum). MRI scans confirmed that L.B.'s corpus callosum was completely sectioned and that R.B. lacked a corpus callosum.

Visual stimuli consisted of pairs of lights whose presentations were separated by small intervals (i.e., 0, 17, 33, 50, and 67 ms). Participants were to judge whether the two lights were presented simultaneously or successively. L.B. demonstrated impairment in temporal judgements for left visual field presentations and was especially impaired with bilateral presentations. However, L.B. was only able to discriminate above-chance when stimuli were separated by 150 ms. R.B.'s performance was impaired with bilateral presentations only and when stimuli were separated by 67 ms or shorter. Corballis et al., (1998) attributed the difference in performance between the two patients to compensatory mechanisms during R.B.'s early childhood, or to the intact anterior and hippocampal commissures in R.B., or to effects as a result of surgery in L.B.

With regard to hemispheric asymmetry, L.B. demonstrated a right visual field advantage, while R.B.'s performance did not indicate lateralization. However, as noted by Corballis et al., (1998), since R.B. is left-handed it is difficult to determine which hemisphere is dominant.

Hemispheric Temporal Processing: Non-clinical Studies

Fewer studies have examined hemispheric asymmetries in judgements of simultaneity among normal adults. Nicholls (1994) examined hemispheric asymmetries in the detection of simultaneous versus successive visual stimuli in 22 right-handed normal adults. The stimuli consisted of light-emitting diodes (LEDs) which were displayed in pairs to either the left visual field or the right visual field.

Nicholls reported a right visual field (left hemisphere) advantage for judgements of simultaneity. That is, participants were significantly more accurate when presentations were directed to the right visual field, relative to presentations directed to the left visual field. However, this advantage was reduced with longer SOAs (i.e., at approximately 25 ms). The author concluded that the left hemisphere is specialized in the discrimination for fine (i.e., short interstimulus intervals) temporal events.

More recently, Corballis (1996) investigated temporal judgements for successive or simultaneously presented stimuli. Instead of presenting stimuli in a unilateral condition only (c.f., Nicholls, 1994), Corballis presented pairs of white discs on a black background in both bilateral and unilateral conditions.

Corballis (1996) reported a left hemisphere advantage in the bilateral situation. That is, when the right disc preceded the left disc, performance in the judgement of successiveness was significantly better than when the left disc preceded the right disc. However, a left hemispheric locus was not revealed when the stimuli were presented in either the left or right hemifield. Corballis concluded that the lack of a significant difference implies that no interhemispheric transfer occurred in the unilateral conditions. These findings suggest that both hemispheres are equally capable of making temporal judgements

when stimuli are presented unilaterally. Corballis' data in the unilateral condition failed to support Nicholls (1994) findings of a left hemispheric locus for temporal judgements.

In contrast to Corballis' (1996) findings, Corballis, Boyd, Schulze, and Rutherford (1998) recently found a slight right visual field advantage for males, but not for females when stimuli were presented at smaller SOA values (i.e., 0, 17, 33, 50, 67 ms). However, the data in the latter study did not reveal a left hemisphere advantage when stimuli were presented bilaterally. Corballis et al., (1998) reported that participants demonstrated better discrimination in unilateral presentations relative to bilateral presentations, when stimuli were presented at 0 and 17 ms SOA values. The authors reasoned that noise and a delay are likely involved with interhemispheric transfer.

Results from studies investigating hemispheric asymmetry for temporal visual processing are not clearer than the findings reported for the tactile modality. Nicholls' (1994) reported left hemisphere locus for temporal processing when stimuli are presented unilaterally. Yet, the Corballis' (1996) results indicate that the left hemisphere is specialized for temporal judgements in bilateral situations only.

The intervals used to separate the stimuli in Nicholls' (1994) study consisted of 5 different SOAs values (i.e., 10, 15, 17, 20, and 25 ms) and the stimuli remained illuminated until a response was given. Corballis (1996) used 2 levels of ISIs (i.e., 50, and 67 ms) to separate the visual stimuli. Nicholls claimed that the left hemisphere advantage dissipated with higher SOA values (at approximately 25 ms). It is possible that in a unilateral condition, a left hemisphere advantage emerges when the presentation of stimuli are separated by very small intervals (e.g., 10, 15 ms), whereas, both hemispheres may process temporal information equally when the stimuli are separated by longer intervals. However,

this reasoning does not explain why Corballis et al. (1998) later found a slight right visual field advantage for males and no hemispheric asymmetry for bilateral presentations when stimuli were presented at short SOA's.

Conclusions

Clearly, it is not possible to conclusively state that the left hemisphere is specialized for temporal sequencing. It is difficult to determine whether there is a left hemispheric locus for temporal judgements even when the stimuli are presented bilaterally. Given that the results from earlier studies are equivocal, it is evident that additional research in hemispheric specialization and temporal processing is needed. It is interesting to note that the more recent work by Efron and his colleagues has demonstrated that the impairment in temporal processing following unilateral brain damage is not restricted to left hemisphere lesions (Efron, 1990). Efron (1990) reported that severe deficits in temporal processing are also evident in individuals with damage to the right hemisphere. Thus, the results from clinical studies do not help to clarify the hemispheric locus for temporal processing.

With respect to non brain damaged individuals, Efron (1963a) demonstrated that there is a left hemisphere specialization for temporal tactile processing. However, Efron did not include unilateral conditions which would have provided information regarding the temporal proficiency of each hemisphere independently. Clark and Geffen (1990) and Geffen et al., (1996) however, reported that both hemispheres are equally capable of processing temporal information. These researchers found that left-sided stimulation did not always have to precede right-sided stimulation in order to perceive two stimuli as simultaneous.

Nicholls (1994) reported a left hemisphere specialization for temporal processing within the visual modality. However, a bilateral condition was not included in his study. In contrast, Corballis (1996) reported that both hemispheres are equally capable of processing visual temporal information for unilateral presentations. Corballis (1996) did however, report a left hemisphere advantage for temporal processing in bilateral presentations. However, Corballis et al., (1998) did not find a left hemisphere advantage in the bilateral situation when small SOA values were employed. As such, it is difficult to determine whether there is a left hemisphere locus for making temporal judgements of stimulus events.

Although Efron (1963c) reported that patients with left hemisphere lesions demonstrated deficits in temporal judgements, several researchers overlooked the fact that some patients with lesions in comparable regions of the right hemisphere also demonstrated difficulties in temporal judgements. This finding provides evidence that the left hemisphere does not mediate temporal processing exclusively. Efron (1990) himself more recently noted that researchers investigating cerebral lateralization failed to acknowledge all of his reported findings. Efron Stated “Ignoring the fact that right-hemisphere damaged patients were also impaired, *they* (researchers) concluded that my experiments had demonstrated the existence of another cognitive *function*, since referred to as temporal or sequential analysis, for which the left hemisphere is ‘specialized’” (1990, p. 21).

In general, the findings for a left hemisphere specialization in processing tactile and visual temporal information are inconclusive at this time. Results of the studies that do demonstrate hemispheric asymmetries in temporal processing indicate that it is the left hemisphere that is specialized in this type of processing.

The evidence in the aging literature suggests that there is an age-related decline in the memory for temporal information. However, it is not known whether these age effects are attributable to memory deficits or to temporal processing deficits.

The research findings have demonstrated an age-related decline in tactile sensitivity. However, little is known as to whether there is an age-related decline in temporal tactile processing when judgements of simultaneity are the focus. An age-related deficit in temporal visual processing has been well documented. It is not known, however, whether the temporal visual processing deficit is confined to one hemisphere.

To date, it appears that no study has examined hemispheric asymmetries in the processing of sensory temporal information by the elderly. The paradigm used by Clark and Geffen (1990) and by Corballis (1996), would be useful to examine age differences in temporal processing proficiency. This paradigm places minimal demands on memory in that the participant is only required to judge whether two sensory events occur simultaneously or successively. As well, this paradigm reduces task complexity. Thus, temporal processing performance between the two hemispheres can be compared in the absence of memory demands and task complexity. This paradigm can also reveal whether temporal processing deficits among the elderly are lateralized to one hemisphere (i.e., right hemi-aging hypothesis).

The Present Study

To date, the reported findings on hemispheric asymmetry for temporal processing are equivocal. Few studies have included both unilateral and bilateral situations (Clark & Geffen, 1990; Corballis, 1996; Geffen et al., 1996) when investigating temporal processing asymmetries. Furthermore, the elderly population has not been included in this area of

research. In fact, judgements of simultaneity for tactile stimuli have yet to be investigated among the elderly. Although age-related differences in temporal visual judgements have been reported, such differences have not been examined from a lateralized perspective.

The present study examines temporal processing abilities of young and older adults by employing lateralized tactile and visual tasks. The tasks minimize memory demands and eliminate task complexity.

Simultaneity thresholds will be examined to determine the temporal processing proficiency of each cerebral hemisphere for young and older adults. Geffen et al., (1996) describe three different models for the hemispheric locus of temporal processing. The left specialization model identifies the left hemisphere as the locus in which all temporal judgements are made. According to this model, temporal information received by the right hemisphere will be transferred to the left hemisphere for judgements. In a bilateral situation, the length of the neural pathway will differ for the two stimuli since each hemisphere receives sensory input from the contralateral body and interhemispheric transfer is necessary for judgements. However, the perceived interval between two stimuli will not be distorted in unilateral situations since the stimuli will travel equal distance (i.e., input to the same hemisphere).

Given the contralateral neural pathways, the left specialization model predicts lower simultaneity thresholds when stimulation to the right hand precedes the left-hand, relative to left-hand stimulation preceding the right hand. In contrast, this model predicts that left-hand stimulation before right-hand stimulation in the bilateral situation will produce the highest thresholds. This prediction is based on the rationale that the first stimulus must be transferred to the left hemisphere and that the transfer time reduces the

perceived interval between the two stimuli. Thus, in left-hand stimulation before right-hand stimulation of the bilateral situation, the actual interval between the two stimuli will have to be larger than that required in other situations in order to perceive the stimulus events as successive.

According to the left superiority model, simultaneity judgements are made in both hemispheres, but with better precision in the left hemisphere (Lackner & Teuber, 1973). For bilateral situations, this model predicts lower simultaneity thresholds when right-hand stimulation precedes left-hand stimulation. The left superiority model also predicts lower thresholds for right within-hand stimulation than left within-hand stimulation. However, unlike the left specialization model, the left superiority model predicts that thresholds for bilateral situations will be higher than unilateral situations since interhemispheric transfer is not necessary in unilateral situations.

Both hemispheres are equally capable of making simultaneity judgements in the hemispheric equivalence model. Therefore, this model predicts no difference in simultaneity thresholds for the order of stimulation in the bilateral situation. As well, according to this model there should be no difference between the threshold values obtained in the unilateral situations. Bilateral thresholds should, however, be higher than the unilateral thresholds since interhemispheric transfer is necessary. This model assumes that the temporal judgement is made in the hemisphere that receives the second stimulus (i.e., the hemisphere contralateral to the hand receiving the second stimulus (Geffen et al., 1996; Mason & Geffen, 1996). Clark and Geffen (1996) argue that, if the judgement of simultaneity for bimanual stimulation were made in the hemisphere receiving the first stimulus, then the bimanual simultaneity thresholds should be lower

(better) than the unimanual thresholds since the second stimulus would need to be transferred, which would increase the perceived time between the delivery of the two stimulus events. For example, if the judgement were made in the contralateral hemisphere to the first stimulus, the interhemispheric time of the second stimulus would increase the perceived time between the two stimulus events. Thus, the participant would most likely not report the two events as simultaneous, which would decrease the interstimulus interval value for the subsequent trial (PEST procedure).

