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Dichotic and Dichoptic Digit Perception in Normal Adults

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Abstract

Background: Verbally based dichotic-listening experiments and reproduction-mediated response-selection strategies have been used for over four decades to study perceptual/cognitive aspects of auditory information processing and make inferences about hemispheric asymmetries and language lateralization in the brain. Test procedures using dichotic digits have also been used to assess for disorders of auditory processing. However, with this application, limitations exist and paradigms need to be developed to improve specificity of the diagnosis. Use of matched tasks in multiple sensory modalities is a logical approach to address this issue. Herein, we use dichotic listening and dichoptic viewing of visually presented digits for making this comparison.

Purpose: To evaluate methodological issues involved in using matched tasks of dichotic listening and dichoptic viewing in normal adults.

Research Design: A multivariate assessment of the effects of modality (auditory *vs.* visual), digit-span length (1–3 pairs), response selection (recognition *vs.* reproduction), and ear/visual hemifield of presentation (left vs. right) on dichotic and dichoptic digit perception.

Study Sample: Thirty adults (12 males, 18 females) ranging in age from 18 to 30 yr with normal hearing sensitivity and normal or corrected-to-normal visual acuity.

Data Collection and Analysis: A computerized, custom-designed program was used for all data collection and analysis. A four-way repeated measures analysis of variance (ANOVA) evaluated the effects of modality, digit-span length, response selection, and ear/visual field of presentation.

Results: The ANOVA revealed that performances on dichotic listening and dichoptic viewing tasks were dependent on complex interactions between modality, digit-span length, response selection, and ear/visual hemifield of presentation. Correlation analysis suggested a common effect on overall accuracy of performance but isolated only an auditory factor for a laterality index.

Conclusions: The variables used in this experiment affected performances in the auditory modality to a greater extent than in the visual modality. The right-ear advantage observed in the dichotic-digits task was most evident when reproduction mediated response selection was used in conjunction with three-digit pairs. This effect implies that factors such as "speech related output mechanisms" and digit-span length (working memory) contribute to laterality effects in dichotic listening performance with traditional paradigms. Thus, the use of multiple-digit pairs to avoid ceiling effects and the application of verbal reproduction as a means of response selection may accentuate the role of nonperceptual factors in performance. Ideally, tests of perceptual abilities should be relatively free of such effects.

Key Words: Auditory processing disorder, speech perception

Abbreviations: APD = auditory processing disorder; CAPD = central auditory processing disorder

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Verbally based dichotic-listening experiments (i.e., the simultaneous binaural presentation of two different speech tokens to each ear) and reproduction-mediated response-selection strategies (i.e., free recall of verbal material) have been used extensively to study perceptual and cognitive aspects of human information processing in normal listeners and those with lesions of the central nervous system (CNS) (e.g., Broadbent, 1954; Kimura, 1961; Musiek, 1983). Ear specific performance asymmetries on these tasks have led investigators to develop various structural and functional models of sensory, cognitive, and language-related functions (e.g., Bryden, 1967). However, there is a lack of consensus among investigators regarding the interpretation of this large literature (e.g., Efron, 1990; Martin and Jerger, 2005). Dichoptic viewing of visually presented symbols (i.e., the simultaneous presentation of two different spatially separated stimuli in the visual field) has also been used to assess for homologous processes of brain function (Bryden and Rainey, 1963), although much less is known about this paradigm owing to a general lack of research. Nevertheless, results from dichoptic viewing experiments reveal a right visual-field effect following *successive* presentation of visual material and a left visual-field effect following *simultaneous* presentation of visual material (e.g., Heron, 1957; Bryden and Rainey, 1963).