Given that the evidence to support a left hemispheric locus for the timing of events, it is anticipated that both cerebral hemispheres are equally capable of processing sensory temporal information. When compared to the younger adults, it is expected that older adults will make judgements of simultaneity when the two sensory events occur further apart from one another. Thus, older adults should have significantly higher simultaneity thresholds than younger adults. The rationale for this expected outcome is based on the reported age-related changes associated with tactile and visual functioning.

Finally, if there are age differences in making judgements of simultaneity for sensory events, then age effects should be observed regardless of modality. Similarly, if the data support the hemispheric equivalence model, then hemispheric equivalence for judgements of simultaneity should be evident for both the tactile and visual tasks.

Method

Participants

A total of 52 participants volunteered. The young age group consisted of 13 males and 13 females and ranged in age from 20 to 40 years ($M = 27.73$ years, $SD = 7.08$). The older group consisted of 13 males and 13 females from 60 to 80 years of age ($M = 68.65$ years, $SD = 6.12$). Each participant was tested in one session lasting from 90 to 110 minutes. Forty-four participants were recruited by responding to a local newspaper article which described the study and emphasized the need for volunteers. Eight young participants were recruited from the Department of Psychology subject pool at the University of Calgary.

All participants were required to be right-handed, have English as their native and primary language, have full use of both hands and never to have been under a doctor's care for a neurological, psychiatric, or severe illness. As well, participants were questioned regarding visual impairments (e.g., cataracts, glaucoma), handedness and substance abuse. All participants were classified as right-handed according to Annett's handedness questionnaire (Annett, 1970).

The young group had significantly more years of formal education ($M = 14.65$ years, $SD = 1.90$) than the older group ($M = 13.14$ years, $SD = 2.77$), $F(1,50) = 5.33$, $p < .05$. All of the participants reported that they were relatively healthy. There were no significant group or gender differences in the self-reports of overall health, nor for the level of physical activity. Fifteen of the older participants reported that they were taking medications (e.g., antihistamines, Premarin, synthroid, anti-inflammatories, Fosomax, and ventalin), whereas one young adult was taking medication (i.e., ventalin).

The study consisted of obtaining informed consent (Appendix A), a questionnaire to acquire general background information including the handedness questionnaire, a near binocular visual acuity assessment, threshold measurements for five blocks of trials for the tactile task, and threshold measurements for five blocks of trials for the visual task. The questionnaire consisted of questions regarding overall health, medication use, physical exercise, and educational level (Appendix B). The handedness questionnaire (Annett, 1970) consisted of six questions and was used to assess hand dominance (Appendix C). Although each participant was questioned regarding handedness before an appointment was established, participants were also asked to simulate the six activities that were related to the questions during the administration of the handedness questionnaire. In order to be classified as right-handed, participants were required to verbally respond “right” to each question, and use only their right hand when simulating the activities. A near binocular acuity assessment was administered in order to ensure that performance of the experimental visual task was not related to visual acuity measurements. A calibrated Landolt C eyechart was used to assess near binocular visual acuity for a distance at 36 cm.

The ordering of the experimental tasks was counterbalanced across groups so that half of the participants received the tactile task first (i.e., the first block of trials), followed by the visual task (first block of trials). After the thresholds for three blocks of trials were collected for both the tactile and visual experimental tasks, each participant was given a rest period during which the questionnaires were administered. The researcher asked the questions and documented the responses. Near binocular visual acuity was assessed immediately following the informed consent for the participants who received the tactile

task before the first visual task. For the participants who received the visual task first, the visual acuity test was administered during the rest period but prior to the questionnaire. Thus, none of the participants received the visual task and visual acuity test consecutively. Appendix D outlines the two different sequences in which the experimental tasks were administered.

Tactile Task

Apparatus

Two mechanical stimulators, similar to those described by Clark and Geffen (1990) and Geffen et al., (1996), were employed (Figure 7). Each stimulator consisted of two enclosed solenoids which were attached to the base of a thin rod. The solenoids and rods were secured in metal housings. When the solenoid was charged, the thin rod was thrust upwards through the central core of the cylinder to where the palmar surface of the finger to-be-stimulated rested. The top surface of each cylinder surrounding each of the four solenoids had a concave surface for resting index and middle fingertips.

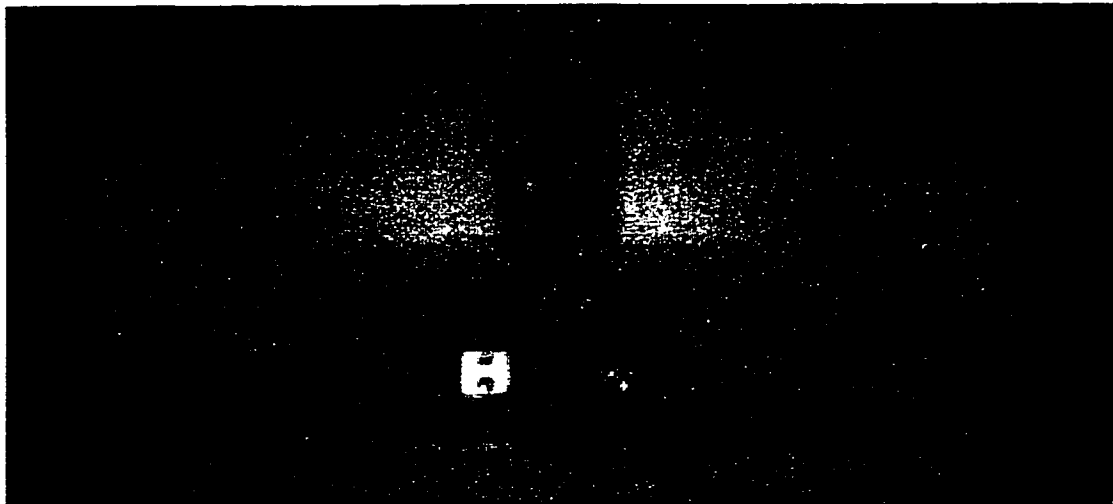


Figure 7: Mechanical tactile stimulators.

The timing of the stimulating rods was matched in regard to rise and fall time (0.05 ms), vertical extension (1 mm skin depression) and plateau duration (9.95 ms). A crystallized controlled oscillator (FOX, 10 megabites) in an external control box provided a very accurate, highly stable 1 ms output signal (see Appendix E for a description of the control box and stimulation systems). A logic analyzer (Hewlett Packard, 1630D) was used to test timing accuracy. The timing accuracy of the crystal control oscillator coupled with the 386 SX computer (Compac) was within 5 microseconds. Therefore, the actual stimulus duration could potentially be between 9.95 to 10.05 ms.

The stimulators were surrounded with foam padding for the participants to rest their elbows and forearms. The foam padding also minimized any vibrations that may have occurred due to stimulus delivery. A Sony stereo cassette recorder (Model TC-126) was used to deliver pink noise binaurally through Sony Digital Reference dynamic stereo headphones (model MDR-CD270). As well, participants wore disposable earplugs in order to minimize sound cues of the firing of the solenoids.

A Compac 386 SX computer, coupled with the timing control was used for stimulus delivery. The computer was programmed (Borland C++, Version 2.0) with a modified version of the Parameter Estimation by Sequential Testing (PEST) algorithm in order to control the delivery of the stimuli (see Appendix F for specifications). The PEST technique allows one to determine the value of thresholds in as few trials as possible (Findlay, 1978; Pentland, 1980). Appendix G provides a detailed description of the modified version of PEST.

Procedure

Participants completed six blocks of trials in one test session. The initial SOA step size was set at 10 ms, while the termination step size was set 1 ms. The simultaneity threshold was the SOA value upon termination for each sequence. Appendix H provides an illustration of a block of trials for the PEST.

The session began with a practice block of trials during which the smallest SOA value (the minimum value at which a “NO” response could confidently be established) was estimated (nonsimultaneity). Fifteen ms were added to this estimated value which served as an initial SOA value for the 5 test blocks of trials. The initial SOA value for the commencement of the test blocks of trials was individualized for each participant. During the practice block, each participant was questioned as to whether they perceived two fingers being stimulated for each trial. All of the participants reported they perceived two fingers being stimulated on every trial.

For the six blocks of trials, stimulus pairs were delivered to the index and middle finger of the right hand (within-right condition), the index and middle fingers of the left hand (within-left condition), and to the index finger of both hands (between-hands condition). Each block of trials consisted of six interwoven sequences of stimulation (left index before right index vs right index before left index for the bimanual condition; index before middle vs middle before index for the unimanual conditions), that were randomized and controlled independently by the PEST program. For each block of trials the order of finger stimulation was counterbalanced. For one half of the trials (within-hands condition) the index finger was stimulated before the middle finger and for the remaining half the middle finger was stimulated before the index finger. For the

between-hands condition, the left index was stimulated before the right index finger for half of the trials, while the right index finger was stimulated before the left index finger in the remaining half.

Participants were instructed to rest their index and middle fingers lightly on the fingertip holders covering the tiny hole (i.e., the concave surface at the top of each cylinder) and to avoid moving the fingers throughout the test session. They were cautioned not to press down (apply pressure) on the fingertip holders. Each participant was asked to focus on a centered fixation point placed 60 cm distant at eye level. The two stimulators were aligned 90 degrees outwards from body midline (see Figure 5, p. 31). The index fingers rested in the first two holders that were closest to the body and the middle fingers of each hand were placed in the farthest two holders. The ordering of the fingers extending from the body outwards for half of the participants was right index finger closest to their body, then left index, then right middle, then left middle. The placement of fingers for the remaining half of the participants was left index finger closest to their body, then right index, then left middle, then right middle. The initial ordering of the placement of fingers was counterbalanced across groups and the 5 test blocks. Participants rested their elbows and forearms on the foam padding surrounding the tactile stimulators.

Participants were instructed that two fingers would be stimulated at any one time. Participants were asked to respond “YES” if they judged the two stimuli to be simultaneous and “NO” if the two stimuli were not simultaneous. Each participant was further instructed that the two stimuli would not be simultaneous at the beginning of each test block of trials and that the interval between the two stimuli would gradually become

smaller. These instructions were provided so that the participants were aware that it is not unusual to respond “NO” for many consecutive trials, especially at the beginning of each block of trials. Verbal responses were recorded by the researcher. The delivery of the stimuli was triggered after each recorded response. Each participant was advised that there were no right or wrong responses and to use their best judgement. Prior to the practice block, the solenoids were activated. Participants wore disposable earplugs and headphones and were asked to increase the volume of the pink noise until they no longer heard the firing of the solenoids. Thus, the intensity of the pink noise was individually set for each participant prior to the practice and test blocks. Participants were asked whether they heard the solenoids firing during the practice block.