From a clinical perspective, dichotic listening paradigms represent one of several types of "sensitized" tasks thought to be useful for detecting auditory processing disorders (APDs). Sensitization of stimuli through filtering, time compression, use of competing messages, addition of noise, etc., increase the difficulty of the task and reduce the extrinsic redundancies of the input signal (Bocca and Colearo, 1963). Consequently, assumptions underlying sensitization imply that these types of stimulus manipulations increase the chances for detecting structural or functional lesions. However, questions concerning what processes are actually being affected by sensitization have never adequately been addressed, and the potential for involving factors that are not of a perceptual nature pose threats to the validity of these procedures (McFarland and Cacace, 2006). An alternative approach that requires demonstrating the specificity of the deficit to the auditory modality considers the use of matched tasks in multiple sensory modalities as a way to elucidate the diagnosis (McFarland and Cacace, 1995; Cacace and McFarland, 2005). This method contrasts with the unimodal inclusive framework, which advocates using auditory stimuli alone for diagnosing APDs. Even though the unimodal framework has been the de facto methodology used clinically over the years, we argue that this approach leads to an indeterminate diagnosis, lacks validity, and has obvious theoretical shortcomings. Thus, to further develop methods for diagnosing APDs by demonstrating the modality specificity of the deficit and to understand better what current tests of auditory processing measure, we investigated the use of dichotic listening and dichoptic viewing under various experimental conditions using acoustic and visually presented digits as stimuli. Carter and Wilson (2000) hold that digit materials are ideal for use in this type of examination because they are relatively immune from cochlear hearing loss, have high intertest reliability over a broad age range, and are generally familiar to most individuals. By inference, the familiarity of digits also applies to their use during visual presentations. By comparing the typical version of the dichotic-digits task that requires free recall (verbal reproduction of stimuli) with one that uses recognition within a forced-choice paradigm, this setting provides the opportunity to assess the role of response requirements in these tasks. By contrasting dichotic listening with dichoptic viewing of spatially separated digits, the role of supramodal factors involved in performance can be evaluated. Because it has been suggested that the auditory and visual systems are not analogous (e.g., King and Nelken, 2009), equating the perceptual requirements of these sensory systems may be difficult. However, our aim is to make these tasks as similar as possible in terms of those features that impact on abilities that are *not* of a perceptual nature, thereby developing tasks that are analogous in terms of their supramodal requirements. That is, if an individual does poorly on one test and much better on another, then we can conclude that he or she does not have difficulty with the common elements involved with these tasks. More specifically, in the case of dichotic or dichoptic digits, if an individual has a deficit restricted to the auditory task, then we can conclude that this is not due to those factors common to the two experimental tasks, such as understanding the response requirements of the task, supramodal memory span, supramodal attentional abilities, and so on. To be clear, this reasoning does not require that the auditory and visual stimuli be equated.

METHODS

Participants

Thirty adults (12 males, 18 females) ranging in age from 18 to 30 yr participated in these experiments. Eighty percent (24/30) were right-handed based on a handedness inventory (http://www.brainmapping.org/shared/Edinburgh.php) modified from Oldfield (1971). Inclusion criteria required participants to have pure tone hearing sensitivity in the normal range, a negative history of speech, language, attentional, perceptual, or cognitive disorders, and normal or corrected-to-normal visual acuity (20/20). This study was approved by the Human Investigation Committee of Wayne State

University, and signed informed consent was obtained from each participant prior to data collection.

Procedures

Individuals were required to pass hearing and vision screenings prior to participation. Hearing screenings were performed at 25 dB HL at octave frequencies from 250 to 8000 Hz bilaterally using a clinical audiometer (Grason-Stadler, Model GSI-61) and standard earphones (Telephonics, TDH-39) enclosed in supra-aural ear cushions (MX-41/AR). Visual acuity was tested via a Snellen eye chart under standard conditions. Because individuals participating in this study (i.e., friends, relatives, students, etc.) were recruited by word of mouth, it was considered a convenience sample.

Stimuli

Auditory stimuli were digitally sampled single-syllable digits (1 through 9, except 7), recorded by an adult male speaker. Single digits were sampled at a rate of 44,100 Hz from the output of a microphone and stored as individual wave files. These stimuli were amplitude normalized using commercially available sound editing software (Sound Forge Pro10, Sony Creative Software, Madison, WI). Temporal measurements of the digits were made from onset to offset of production by simultaneously viewing the stimulus waveform and hearing the acoustic output from a speaker using a cross platform audio editor and recorder (Audacity, release 1.3.11). The duration of individual files, including the offset silent interval of individual digits, was adjusted to the longest recorded stimulus (digit 9), which approximated 500 msec. This method followed the approach of Strouse and Wilson (1999), although it differed slightly because they concatenated a silent interval to the end of an individual file, to equalize file lengths to the longest digit. Nevertheless, while different methods were involved, the end result would be the same because neither authors altered the individual stimuli in any way. Dichotic digit files were aligned according to their speech production onsets (change of visible energy from baseline) and remained active until the 500 msec termination time was reached. Acoustic presentation of the dichotic stimuli was via circumaural earphones (Bose, QuietComfort 2) at 60 dB SPL. These earphones were calibrated using a flat-plate coupler and a .5 in condenser microphone (Bruel and Kjaer, type 4134) routed to a sound-level meter (Bruel and Kjaer, type 2209).

Visual analogs of the acoustic stimuli were visual representations of the same single digits. Visual stimuli (sans serif font/~1.5 cm display size) were presented on the screen of a laptop computer (Dell, model XPS), at eye level, and with participants instructed to focus on a fixation point (cross) located in the center of the screen during stimulus presentation. Eye-to-screen distance was 55.88 cm with digit presentations subtending a visual angle of 8.5° from the central fixation point. Testing was conducted within a well-lit commercially constructed sound booth (Acoustic Systems, Austin, TX; Model RE-144) or in a quiet room where sound levels did not exceed 34 dB (A). Custom designed software written in C^{++} was used to present stimuli, control all timing aspects of the experiment, and save data of individual trials as a text file for off-line analysis.

Stimulus Presentation

Figure 1 shows the sequence of the two different psychophysical paradigms in diagrammatic form. Both paradigms share a common structure: the sequence of each trial begins with an alerting interval, is followed by a stimulus presentation interval, and ends with a response interval. The timing of the individual intervals, the silent intervals between trials, the number of trials, the number of stimulus pairs per condition, and the modality of presentation (auditory or visual) were parameters that are selectable from within the computer program. Once assigned, the experimental parameters are stored as files such that each condition could be recalled to facilitate testing during a specific component of the experiment.

The alerting interval and each digit-pair presentation were 500 msec in total duration and were separated by a silent 500 msec interstimulus/interdigit interval. Then, a visual cue indicating that a response was required remained visible on the computer monitor until a response was made. The silent intertrial interval, defined from the offset of the response to the onset of the next stimulus pair, was 1000 msec. Feedback was not used in any of the conditions. The timing parameters were similar to those used on a CD version of the test (Department of Veterans Affairs, *Tonal and Speech Materials for Auditory Perceptual Assessment, Disc 2.0*). The alerting interval was a visual cue consisting of two white boxes on a gray background. The stimulus presentation interval provided the setting where one-, two-, or three-digit pairs were simultaneously presented to each ear or to the left and right hemifields within two white boxes. Forty presentations of one-, two-, and three-digit pair combinations were presented separately to each sensory modality. Digit-pair combinations were not intermingled, as in the paradigm used by Moncrief and Wilson (2009). Moreover, individual digits were selected randomly without replacement; but the same digit could not be presented more than once within a given stimulus trial.

When reproduction was used as the form of response selection (Fig. 1, left), after stimuli were presented, a prompt appeared on the screen that provided a visual