Visual Task

Apparatus

The visual stimuli consisted of six red light emitting diodes (LEDs), 5.0 mm in diameter, which were placed on a horizontal plane against a white background (32 X 39 inches). The LEDs were equally spaced at 33 mm (center to center) and symmetrically arranged with respect to the center of the visual display (Figure 8). A black cross in the center of the screen served as the central fixation point. Three LEDs were positioned on each side of the black cross. The method used in this study was similar to that used by Corballis (1996).

The viewing distance was 57 cm so that each cm of the display subtended 1° at the participant's eyes. Therefore, each pair of LEDs was separated by 3.3° of visual angle. For the bilateral 1 presentation (Bil 1), each LED (#3 and #4) was placed 1.65° from fixation. This amount of separation is sufficient so that each LED is projected to the

contralateral hemisphere (Fendrich & Gazzaniga, 1989). For the bilateral 2 presentation (Bil 2), each LED (# 2 and # 5) was placed 4.95° from fixation. Thus, stimuli presented in the left hemifield will be projected to the right hemisphere, while right hemifield presentations will be projected to the left hemisphere. A white side panel (32 X 20 inches) was placed on each side of the white background visual display in order to minimize any visual distractions.

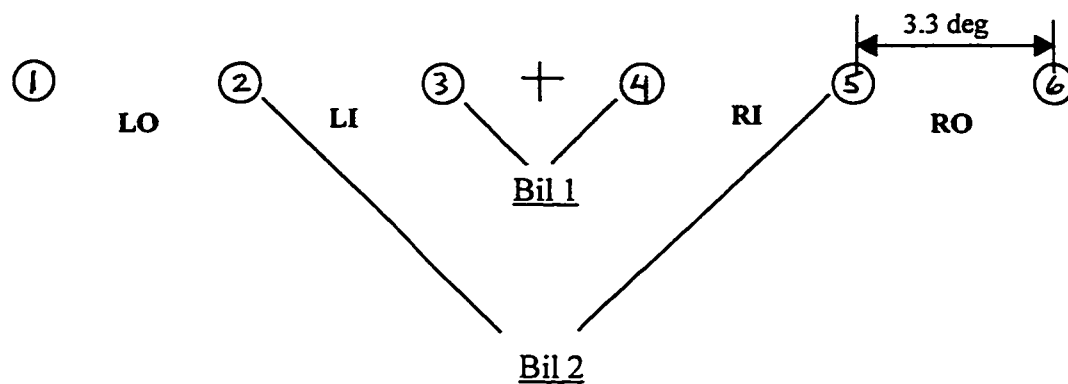


Figure 8: Illustration of the six locations of LEDs and the the six locations of the pairs of spatially separated LEDs. Deg = degree; LO = left outer; LI = left inner; Bil 1 = bilateral first pair; RI = right inner; RO = right outer; Bil 2 = bilateral second pair.

A Minolta luminance meter (Model SLS-110) was used to measure the mean light intensity of the LEDs and luminance intensity of the visual display. The mean red light intensity emitted by the LEDs was 123 candelas cd/m^2 (range 103 to 158 cd/m^2) and was measured prior to data collection. The luminance of the visual display including the top, bottom, right-side, and left-side portions was 46 cd/m^2 . The luminance of all four quadrants of the display were relatively equal (i.e., range 44 to 47 cd/m^2). Luminance was measured approximately halfway through data collection. The mean light intensity

emitted by the LEDs was 122 cd/m^2 (range 105 to 159 cd/m^2). The visual display luminance was 46 cd/m^2 (range 44 to 48 cd/m^2).

The crystallized controlled oscillator in an external control box provided precise timing (highly stable 1 ms output signal). As in the tactile task, the timing accuracy of the crystal control oscillator coupled with the 386 SX computer was within 5 microseconds. The PEST program was used to control the delivery of the stimuli. A Sony SMF video camera (Model HVC 2800) was mounted at the rear of the display facing the participant. The lens of the video camera was aligned with a small hole in the visual display that was just above the central fixation point. A black and white Zenith data systems monitor (11.5 inches) was used to observe the participant's eyes. A chin-rest was used to fix the viewing distance at 57 cm.

Procedure

Participants completed six blocks of trials in one test session. Each session began with a practice block of trials during which the smallest SOA value (the minimum value at which a "NO" response could confidently be established) was estimated (nonsimultaneity). Fifteen ms were added to this value which served as the initial SOA value for the 5 test blocks. Therefore, the initial SOA value for the commencement of the test blocks was individualized for each participant.

In each block of trials there were 6 paired locations for the illumination of the LEDs (i.e., LO, LI, Bil 1, RI, RO, and Bil 2). Thus, for each block of trials there were 12 interwoven sequences of stimulation (left before right vs right before left for each of the six conditions) that were randomized and controlled independently by the PEST program. For each SOA, the left LED was illuminated first for half of the trials, and the

right LED for the remaining half. Onsets differed but the offsets for each LED pair were simultaneous. The pair of LEDs remained illuminated for a duration of 1000 ms once both LEDs were illuminated. The initial SOA step size was set at 10 ms while the termination step size was set 1 ms. The simultaneity threshold was the SOA value which terminated the PEST program.

Participants were instructed to focus on the fixation point (cross) with their chin resting on the chin rest. Participants were advised that a video camera was positioned behind the small hole in the display. The importance of maintaining focus on the central fixation point was stressed to each participant. The viewing distance was 57 cm for each participant. Participants were instructed that two of the six lights would be illuminated on each trial. Participants were asked to respond “YES” if they judged the illumination onsets to be simultaneous and “NO” if they judged the illumination onsets to be different. Each participant was further instructed that each block of trials would begin with onset differences in the illumination of the lights and that these differences would gradually become smaller. Verbal responses were recorded by the researcher. The delivery of each stimulus pair was triggered following each recorded response. Each participant was instructed that there were no right or wrong responses and to use their best judgement. Participants were advised that should they become fatigued during the task they could take a break after giving their verbal response to the previous trial.

Results

The Biomedical Computer Programs-P4v series (BMDP) was employed for all analyses of variance (ANOVAs) and simple effects. An alpha of $p < .05$ was employed for all tests of statistical significance. Figural presentation of the data include standard error bars.

Tactile Task

For each participant, simultaneity thresholds were calculated from the mean of the five test blocks of trials for each of the three conditions. An analysis of the mean simultaneity thresholds of the Bimanual Condition was undertaken. Mean simultaneity thresholds for the Bimanual Condition were subjected to a Group (young, old) X Gender (male, female) X Order (left before right, right before left) mixed ANOVA with Order being a repeated measure (Appendix N, Table 1).

A significant main effect for Group $F(1, 48) = 46.99$, $p < .001$ was found. Simultaneity thresholds of young adults ($M = 31.68$ ms, $SD = 10.74$) were significantly lower (better) than for older adults ($M = 74.95$ ms, $SD = 31.20$). There were no other significant findings.

Hemispheric difference can also be determined by comparing the threshold values of the left-and -right unimanual conditions. Mean simultaneity thresholds of the Unimanual Conditions were subjected to a Group (young, older) X Gender (male, female) X Hand (left, right) X Order (index before middle, middle before index) mixed ANOVA with Hand and Order being repeated measures (Appendix N, Table 2).

A significant main effect for both Group $F(1,48) = 35.87$, $p < .001$ was obtained. Simultaneity thresholds of young adults ($M = 22.48$ ms, $SD = 7.58$) were significantly

lower than those of the older adults ($M = 54.62$ ms, $SD = 27.13$). A significant main effect for Order $F(1,48) = 6.52$, $p < .05$ was also found. A simple effects analysis revealed that simultaneity thresholds were significantly lower when the middle finger ($M = 37.40$ ms, $SD = 25.72$) was stimulated before the index finger ($M = 39.68$ ms, $SD = 25.58$).

A significant Hand X Order interaction was found $F(1,48) = 6.52$, $p < .05$ (Figure 9). Further analysis of the interaction revealed that simultaneity thresholds were lower when the stimulation of the middle finger ($M = 36.85$ ms, $SD = 25.92$) preceded that of the index finger ($M = 40.75$ ms, $SD = 25.92$) for the right hand only. As noted in the Method section, all participants in the study were right-handed (p. 50).

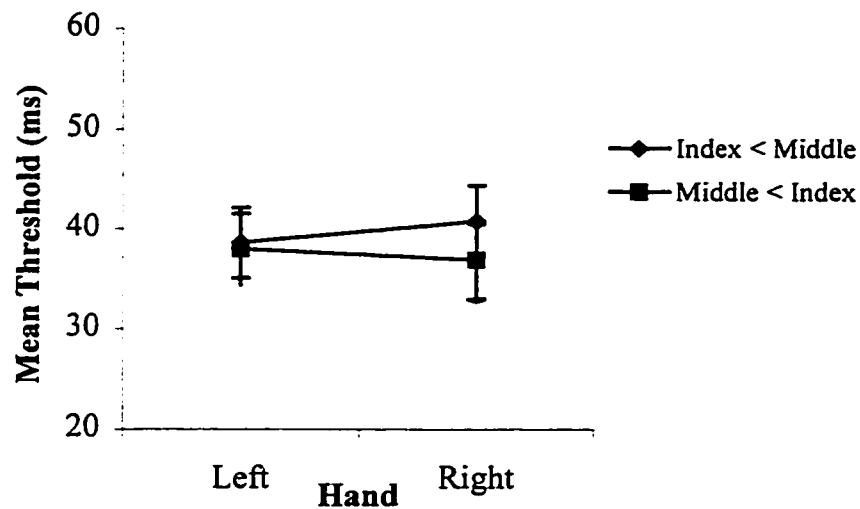


Figure 9: Mean tactile simultaneity thresholds for the left and right hand as a function of Order.

To compare the simultaneity thresholds for the bimanual and unimanual conditions, the mean simultaneity thresholds were subjected to a Group (young, old) X Gender (male, female) X Condition (bimanual, left unimanual, right unimanual) mixed ANOVA with Condition being a repeated measure (Appendix N, Table 3).

A significant main effect for Group $F(1,48) = 42.75, p < .001$ was found. Simultaneity thresholds for the young adults ($M = 25.53$ ms, $SD = 9.61$) were significantly lower than for the older adults ($M = 61.40$ ms, $SD = 29.57$). A significant main effect for Condition $F(2, 96) = 64.38, p < .001$ was also found. A simple effects analysis revealed that the bimanual thresholds ($M = 53.32$ ms, $SD = 31.76$) were significantly higher (poorer) than those of the Left unimanual ($M = 38.28$ ms, $SD = 25.28$) and the Right unimanual ($M = 38.80$ ms, $SD = 25.42$) conditions, which did not differ.

A significant Group X Condition interaction was found, $F(2, 96) = 9.27, p < .001$ (Figure 10). Although, further analysis of the interaction indicated that simultaneity thresholds of the young group were significantly lower than those of the older group for all three conditions, the magnitude of the Group difference was greatest in the bimanual situation.