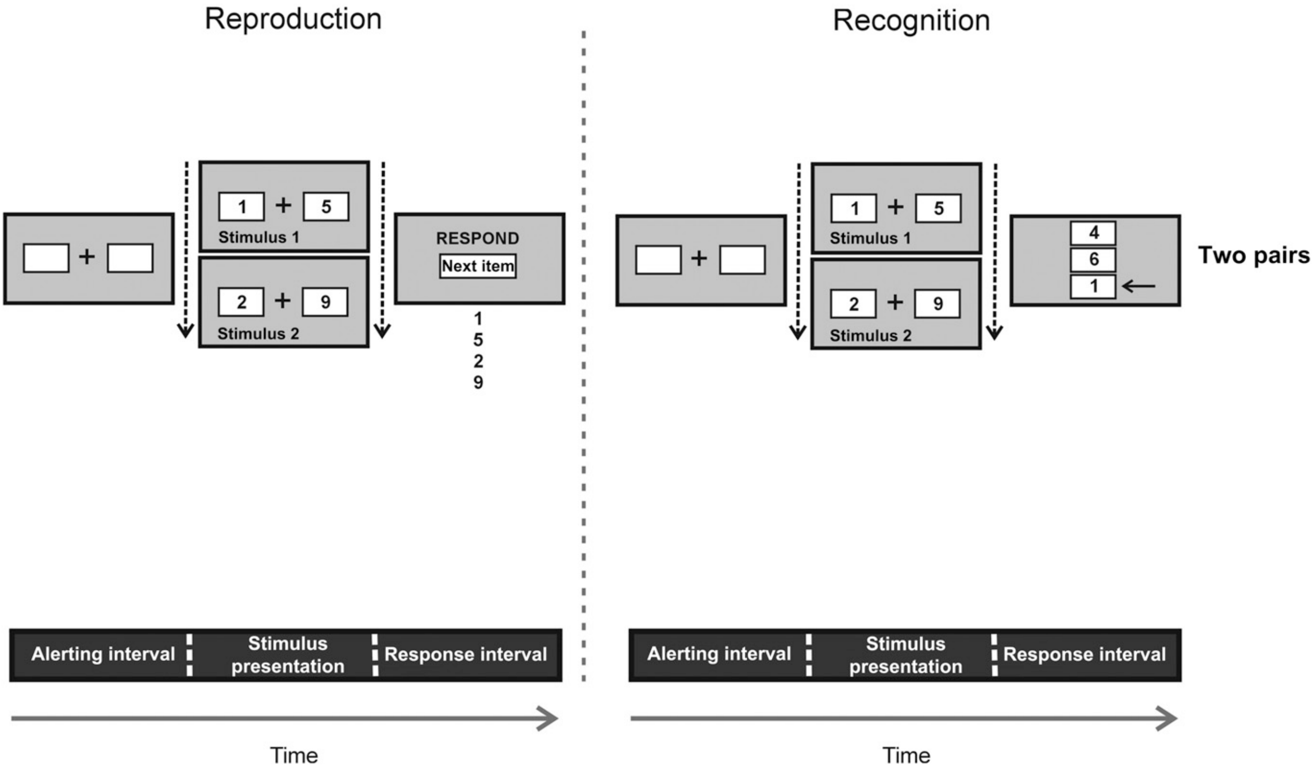

Figure 1. Reproduction (*left*) and recognition (*right*) trial formats. Two empty boxes and a cross are presented during the alerting interval. Next, the stimulus pairs are presented, either visually or auditorally. Then a response is required. For the reproduction format, individuals were instructed to pay close attention, hold the digits in memory, and reproduce all digits to the best of their abilities after the visual cue "respond" is presented on the computer screen. Once their response is completed, participants were instructed to select a box labeled "next item" with the mouse, to initiate the next trial. If the stimuli are presented visually, they were instructed to focus on the central fixation point (cross) in the middle of the screen during stimulus presentation. For the recognition format, individuals were instructed to select the digit that corresponded to one that was presented in the immediately preceding stimulus sequence, from two foils that were not in the previous sequence. The selection consisted of three vertically arranged response buttons. After the selection was made, a new trial was automatically initiated, and the process was continued until 40 trials were completed.

cue for participants to "respond." In this condition, participants were required to verbally reproduce the sequence of all stimuli presented within the stimulus interval. This approach is equivalent to "free recall" where verbal reproduction of the stimuli in any order is required. After responding, the participant would select via a mouse pointing device a box labeled "next item" on the computer monitor to initiate the subsequent trial. This same sequence of events was repeated until 40 trials were completed. Verbal responses during the reproduction component of the experiment were also tape recorded, and an output file with the ordered stimulus presentations of the individual conditions facilitated off-line scoring and tabulation of results by the experimenter.

When the recognition task was used (Fig. 1, right), after stimulus presentation, participants were forced to select one of three visually presented digits corresponding with vertically arranged response buttons where the correct digit was a member of one of the immediately preceding stimulus pairs while the two foils were not. After a response selection was made, a new trial was automatically initiated, and this process was repeated until termination after 40 trials. In the recognition paradigm, correct responses, stimulus information, and computation of performance for left and right ears were stored in an output file for subsequent tabulation and statistical analysis.

Individual performance scores were computed as the percent correct per ear or visual hemifield of presentation (left and right). Each participant completed all combinations of modality of presentation (auditory/dichotic; visual/dichoptic), digit pairs (one, two, and three), and response selection strategies (recognition and reproduction). Data collection was completed within two one-hour sessions, and individuals were not paid for their participation.

Statistical Analysis

A four-way ($2 \times 2 \times 2 \times 2$) repeated measures analysis of variance (ANOVA) was used to evaluate the effects of modality (auditory *vs*. visual), ear/visual hemifield of presentation (left *vs*. right), response selection (recognition *vs*. reproduction), and number of digit pairs (two and three) corresponding to span lengths of four or six digits. The one-digit pair condition was not included in this analysis due to ceiling effects. An a priori alpha level of $p \leq 0.05$ was used as a minimum criterion for statistical significance. Pearson product-moment correlation analyses were used to evaluate overall performances and laterality indices on auditory and visual recognition and reproduction tasks.

RESULTS

The raw data for each experimental condition is shown in scatterplots (Fig. 2, auditory/dichotic; Fig. 3, visual/dichoptic), where x- and y-axes represent right and left ear/visual hemifield performance in terms of percent correct performance. If performances between the left and right ears or left and right visual hemifields were identical, then individual data points would fall along the solid diagonal line on the plots. If asymmetries in performance were observed, then data points would fall above or below the diagonal line of the plot. These data are also summarized in numerical form (Table 1).

Dichotic Recognition

Ceiling effects (i.e., data points on the scatterplot where performances clustered at or near 100%) were observed for one digit pairs. The performances on the two- and three-digit pairs had a broader range of values and were distributed relatively symmetrically along the diagonal.

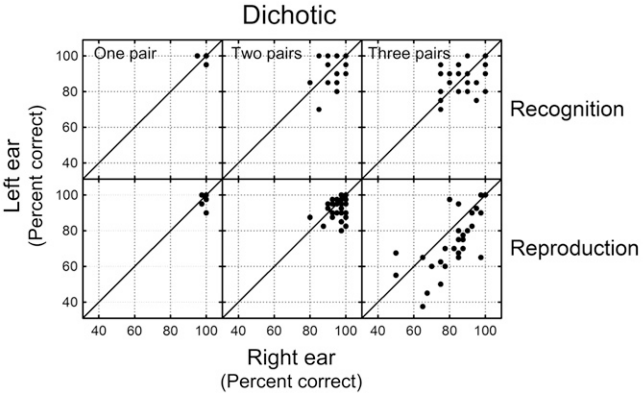

Figure 2. Auditory percent correct for recognition (*top panels*) and reproduction (*bottom panels*) with one-, two-, or three-digit pairs. The y-axis represents the left ear, and the x-axis represents the right ear. Note that data points would fall along the diagonal for identical performance for the two ears. Asymmetries are indicated when the data points fall either above or below the diagonal line.

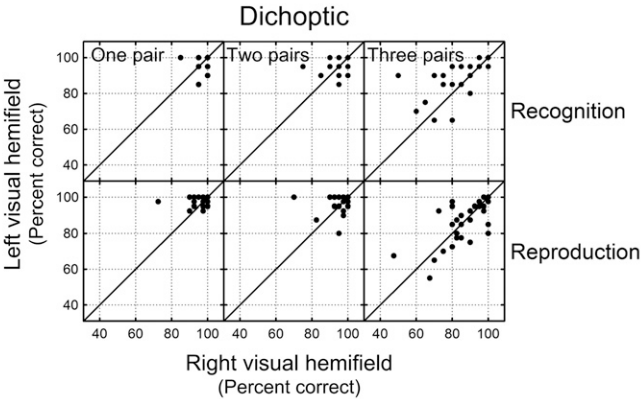

Figure 3. Visual percent correct for recognition (*top panels*) and reproduction (*bottom panels*) with one-, two-, or three-digit pairs. The y-axis represents the left ear, and the x-axis represents the right ear. Note that data points would fall along the diagonal for identical performance for the two ears. Asymmetries are indicated when the data points fall either above or below the diagonal line.