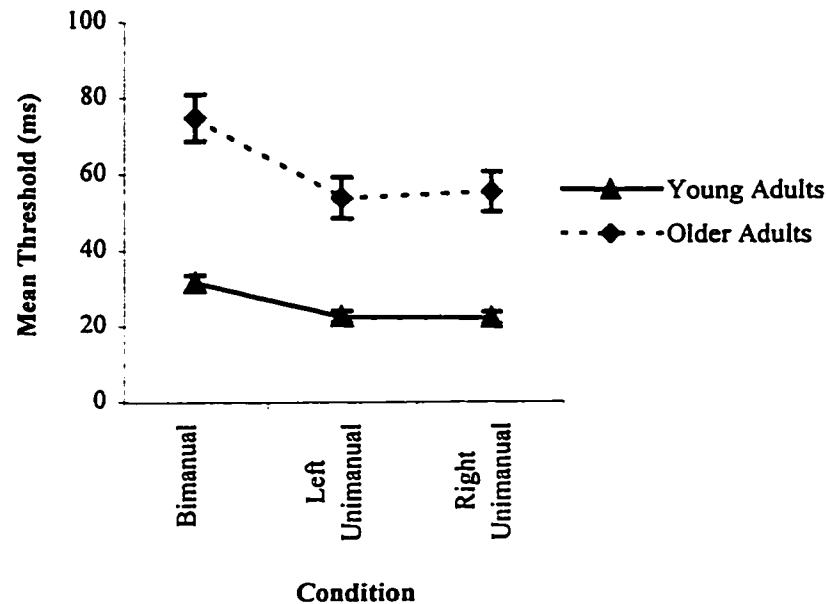


Figure 10: Mean tactile simultaneity thresholds for the Young and Older Group as a function of Condition.

Interhemispheric transfer time refers to the amount of time that is required to transfer information from one hemisphere to another, which is necessary in bilateral situations for judgments of simultaneity. An estimate of interhemispheric transfer time was calculated by taking the difference between the means of the bimanual and the combined means of the unimanual conditions (Geffen et al., 1996). These values were subjected to a Group (young, old) X Gender (male, female) ANOVA (Appendix N, Table 4). A significant main effect for Group was obtained, $F(1, 48) = 11.33, p < .01$. The

mean interhemispheric transfer time for the older group (\underline{M} = 20.33 ms, \underline{SD} = 15.63) was twice that of the young group (\underline{M} = 9.23 ms, \underline{SD} = 6.71).

Given the nature of the PEST technique, the determination of threshold values differs for each subject thus producing a different number of trials for each subject. The number of trials was examined. The mean number of trials across the five test blocks was subjected to a Group (young, old) X Gender (male, female) ANOVA. There was no significant difference for Group (Appendix I). Although a gender difference indicated that males had fewer trials, the difference only approached significance, $\underline{F}(1,48) = 3.02$, $p = .088$.

Visual Task

For each participant, simultaneity thresholds were calculated from the mean of the five test blocks of trials for each of the six paired LED locations (LO, LI, Bil 1, RI, RO, and Bil 2) (Figure 7, p.57). The mean simultaneity thresholds were subjected to a Group (young, old) X Gender (male, female) X Condition (LO, LI, Bil 1, RI, RO, Bil 2) X Order (left before right, right before left) mixed ANOVA with Condition and Order being repeated measures (Appendix O, Table 5).

A significant main effect for Group $\underline{F}(1, 48) = 84.92$, $p < .001$ was found. Simultaneity thresholds were significantly lower for young adults (\underline{M} = 28.33 ms, \underline{SD} = 8.35) than for older adults (\underline{M} = 65.84 ms, \underline{SD} = 21.22). A significant main effect for Gender $\underline{F}(1,48) = 6.70$, $p < .05$ was obtained. Post-hoc analysis of the significant Gender effect revealed that the thresholds of males (\underline{M} = 41.82 ms, \underline{SD} = 20.42) were significantly lower than those of females (\underline{M} = 52.35 ms, \underline{SD} = 27.87).

A significant main effect for Condition $F(5, 240) = 28.77, p < .001$ was also obtained. For the Condition main effect, comparisons of threshold values for paired locations were conducted (i.e., LO vs LI; RO vs RI; LO vs RO; LI vs RI; Bil 1 vs Bil 2). Mean threshold values for each condition are displayed in Table 6. Thresholds for the LO condition were significantly higher than those for the LI condition. Similarly, thresholds of the RO condition were significantly higher than the thresholds of the RI condition. Simultaneity thresholds were highest for the outer LED paired locations when compared to the inner paired LED locations. No significant differences were found when the thresholds of the LO and RO conditions were compared, nor with comparisons of thresholds associated with the LI and RI conditions.

The threshold values of the Bil 1 condition were significantly lower (better) than the Bil 2 condition. Again, threshold values increased significantly from central locations to peripheral locations. There was no evidence of hemispheric asymmetry in simultaneity thresholds for any of the paired comparisons.

Table 6

Mean Simultaneity Threshold and Standard Deviation for Each of the Six Conditions.

Condition	Mean	SD
Bil 1	46.83	24.78
Bil 2	54.66	28.86
LO	48.55	24.68
LI	42.95	24.61
RI	41.87	23.96
RO	47.65	25.20

A significant Group X Gender interaction (Figure 11) was obtained, $F(1, 48) = 5.66$, $p < .05$. Further analysis of the interaction indicated that threshold values for both young males and young females were significantly lower than those of older females and older males. It was also found that the threshold values of older males were significantly lower than the thresholds of older females.

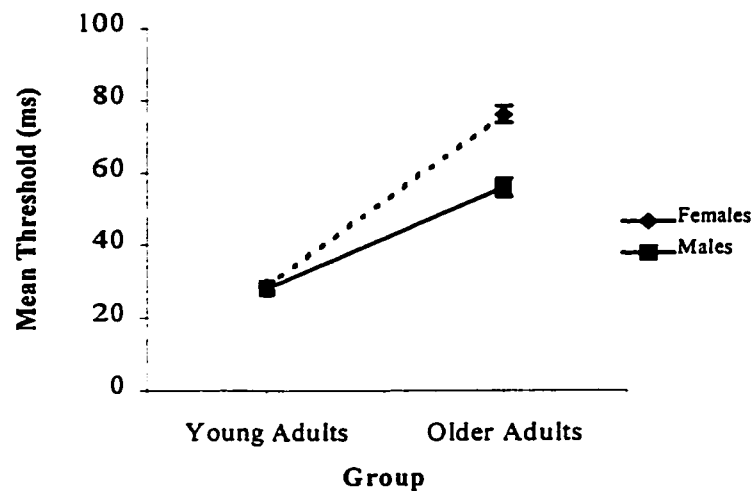


Figure 11: Mean simultaneity thresholds for the young and older Group as a function of Gender.

A significant Group X Condition X Order was also obtained, $F(5, 240) = 3.12$, $p < .01$ (Figure 12). Further analysis of the interaction revealed a stimulus order effect for the young adults under the LI and RI conditions only. Threshold values were lower (better) when the onset of the left LED preceded the right LED for the LI location, while the reverse held for the RI location. That is, threshold values for the RI location were lower when the right LED preceded the left LED. This finding suggests that judgements of simultaneity are lower for the inner locations when the implied motion is directed

towards central fixation. A left hemisphere advantage would have been supported by lower thresholds when the illumination of the right LED preceded the left LED (i.e., leftward motion), relative to left preceding right (i.e., rightward motion) in the bilateral conditions (Efron, 1963a). There was no evidence of hemispheric asymmetry in any of the statistical analyses.

The mean visual threshold for the young and older groups for each condition as a function of order can be found in Appendix J.

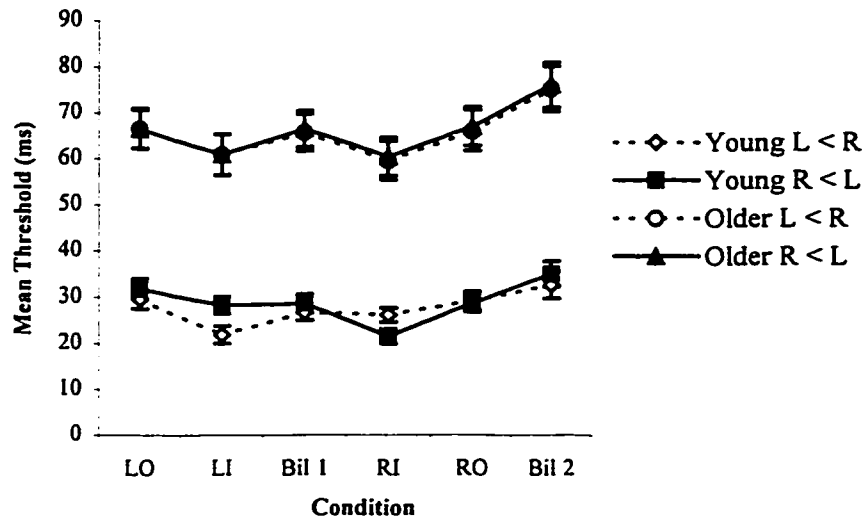


Figure 12: Mean visual simultaneity thresholds for the young and older Group as a function of Condition and Order.

Since older females had significantly higher thresholds than the older males and young adults, a separate ANOVA for the older group was undertaken to determine whether age may have had an influence on gender differences. The simultaneity thresholds of a young-old group consisting of 8 females (61 to 67 years) and 7 males (61 to 69 years), and an old-old group consisting of 5 females (70 to 80 years) and 6 males

(70 to 79 years) were subjected to a Group (young-old, old-old) X Gender (male, female) X Condition (LO, LI, Bil 1, RI, RO, Bil 2,), mixed ANOVA with Condition being a repeated measure.

A significant main effect for Gender was found $F(1, 22) = 7.68, p < .05$. Post-hoc analysis revealed that the females ($M = 75.94$ ms, $SD = 19.47$) had significantly higher thresholds than the males ($M = 55.73$ ms, $SD = 20.46$) for the six conditions. No significant group effects were found suggesting that the significant gender difference among the elderly was not influenced by chronological age.

In an attempt to determine whether visual acuity measures may have influenced the gender effects in the older group, a correlational analysis of acuity scores was undertaken. The results indicated no relationship between simultaneity threshold values and visual acuity measurements of older males and females ($Z = .2246, p > .05$). In addition, the visual acuity of a young female, who had an average visual acuity score and average thresholds for that particular group, was matched to that of an older female and retested in a further attempt to determine whether visual acuity had an influence on simultaneity judgements. The simultaneity thresholds increased, but not significantly. Appendix K describes the correlation analysis and the matched vision procedure.

In order to determine whether the bilateral simultaneity thresholds were significantly higher than unilateral conditions, two separate ANOVAs were conducted. The mean simultaneity thresholds of the Bil1, LI, and RI were analyzed in the first analysis and the mean simultaneity thresholds of the Bil2, LO, and RO were analyzed in the second analysis. For the first analysis, mean simultaneity thresholds were subjected

to a Group (young, old) X Gender (male, female) X Condition (Bill, LI, RI) mixed ANOVA with Condition being a repeated measure (Appendix O, Table 7).

A significant main effect for Group $F(1, 48) = 86.82$, $p < .001$ was found. Simultaneity thresholds were significantly lower for young adults ($M = 25.53$ ms, $SD = 8.23$) than older adults ($M = 62.24$ ms, $SD = 21.14$). A significant main effect for Gender $F(1, 48) = 6.38$, $p < .05$ was also found. A simple analysis revealed that the thresholds of males ($M = 38.91$ ms, $SD = 19.55$) were significantly lower than those of females ($M = 48.86$ ms, $SD = 27.65$). A significant effect for Condition $F(2, 96) = 17.28$, $p < .001$ was obtained. The analysis of the Condition main effect revealed that the Bill thresholds ($M = 46.83$ ms, $SD = 24.78$) were significantly higher than the LI thresholds ($M = 42.95$ ms, $SD = 24.61$) and the RI thresholds ($M = 41.87$ ms, $SD = 23.96$), which did not differ.

A significant Group X Gender interaction (Figure 13) was obtained $F(1, 48) = 6.34$, $p < .05$. Further analysis of the interaction revealed that threshold values for both young males and young females were significantly lower than those of older males and older females. In addition, thresholds for the older females were significantly higher than those of the older males.

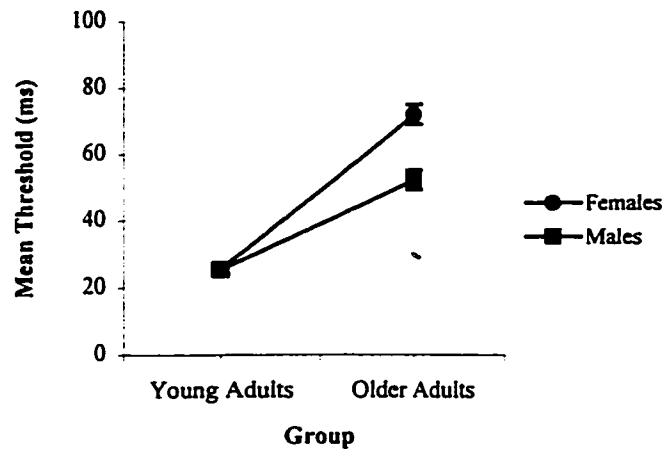


Figure 13: Mean simultaneity thresholds for the young and older Group as a function of gender.

For the second analysis, mean simultaneity thresholds were subjected to a Group (young, old) X Gender (male, female) X Condition (Bil 2, LO, RO) mixed ANOVA with Condition being a repeated measure (Appendix O, Table 8).

A significant main effect for Group $F(1, 48) = 78.68, p < .001$ was found. Simultaneity thresholds were significantly lower for young adults ($M = 31.14$ ms, $SD = 10.99$) than older adults ($M = 69.44$ ms, $SD = 23.05$). A significant main effect for Gender $F(1, 48) = 6.63, p < .05$ was obtained. A simple analysis revealed that the thresholds of males ($M = 44.73$ ms, $SD = 22.49$) were significantly lower than females ($M = 55.85$ ms, $SD = 28.76$).

A significant main effect for Condition $F(2, 96) = 17.28, p < .001$ was also obtained. The simple analysis revealed that the Bil 2 thresholds ($M = 54.66$ ms, $SD = 28.86$) were significantly higher than the LO thresholds ($M = 48.55$ ms, $SD = 24.68$) and the RO thresholds ($M = 47.65$ ms, $SD = 25.20$), which did not differ.

A significant Group X Gender interaction (Figure 14) was obtained $F(1, 48) = 4.78, p < .05$. Further analysis of the interaction revealed that threshold values for both young males and young females were significantly lower than those of older males and females. Thresholds for the older females were significantly higher than those of the older males.

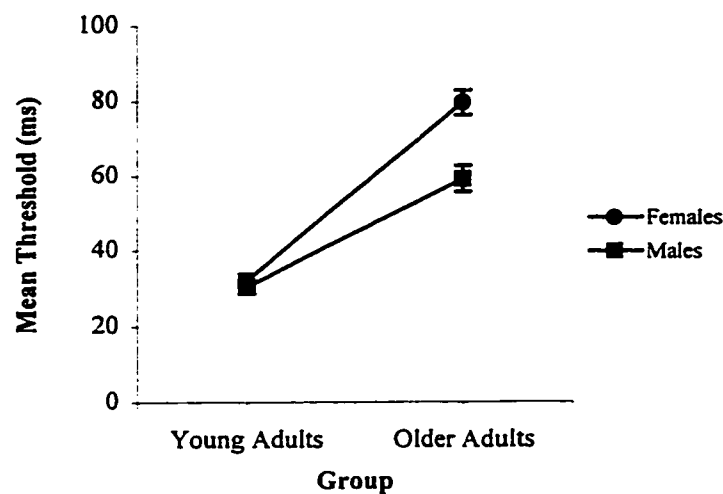


Figure 14: Mean simultaneity thresholds for the young and older Group as a function of gender.

An estimate of the interhemispheric transfer time for temporal visual processing was calculated by taking the difference of the means between the bilateral 1 situation and the combined means of the LI and RI unilateral conditions. Rather than including all of the visual conditions in the interhemispheric transfer time estimate, these two conditions were chosen in an attempt to match the interhemispheric transfer time analysis of the tactile task (i.e., two unilateral situations and one bilateral situation). These estimates

were subjected to a Group (young, old) X Gender (male, female) ANOVA (Appendix O, Table 9). A significant main effect for Gender was obtained $F(1,48) = 4.87, p < .05$. Males ($M = 6.24$ ms, $SD = 5.44$) had significantly longer interhemispheric transfer time estimates relative to females ($M = 2.60$ ms, $SD = 6.50$).

Given the nature of the PEST technique, the determination of threshold values differs for each subject thus producing a different number of trials for each subject. In order to examine whether the higher thresholds of the older group were associated with a greater number of trials the mean number of trials across the five test blocks was subjected to a Group (young, old) X Gender (male, female) ANOVA. A significant effect for Group was found $F(1,48) = 4.66, p < .05$. Interestingly, the mean number of trials for the older group ($M = 91.03$, $SD = 16.43$) was significantly lower than the mean number of trials of the younger group ($M = 95.01$, $SD = 14.71$). A significant effect for Gender also emerged $F(1,48) = 9.80, p < .01$. Males ($M = 89.24$, $SD = 13.30$) had a significantly lower mean number of trials relative to the females ($M = 100.78$, $SD = 13.98$). The results show that the young females required significantly more trials to establish a simultaneity threshold (Appendix L).

Correlations were conducted in order to determine whether age, educational level, medication use, visual acuity, and whether tactile simultaneity thresholds were related to visual simultaneity thresholds. Four correlation matrices, one for each of the four groups (young females, young males, older females, older males), that included age, educational level, medication use, visual acuity measures, tactile simultaneity thresholds, and visual simultaneity thresholds were examined (Appendix M). For each of the four groups, a significant correlation between tactile and visual simultaneity thresholds was found. The

absence of significant correlations between the remaining variables and simultaneity thresholds indicates that simultaneity judgements were not related to visual acuity, medication use, and educational level.

Discussion

Hemispheric Temporal Processing

With respect to cerebral lateralization, the present findings for the tactile task support the hemispheric equivalence model proposed by Geffen et al., (1996). The bimanual tactile simultaneity thresholds were similar regardless of stimulation order; the thresholds of the unimanual conditions did not significantly differ one from the other; and higher (poorer) thresholds were demonstrated in the bimanual condition relative to the unimanual conditions. These results support the view of Geffen and her colleagues (1996) in that judgements of simultaneity to bilateral presentations are most probably made in the hemisphere that is contralateral to the second stimulus. If the judgement were made in the hemisphere contralateral to the first stimulus, the interhemispheric transfer time of the second stimulus would be perceptually added to the time between the delivery of the two stimulus events. Given this added time, the participant would most likely report the two events as not simultaneous. The PEST program would then decrease (step down) the interval between the two stimulus events for the subsequent trials, which would result in lower (better) threshold levels for the bimanual relative to the unimanual conditions (Geffen, et al., 1996; Mason & Geffen, 1996).

With respect to the visual task, the findings again support the hemispheric equivalence model as proposed by Geffen et al., (1996). This is especially evident in that there were no significant threshold differences in the stimulus order in the two bilateral conditions (i.e., Bil 1, Bil 2). Comparisons of simultaneity thresholds for paired locations (i.e., LO vs LI; RO vs RI; LO vs RO; LI vs RI; Bil 1 vs Bil 2) did not reveal a hemispheric advantage. The bilateral simultaneity thresholds were significantly poorer

than the unilateral simultaneity thresholds, which support the findings of Corballis et al (1998).

The present results are not consistent with the earlier findings reported by Corballis (1996) and Nicholls (1994). Corballis (1996) reported a left hemisphere advantage when stimuli were presented bilaterally, while Nicholls (1994) reported a right visual field (left hemisphere) advantage for judgements of simultaneity when stimuli were presented unilaterally. However, more recently, Corballis et al., (1998) reported a left hemisphere advantage for temporal judgements in males when stimuli were presented in the right visual field only. Their bilateral presentations failed to reveal a left or right hemisphere advantage. The present data are not inconsistent with those of Corballis et al. (1998) in that a left hemisphere advantage was not exhibited in bilateral presentations.

Right Hemi-Aging Hypothesis

The present findings not only indicate that both cerebral hemispheres are equally capable of processing tactile temporal information, but that the hemispheric equivalence for making judgements of simultaneity remains stable through adulthood. Evidence supporting hemispheric equivalence with advanced age was revealed by similar threshold values between the two unilateral conditions as well as by the similar threshold values for the order of stimulation in the bilateral presentations. In addition, the findings for the visual task provide evidence for the uniform aging of the cerebral hemispheres (Borod & Goodglass, 1980; Hoyer & Rybash, 1992) in that there is not an age-related differential hemispheric decline in judgements of simultaneity.

The findings of hemispheric equivalence for both age groups lend support to other findings (Borod & Goodglass, 1980; Hoyer & Rybash, 1992). The present findings

suggest that the right hemi-aging hypothesis may be artifact of methodology. That is, when the testing material employed for lateralization studies is not equated for complexity and familiarity, lateralization effects may emerge. Lifelong experience with verbal material (usually processed by the left hemisphere) may explain why left hemisphere advantages are sometimes observed among the elderly.

Age-Related Increase in Simultaneity Thresholds

The present findings indicate that thresholds for judgements of simultaneity to tactile stimuli increase significantly with advanced age. The age-related difference was apparent for both unilateral and bilateral conditions of the tactile task. The significant age differences in simultaneity thresholds may be attributed to an overall general slowing (less efficient) of the nervous system that occurs as a result of neuronal loss, neuronal shrinkage, a reduction in the number of synapses, and the loss of myelin, to name some of the contributors (Desmedt & Cheron, 1980; Selkoe, 1992). An overall slowing in neural transmission time is especially apparent when one examines the age differences in interhemispheric transfer. Interhemispheric transfer estimates are obtained by subtracting the unilateral simultaneity thresholds from the bilateral simultaneity thresholds (Clark & Geffen, 1990; Mason & Clark, 1996). Clark & Geffen, (1996) reported mean interhemispheric transfer estimates of 5 ms and 11 ms for young adults in two separate studies. In the present study, the mean interhemispheric transfer estimate for older adults was more than double that of the younger adults ($\bar{M} = 20.33$ ms vs. $\bar{M} = 9.23$ ms respectively). Thus, mean interhemispheric estimate for the young adults of the present study appears to be within the range reported by Clark and Geffen (1996).