Dichotic Reproduction

Similar to the recognition task, a ceiling effect was observed for the one-digit pairs. However, in contrast to recognition mediated response selection, a right-ear advantage (i.e., data points clustering below the diagonal line of the scatterplot) was observed for the two- and three-digit pair performances.

Dichoptic Recognition

A ceiling effect for one- and two-digit pairs was also observed. Like the dichotic results, performances on the three-digit pairs had a broader range of values and were distributed relatively symmetrically along the diagonal.

Dichoptic Reproduction

Similar to the recognition task, a ceiling effect was apparent for the one-digit pairs. However, asymmetries were observed in the two- and three-digit pair performance data, which corresponded to a slight left visual field effect.

Because asymmetries were observed in some of the experimental conditions, we constructed a laterality index based on Equation 1 to further evaluate these effects:

$$\text{Laterality index } (\%) = (\text{right} - \text{left})/(\text{right} + \text{left}) * 100 \qquad \text{(Equation1)}$$

Vertical bar graphs were used to represent the laterality data (Fig. 5A, reproduction, top; 5B, recognition, bottom), where the zero horizontal solid line indicates no difference between left or right ears or left or right visual hemifields of presentation; positive or negative values indicate whether the data favored one ear/visual

Table 1. Descriptive Statistics for Auditory and Visual Recognition and Reproduction Tasks

	Auditory recognition					
	Right ear Digit pairs			Left ear Digit pairs		
	1	2	3	1	2	3
Mean	99.8	95.7	89.2	99.6	93.8	86.7
SD	1.9	5.5	8.9	1.3	7.4	7.6
	Visual recognition					
	Right visual hemifield Digit pairs			Left visual hemifield Digit pairs		
	1	2	3	1	2	3
Mean	97.7	95.3	84.8	97.5	96.2	88.7
SD	3.9	6.0	12.4	3.4	4.9	9.4
	Auditory reproduction					
	Right ear Digit pairs			Left ear Digit pairs		
	1	2	3	1	2	3
Mean	99.4	95.8	82.0	99.3	92.9	71.6
SD	1.1	4.6	13.0	2.2	5.8	18.7
	Visual reproduction					
	Right visual hemifield Digit pairs			Left visual hemifield Digit pairs		
	1	2	3	1	2	3
Mean	95.7	95.9	86.5	98.2	97.2	86.3
SD	7.1	6.2	12.1	2.5	4.7	12.0

hemifield or the other. The dichotic recognition data showed a subtle right-ear advantage that increased with digit-span length. The dichoptic recognition data showed a slight left visual hemifield advantage for two- and three-digit pairs. The dichotic reproduction data showed a prominent right-ear advantage for three-digit pairs. In contrast, the dichoptic reproduction data showed performance to be close to the zero point.

Statistical Analysis

Due to ceiling effects noted above, some data were negatively skewed. Therefore, the arcsine transformation was used to help normalize the frequency distributions prior to the formal statistical analysis. Using the arcsine transformed data, the results from the ANOVA revealed significant main effects of modality ($F = 10.57$, $p < 0.003$), ear/visual hemifield of presentation ($F = 6.96$, $p < 0.02$), response selection ($F = 7.79$, $p < 0.01$), and digit-span length ($F = 133.88$, $p < 0.0002$). There were significant two-way response selection × digit span ($F = 5.14$, $p < 0.04$) and modality × response selection interactions ($F = 14.34$, $p < 0.001$). Lastly, there were also two significant three-way modality × side × digit span ($F = 6.33$, $p < 0.02$) and modality × response selection × digit span interactions ($F = 6.40$, $p < .02$). Plots of the two three-way interactions are shown in Figure 4. The modality × side × digit span interaction (left plots) showed a right-ear advantage for dichotically presented two- and three-digit span pairs. The modality × response selection × digit span interaction (right plots) demonstrated better performance for the recognition based response selection task specifically for the auditory modality. With the exception of digit-span length, it is clear that the remaining experimental variables affected the auditory modality to a greater extent than the visual modality.