If the age-related increase in simultaneity thresholds is attributed to changes in the properties of the skin, as opposed to an overall neural slowing, then one would expect the older women to have better thresholds than men since older females have greater skin sensitivity than older males (Gescheider, Bolanowski, Hall, Hoffman, & Verrillo, 1994; Woodward, 1993). Although the gender differences in tactile thresholds were not significant in the present study, the thresholds of older females were consistently poorer than those of the older males in each tactile condition. It is therefore doubtful that the age increase in simultaneity thresholds is attributed solely to age-related changes in the mechanical properties of the skin.

The overall mean tactile simultaneity threshold of 26 ms for the young adults in the present study can be compared to those (32 – 33 ms) reported by Clark and Geffen (1990) and Geffen et al. (1996). The mean estimate of interhemispheric transfer for young adults in this study (9 ms) is also congruent with that reported by Geffen and her colleagues (11 ms). Due to the absence of data indicating the tactile threshold values for simultaneity judgements among the elderly it is not possible to compare the present results (elderly participants) with other studies.

The findings of the visual task further support the view that there is an age-related decline in the ability to make visual temporal judgements (Schieber & Kline, 1982). The results further indicate that the age-related increase in simultaneity thresholds may be attributed to changes in the nervous system relative to the age-related changes that typically occur in the properties of the eye itself (Elliott, Whitaker, & MacVeigh, 1990; Kline, Ikeda, & Schieber, 1982). That is, age-related deficits are not significantly reduced when young and older adults are equated with respect to visual ability.

When the significant gender difference in the visual simultaneity thresholds was examined, it was found that simultaneity thresholds of older females were significantly poorer than the thresholds of all other participants, in the study.

Visual simultaneity thresholds for both young and older adults appear to be consistent with values reported by other researchers. In the present study, an overall visual mean simultaneity threshold of 28 ms was observed for the young adults and 66 ms for older adults. Corballis et al., (1998) report that young adults begin to discriminate non-simultaneity consistently when the stimuli were separated by SOAs of 33 ms or greater. In addition, Schieber and Kline (1982) reported above-chance performance (i.e., ceiling effects) at 45 ms for young adults and 90 ms for older adults in the discrimination of non-simultaneity.

The interhemispheric transfer estimate of 3.21 ms for the younger adults appears to be comparable to the estimate of 3 to 6 ms, which was reported by Efron (1963c). Unfortunately, the consistency of the interhemispheric transfer estimates for the older adults (value) cannot be evaluated since other studies have failed to report such data.

The interhemispheric transfer time estimates for the young adults in the tactile task (i.e., 9.23 ms) is nearly three times that of the visual task (i.e., 3.21). If the interhemispheric transfer time estimate represents the time to transfer information to the contralateral hemisphere, then one would expect the interhemispheric transfer time estimates of the two modalities to be somewhat similar.

The present results indicate that the age-related decline observed in temporal memory tasks is not necessarily attributed to problems associated with memory processing, but rather with the temporal aspects of the tasks. The task demands of the

present study were minimal. Making judgements of simultaneity in response to tactile and visual stimuli does not place demands on memory, nor does it place demands on mental processing resources. By minimizing task complexity, task demands and memory demands, the current findings suggest that some cognitive age-related deficits may be attributable to an age-related decline associated with temporal demands of the task.

Conclusions

The present findings support the hemispheric equivalence model proposed by Geffen et al., 1996 in that (i) both hemispheres revealed roughly equal simultaneity thresholds for tactile and visual stimuli, and (ii) simultaneity thresholds for both the tactile and visual task were significantly poorer in the bilateral condition relative to the unilateral conditions suggesting a cost related to interhemispheric transfer.

The present findings failed to support the right hemi-aging hypothesis proposed by Taylor, McDowd, & Hellige, (1991) in that (i) tactile and visual simultaneity thresholds for both hemispheres were similar for the older adults, and (ii) the older adults also had significantly poorer thresholds in the bilateral condition relative to the unilateral conditions, suggesting that the judgement of simultaneity for older adults is also made in the hemisphere contralateral to the second stimulus. These findings indicate that the hemispheric equivalence for processing tactile and visual temporal stimuli remains stable across adulthood.

The present findings suggest that there is a significant age-related decrease in the ability to make simultaneity judgements in the tactile and visual modalities. The results also revealed significantly poorer visual simultaneity thresholds for the older females, suggesting that females may be more susceptible than males to the age-related decline in

the ability to time visual information. The observed age differences in simultaneity thresholds may be attributed to the age-related changes that occur in the nervous system which would result in slower neural processing (Woodward, 1993). If skin mechanoreceptors were contributing significantly to the age-related increase in tactile simultaneity thresholds, then older females should have exhibited lower (better) thresholds than older males given their greater sensitivity to tactile stimulation.

With respect to hemispheric asymmetries being more prevalent among males relative to females (Corballis et al., 1998; Levy, 1974; McGlone, 1980; Shaywitz, Shaywitz, Pugl, Constable, Skudlarski, Fulbright, Bronen, Fletcher, Shankweiler, Katz, & Gore, 1995), the present findings fail to support the current view that males tend to be more lateralized than females. However, visual interhemispheric transfer time estimates indicate that females are significantly more efficient than males in transferring visual information interhemispherically.

Reliable simultaneity thresholds may serve as a useful diagnostic index for changes that occur in the tactile and visual modalities that occur as a result of disease, injury, and aging (Stevens & Cruz, 1996). As well, a lateralized approach would provide information with respect to hemispheric function and may prove useful for detecting hemispheric anomalies.

It appears that both hemispheres are equally capable of processing tactile and visual temporal information and that hemispheric equivalence for judgements of simultaneity remains stable through adulthood. This study is unique to the aging literature in that (i) temporal processing was examined from a lateralized perspective, (ii) the same testing stimuli were used for both hemispheres so that task-related demands

were equated (low complexity), and (iii) age-related differences in simultaneity judgements to tactile stimuli were examined.

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CONSENT FOR RESEARCH PARTICIPATION

I, the undersigned, hereby give my consent to participate in a research project entitled "Asymmetrical Hemispheric Decline and the Analysis of Temporal Processing in the Aged."

I understand that such consent means that I will take part in a study that involves 1) taking a visual test, 2) respond to general background questions, 3) report whether or not I perceive two harmless vibrations to my fingertips as simultaneous, 4) report whether or not I perceive the onset of two lights as simultaneous, and 5) simulate six simple activities.

I understand that since I volunteered my time for this study, my name will be entered into a draw (gift certificate: Dinner for Two). I understand that my performance as a participant is in no way related to the draw.

I understand that participation in this study may be terminated at any time by my request or at the request of the investigator. Participation in this project and/or withdrawal from this project will not adversely affect me in any way.

I understand that the study requires a certain level of visual acuity. I also understand that the study requires that I be right-handed and that I do not suffer from any neurological and/or psychiatric illnesses, severe arthritis, or alcohol abuse.

I understand that this study will not involve any risks other than those ordinarily occurring in daily life.

I understand that the responses will be kept in the strictest of confidence.

I understand that only group data will be used in any published papers or reports of the research.

I have received a copy of this consent form. I understand that if I have any questions I can contact the researcher at 220-7370, her supervisor at 220-5561, the Chairperson, Faculty of Education Joint Ethics Committee at 220-5626, or the Office of the Vice-President (Research) at 220-3381.

Date

(Signature)

Participant's Printed Name

Participant Interview

Date _____ Participant # _____
 Gender: Male _____ Female _____ Age _____ Time of Testing: _____

What is the first language you learned as a child? _____

How frequently do you drink alcohol

- daily, weekly, monthly, yearly, never?

Approximately how many drinks is your intake per .week?...

1 - 5, 5-10, 10-15, 15-20, 20-25 25+

Do you have any severe visual impairment (e.g. cataracts, glaucoma)? Y N

Do you have full use of both hands? Y N

Are your daily activities in any way impaired because of your health? Y N

What is your physical activity level? light moderate heavy

Have you ever had a stroke? Y N If yes, how long ago?

Do you have arthritis? Y N If yes, where? _____

Have you ever been diagnosed with a neurological illness? Y N

If so, what type of illness?

Have you ever been diagnosed with a psychiatric illness? Y N

If so, what type of illness?

Are you taking medications on a regular basis? Y N

If yes what are they?

How would you rate your overall health?

Poor: _____ Fair _____ Average _____ Good _____ Excellent

Do you participate in sports? Y N If so what sports. _____

Do you exercise regularly? Y N If so how frequently per week?

What is the highest level of education that you have completed _____

Are you working at this time? Y N What is/was your occupation?

Number of years at this occupation? _____

Are you retired? Y N If yes, when did you retire _____

As a child, were you ever forced/encouraged to use your nondominant hand?

Y N

APPENDIX C

Handedness Assessment Questionnaire

Which hand do you use:

- 1) To hold a racket in tennis, squash, or badminton? _____
- 2) To write a letter legibly? _____
- 3) To throw a ball to hit a target? _____
- 4) To hold a match while striking it? _____
- 5) To hammer a nail into wood? _____
- 6) To hold a toothbrush while cleaning your teeth? _____

APPENDIX D

Ordering of Experimental Tasks

Ordering one:

Visual Acuity Test.

Practice block of trials for the tactile task.

First block of trials for the tactile task.

Practice block of trials for the visual task.

First block of trials for the visual task

Second block of trials for the tactile task

Second block of trials for the visual task

Third block of trials for the tactile task

Third block of trials for the visual task

Rest, background questionnaire administered.

Fourth block of trials for the tactile task

Fourth block of trials for the visual task

Fifth block of trials for the tactile task

Fifth block of trials for the visual task

Ordering two:

Practice block of trials for the visual task.

First block of trials for the visual task.

Practice block of trials for the tactile task.

First block of trials for the tactile task

Second block of trials for the visual task

Second block of trials for the tactile task

Third block of trials for the visual task

Third block of trials for the tactile task

Visual Acuity Test.

Rest & background questionnaire administered.

Fourth block of trials for the visual task

Fourth block of trials for the tactile task

Fifth block of trials for the visual task

Fifth block of trials for the tactile task

APPENDIX E

Description of the Control Box and Stimulation Systems

There are two circuits included in this unit – one to control the LED's for visual stimulation, the other for operating the solenoids for tactile stimulation. These two circuits are independent, and are separately addressed by the program. Other circuits included are the timer for providing an accurate 1 ms pulse and the switch detection circuit to decode the response entered by the user.

The unit is addressed through the parallel port of the computer. The default port is LPT2 (second printer port). The selection of tactile or visual stimulation is provided by control lines on the parallel port which are switched under program control. Data are in written form using the 8 data lines. The 8 data lines on the parallel port provide the selection of which LED's or solenoids are turned on and/or off.

The selection is made by enabling one of two 74LS245 buffer chips using the control lines 0 (for solenoids) and 1 (for LED's). These correspond to the printer control bits/strobe and /autofeed.

For the LED driver the output of the buffer is used to control 6 2N2222 transistors which are connected in series with the LED's. These transistors provide sufficient current sinking to fully drive the LED's. Brightness is adjusted by varying the supply voltage to the LED's between 0 and 5 volts.

The solenoid drivers are more complex. The output of the buffer is level shifted to 15 volts, then drives an emitter follower pair consisting of a 2N2222 and a 2N2907 set of transistors. These drive the gate of an IRF520 power MOSFET. The high level of drive (15 volts) is required because of the high current draw of the solenoids (7 amps at 25 volts). The high supply voltage and current are necessary to ensure fast and consistent switching of the solenoids (rise time is approximately 5 ms).

The response (yes/no) is read using the status lines 4 and 5. The status line 6 (/Acknowledge) carries the 1 ms timing signal to the computer for timing measurements. This timer was added after attempts to provide accurate delay measurements using software algorithms proved inconsistent and unreliable. Delay timing is achieved by first waiting for a rising edge on the timing signal, then counting the required number of pulses to provide an accurate time period. The control programs are internally documented. These are written and compiled using Borland C++ version 2.0.

APPENDIX F

Modified Version of Parameter Estimation by Sequential Testing Algorithm

A description of the program.

A response “yes” is given if the two stimuli are perceived as occurring simultaneously.

A response “no” is given if the two stimuli are perceived as occurring at different times.

The program initially uses the values supplied by the user. The two stimulus events are then delivered but separated by the specified stimulus onset asynchrony (SOA) interval. A response of “no” causes the program to reduce the SOA by the specified (i.e., 10 ms) “update” time. The SOA will continue to be decreased by this specified “update” time (i.e., 10 ms) providing the responses continue to be “no.” Potentially, this process can cause the SOA to be reduced to zero. The program will not permit the SOA to be a value less than zero.

When a “yes” response is received, the program then takes the following steps:

The value of the “update” time is halved (e.g., 5 ms) and then added to the SOA value at which the “yes” response was given in order to increase the time separation of the two events.

If the next response is “no” then this “update” time (i.e., 5 ms) value is subtracted from the SOA value in order to decrease the time separating the two events.

If the following response is “yes” then the “update” time is halved and added to the SOA value at which the “yes” response was given.

The value of the “update” cannot be decreased below the value of one. This means that the value of the SOA will oscillate around the final position in steps of one.

Expressed somewhat more mathematically:

If No:

SOA value = SOA value – “update” value

If SOA < 0 then SOA value = 0

If Yes:

“update” value = “update” value / 2

if “update” value < 1 then “update” value = 1

SOA value = SOA value + “update” value

Where:

SOA value = the time interval between the onset of the first stimulus and the onset of the second stimulus.

Update value = the step change

APPENDIX G

PEST Procedures

Unlike the psychophysical techniques where the testing values are established in advance, the testing values of the PEST technique are determined by a set of rules which operate by using a binary forced-choice (YES/NO) paradigm. That is, the interval between the onset of the first stimulus to the onset of the second stimulus (Stimulus Onset Asynchrony, SOA) was adjusted (increased or decreased) according to the participant's previous response. For example, the participant would respond "NO" if the occurrence of two stimuli were perceived as not simultaneous. The step size of the SOA would continue to be reduced by a constant value (i.e., 10 ms) until a "YES" response is reached for the two stimuli in question. A "YES" response to the perception that the two stimuli occurred simultaneously would reverse the step direction such that the SOA step size would increase the next time the same two stimuli were in question. However, the previous value of the SOA (e.g., 10 ms) would be halved (e.g., 5 ms) the next time the same two stimuli were in question. The SOA step size changed by a constant value in association to "NO" responses, and the SOA step size would increase by half of the previous SOA value in association to "YES" responses. Thus, a value change in SOA step sizes only occurred with step reversals associated with "YES" responses. The program terminated when the SOA step size reached 1 ms.

APPENDIX H

Example of a Block of Trials for the Visual Task:

Subject age: 35
 Subject gender: female
 Subject handedness: right
 L = left before right
 R = right before left

Starting SOA value: 75
 Start decreases at: 10 ms
 Duration of LEDs: 1000
 Terminate at: 1 ms difference

Trial	LO		LI		Bil 1		RI		RO		Bil 2		Response
	L	R	L	R	L	R	L	R	L	R	L	R	
1		65											no
2		55											no
3						65							no
4		45											no
5						55							no
6							65						no
7									65				no
8										65			no
9			65										no
10								65					no
11	65												no
12			55										no
13									55				no
14			45										no
15		35											no
16							55						no
17							45						no
18										55			no
19											65		no
20	55												no
21										45			no
22							35						yes
23						45							no
24				65									no
25									45				no
26											55		no
27							40						no
28		25									45		no
29			35										no
30										35			no

119		22											yes
120											18		yes
121		23											yes
122				26									yes
123						15							yes
124						17							yes
125						18							yes
126	33	23	13	26	18	18	26	18	27	28	18	28	threshold

Numbers indicate SOA value for that particular trial.

Although presented in block form, all 12 sequences (6 conditions) were randomly interwoven within each block.

The SOA step size changed by a constant value in association to “NO” responses, and the SOA step size would increase by half of the previous SOA value in association to “YES” responses.

Thus, a step change in step size only occurred with step reversals associated with “YES” responses.

The program terminated when the SOA step size reached 1 ms.

APPENDIX I

Means and Standard Deviations for Starting SOA Values, Number of Trials, and Overall Tactile Simultaneity Thresholds as a Function of Group and Gender.

Group	Starting SOA Values	Number of Trials	Overall Mean Thresholds
Young			
Females	$\underline{M} = 63.46$ (9.66)	$\underline{M} = 54.32$ (6.47)	$\underline{M} = 25.76$ (8.33)
Males	$\underline{M} = 60.77$ (7.32)	$\underline{M} = 51.55$ (5.88)	$\underline{M} = 25.30$ (7.72)
Older			
Females	$\underline{M} = 108.07$ (21.65)	$\underline{M} = 57.60$ (10.19)	$\underline{M} = 68.07$ (27.02)
Males	$\underline{M} = 85.38$ (19.41)	$\underline{M} = 52.06$ (10.79)	$\underline{M} = 61.40$ (27.12)

APPENDIX J

Mean Simultaneity Thresholds for the Young Group as a Function of Condition and Stimulus Order.

Condition	Left before Right	Right before Left
LO	$\underline{M} = 29.55$ (10.50)	$\underline{M} = 31.81$ (11.15)
LI	$\underline{M} = 21.88$ (9.44)	$\underline{M} = 28.28$ (9.36)
Bil 1	$\underline{M} = 26.72$ (8.57)	$\underline{M} = 28.62$ (10.20)
RI	$\underline{M} = 26.14$ (7.75)	$\underline{M} = 21.53$ (8.07)
RO	$\underline{M} = 29.18$ (9.90)	$\underline{M} = 28.69$ (9.76)
Bil 2	$\underline{M} = 32.62$ (14.77)	$\underline{M} = 34.97$ (13.85)

Mean Simultaneity Thresholds for the Older Group as a Function of Condition and Stimulus Order.

Condition	Left before Right	Right before Left
LO	$\underline{M} = 66.46$ (22.70)	$\underline{M} = 66.38$ (21.55)
LI	$\underline{M} = 60.81$ (22.77)	$\underline{M} = 60.82$ (22.76)
Bil 1	$\underline{M} = 65.58$ (20.68)	$\underline{M} = 66.40$ (20.22)
RI	$\underline{M} = 59.48$ (21.90)	$\underline{M} = 60.34$ (21.25)
RO	$\underline{M} = 65.84$ (24.04)	$\underline{M} = 66.89$ (21.43)
Bil 2	$\underline{M} = 75.10$ (25.41)	$\underline{M} = 75.94$ (24.84)

APPENDIX K

Visual Acuity Correlation and Visual Manipulation

Visual acuity scores between older females (20/35) and older males (20/30) were significantly different $t(1,24) = -2.40, p < .05$. In order to test whether visual acuity influenced performance, a correlation analysis between visual acuity scores and overall mean simultaneity threshold values of male and female older adults was conducted. Visual acuity scores of older males and females were transformed into Z scores. The results indicated no relationship between simultaneity threshold values and visual acuity measurements of older males and females ($Z = .2246, p > .05$). These results suggest that the high simultaneity threshold values of the older females are not related to visual acuity.

In a further attempt to discount the possibility that the overall poorer visual acuity of older females may have influenced their performance, another testing procedure was undertaken to manipulate the visual acuity of a young person. A young female with an average (median) acuity score for her group was selected from the young female age group. As well, her simultaneity threshold values were representative of the young female participants. With the use of neutral density filters, and lens to induce optical blur, the visual acuity of the young female was matched to that of a 69 year old (20/35), which was the average acuity score of the older females. It was found that the simultaneity thresholds for the six pairwise locations of the young female did not significantly increase when they were compared to her original thresholds. The table below provides the mean simultaneity thresholds for the non-manipulated vision of a young female, manipulated vision of young females, and a 67 year old female.

Subject	LO	LI	Bil 1	RI	RO	Bil 2
Young Non-manipulated	38.8	27.9	23.6	32.3	20.7	33.5
Manipulated Vision	40	30.2	29.4	36.9	24.9	32.3
Average Older	57	58.5	65.10	67.8	77.6	70.9

APPENDIX L

Means and Standard Deviations for Starting SOA Values, Number of Trials, and Overall Visual Simultaneity Thresholds as a Function of Group and Gender.

Group	Starting SOA Values	Number of Trials	Overall Mean Thresholds
Young			
Females	$\underline{M} = 59.62$ (6.91)	$\underline{M} = 105.15$ (10.42)	$\underline{M} = 28.76$ (10.46)
Males	$\underline{M} = 53.08$ (6.30)	$\underline{M} = 92.82$ (9.92)	$\underline{M} = 27.90$ (9.72)
Older			
Females	$\underline{M} = 104.23$ (17.06)	$\underline{M} = 96.4$ (16.03)	$\underline{M} = 75.94$ (19.47)
Males	$\underline{M} = 78.08$ (16.27)	$\underline{M} = 96.4$ (15.57)	$\underline{M} = 55.73$ (20.46)

APPENDIX M

Correlations for the Young Females.

Item	Meds	Ed Level	Visual Acuity	Tactile Thresholds	Visual Thresholds
Age	.00	.504	.177	-.495	-.168
Meds		.00	.00	.00	.00
Ed Level			.207	.035	.073
Visual Acuity				.208	.488
Tactile Thresholds					.670 **

* $p < .05$ ** $p < .01$

Correlations for the Young Males.

Item	Meds	Ed Level	Visual Acuity	Tactile Thresholds	Visual Thresholds
Age	-.199	.637 *	-.282	.327	-.130
Meds		.131	-.490	-.282	.138
Ed Level			-.133	.249	-.021
Visual Acuity				.227	.169
Tactile Thresholds					.522 *

* $p < .05$

Correlations for the Older Females.

Item	Meds	Ed Level	Visual Acuity	Tactile Thresholds	Visual Thresholds
Age	-.081	-.149	.540 *	.339	.456
Meds		-.179	.049	.056	-.222
Ed Level			-.149	-.291	-.033
Visual Acuity				.421	.249
Tactile Thresholds					.760 **

* $p < .05$ ** $p < .01$

Correlations for the Older Males.

Item	Meds	Ed Level	Visual Acuity	Tactile Thresholds	Visual Thresholds
Age	.467	-.407	.114	.640	.544
Meds		-.371	.129	.375	.081
Ed Level			-.207	-.279	-.348
Visual Acuity				.411	.310
Tactile Thresholds					.670 *

* $p < .05$ ** $p < .01$

APPENDIX N

Source Tables: Tactile Main ANOVAs

Table 1

Source Table for Main ANOVA (Bimanual)

SOURCE	SS	MS	DF	F	P
Group (G)	48669.23	48669.23	1, 48	46.99	.0000 *
Sex (S)	2004.65	2004.65	1, 48	1.94	.1706
G X S	2526.53	2526.53	1, 48	2.44	.1249
ERROR	49713.02	1035.75			
Order (O)	.32	.32	1, 48	.01	.9101
O X G	.01	.01	1, 48	.00	.9845
O X S	35.78	35.78	1, 48	1.43	.2384
O X G X S	44.72	44.72	1, 48	1.78	.1883
ERROR	1204.94	25.10			

* $p < .001$

Table 2

Source Table for Main ANOVA (Unimanual Conditions)

SOURCE	SS	MS	DF	F	P
Group (G)	53793.39	53793.39	1, 48	35.87	.0000 **
Sex (S)	1854.04	1854.04	1, 48	1.24	.2717
G X S	1168.50	1168.50	1, 48	1.48	.3818
ERROR	71989.21	1499.78			
Hand (H)	14.54	14.54	1, 48	.31	.5800
H X G	44.86	44.86	1, 48	.96	.3327
H X S	2.72	2.72	1, 48	.06	.8105
H X G X S	2.63	2.63	1, 48	.06	.8136
ERROR	2248.63	46.86			
Order (O)	137.31	137.31	1, 48	6.52	.0139 *
O X G	2.63	2.63	1, 48	.12	.7253
O X S	35.78	35.78	1, 48	1.43	.2384
O X G X S	8.40	8.40	1, 48	.40	.5308
ERROR	1011.58	21.07			
H X O	269.13	269.13	1, 48	4.18	.0465 *
H X O X G	36.39	36.39	1, 48	.56	.4561
H X O X S	25.47	25.47	1, 48	.41	.5247
H X O X G X S	35.06	35.06	1, 48	.54	.4644
ERROR	3093.86	64.46			

** $p < .001$ * $p < .05$

Table 3

Source Table for Main ANOVA (Condition)

SOURCE	SS	MS	DF	F	P
Group (G)	50163.12	50163.12	1, 48	42.75	.0000 **
Sex (S)	1860.93	1860.93	1, 48	1.59	.2140
G X S	1620.56	1620.56	1, 48	1.38	.2457
ERROR	56326.79	1173.48			
Condition (C)	7577.98	3788.99	2, 96	64.38	.0000 **
C X G	1090.62	545.31	2, 96	9.27	.0002 **
C X S	69.78	34.87	2, 96	.06	.1494
C X G X S	228.27	114.13	2, 96	.06	.8136
ERROR	5650.14	58.86			

** $p < .001$

Table 4

Source Table for Tactile Interhemispheric Transfer Time ANOVA

SOURCE	SS	MS	DF	F	P
Group (G)	1602.29	1602.29	1, 48	11.33	.0015 *
Sex (S)	102.62	102.62	1, 48	.73	.3985
G X S	340.43	340.43	1, 48	2.41	.1274
ERROR	1703.62	35.49			

* $p < .01$

APPENDIX O

Source Tables: Visual Main ANOVAs

Table 5

Source Table for Main Visual ANOVA

SOURCE	SS	MS	DF	F	P
Group (G)	219427.50	219427.50	1, 48	84.92	.0000 ***
Sex (S)	17318.91	17318.91	1, 48	6.70	.0127 *
G X S	14614.09	14614.09	1, 48	5.66	.0214 *
ERROR	124025.31	2593.86			
Condition (C)	10834.69	2166.94	5, 240	28.77	.0000 ***
C X G	695.73	139.15	5, 240	1.85	.1043
C X S	322.51	64.50	5, 240	.86	.5111
C X G X S	291.67	58.33	5, 240	.77	.5689
ERROR	18074.43	75.31			
Order (O)	138.33	138.33	1, 48	2.99	.0902
O X G	19.88	19.88	1, 48	.43	.5151
O X S	.939	.939	1, 48	.02	.8873
O X G X S	51.81	51.81	1, 48	1.12	.2952
ERROR	2219.97	46.25			
C X O	366.25	73.25	5, 240	2.23	.0517
C X O X G	511.88	102.38	5, 240	3.12	.0095 **
C X O X S	179.69	35.94	5, 240	1.10	.3633
C X O X G X S	55.65	11.13	5, 240	.34	.8887
ERROR	3093.86	64.46			

*** $p < .001$ ** $p < .01$ * $p < .05$

Table 7

Source Table for the Bill, LI, and RI ANOVA

SOURCE	SS	MS	DF	F	P
Group (G)	52558.07	52558.07	1, 48	86.82	.0000 **
Sex (S)	3864.08	3864.08	1, 48	6.38	.0149 *
G X S	3836.26	3836.26	1, 48	6.34	.0152 *
ERROR	29058.65	605.39			
Condition (C)	707.77	353.88	2, 96	17.28	.0000 **
C X G	51.47	25.73	2, 96	1.26	.2888
C X S	118.26	59.13	2, 96	2.89	.0605
C X G X S	12.72	6.36	2, 96	.31	.7337
ERROR	1965.74	20.48			

** $p < .001$ * $p < .05$

Table 8

Source Table for the BIL2, LO, and RO ANOVA

SOURCE	SS	MS	DF	F	P
Group (G)	57204.88	57204.88	1, 48	78.68	.0000 **
Sex (S)	4821.85	4821.85	1, 48	6.63	.0132 *
G X S	3475.24	3475.24	1, 48	4.78	.0337 *
ERROR	34898.55	727.05			
Condition (C)	1511.49	755.75	2, 96	14.15	.0000 **
C X G	247.19	123.59	2, 96	2.31	.1043
C X S	16.50	8.25	2, 96	.15	.8570
C X G X S	128.65	64.33	2, 96	1.20	.3043
ERROR	5126.93	53.41			

** $p < .001$ * $p < .05$

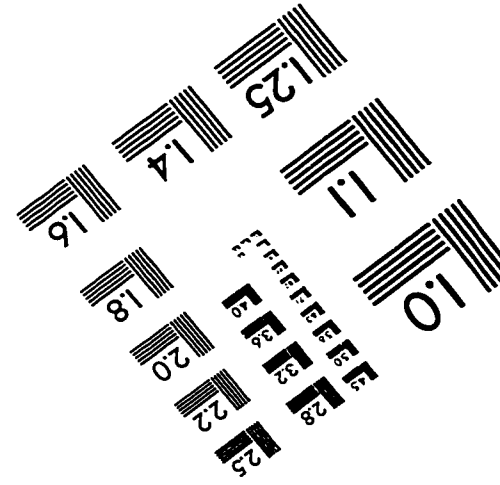
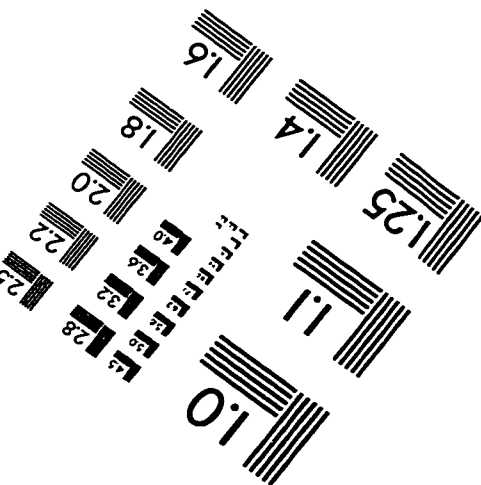
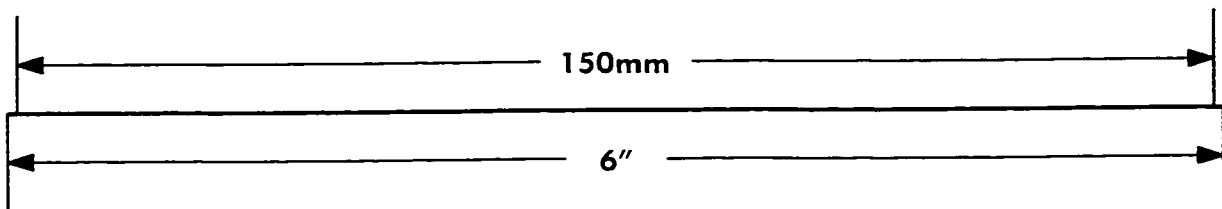
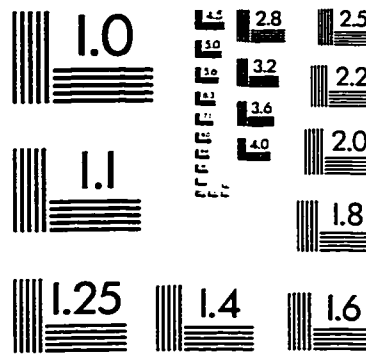
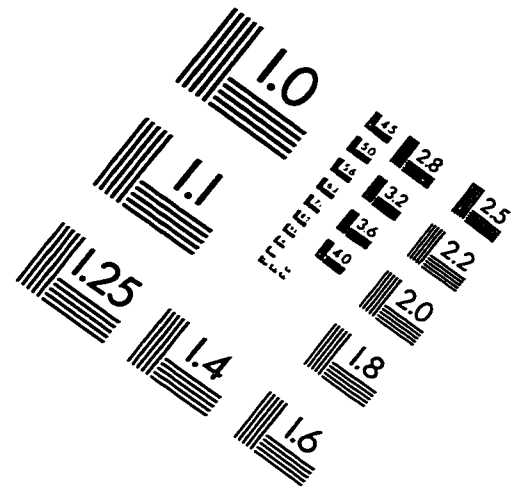
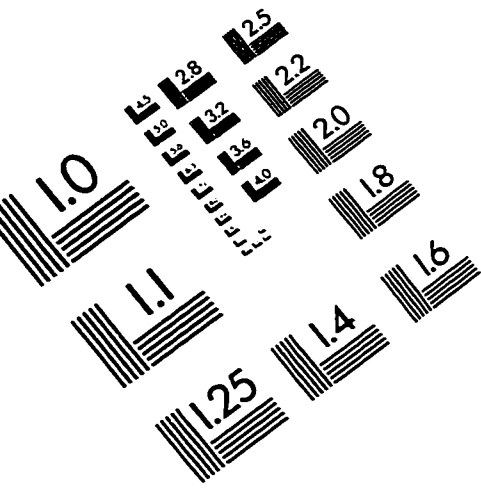
Table 9

Source Table for Visual IHTT ANOVA

SOURCE	SS	MS	DF	F	P
Group (G)	76.08	76.08	1, 48	2.14	.1497
Sex (S)	172.83	172.83	1, 48	4.87	.0322 *
G X S	16.17	16.17	1, 48	.05	.5029
ERROR	1703.62	35.49			

* $p < .05$

IMAGE EVALUATION TEST TARGET (QA-3)



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