Correlations between total scores, summed across side-of-presentation and digit-span length, are presented in Table 2. These data represent overall accuracy measures

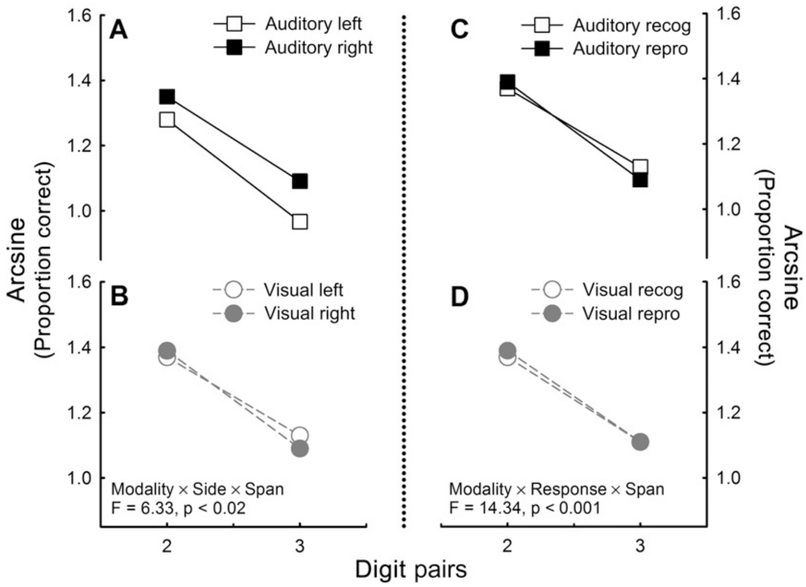

Figure 4. Arcsine transformation of the proportion correct as a function of number of digit pairs. *A:* Auditory ear effects; *B:* Visual field effects; *C:* Auditory response mode effects; *D:* Visual response mode effects.

for each experimental condition. The correlations were uniformly positive and generally significant. They show that individual differences in overall accuracy of performance are related in auditory and visual reproduction and recognition tasks. Correlations between the laterality indices, summed across digit-span length, are shown in Table 3. They show that only the auditory laterality indices for recognition and reproduction are significantly correlated. Thus, unlike overall accuracy, there does not appear to be a relationship between laterality indices for auditory and visual versions of these tasks.

DISCUSSION

The results from the present study show that obtaining a right-ear advantage with a dichotic digits task in normal young adults depends on the use of multiple-digit pairs and reproduction mediated response selection. These findings confirm and extend the results of Moncrieff and Wilson (2009) and Wilson and Jaffe (1996) based on findings in children and in young and older adults (60–75 yr of age). Use of single-digit pairs produces near perfect performance (a ceiling effect) so that it is unlikely that any effects could be observed under these conditions. Ceiling effects for one and two dichotically presented digit pairs using reproduction mediated response selection are age dependent (Wilson and Jaffe, 1996; Moncrieff and Wilson, 2009) and also represent a consistent finding in young adults (e.g., Musiek, 1983; Martin and Cranford, 1991; Bellis et al, 2008; present study). Based on the cross-sectional study of Moncrieff and Wilson (2009), the pronounced right-ear advantage observed in 10- to 14-yr-olds is reduced markedly in the 15- to 28-yr-old age groups. In young adults, using two-digit pair presentations and reproduction mediated response selection, the mean right-ear advantage is generally negligible (Dirks, 1964, 6.2%; Musiek, 1983, 1.3%; Martin and Cranford, 1991, 0.5%; Bellis et al, 2008, 1.7%; Moncrieff and Wilson, 2009, <1.0%; present study, 1.5%). In older adults, while overall performance declines, Wilson and Jaffee (1996) found that when reproduction is used as a form of response selection, the right-ear advantage increases with age. Also, consistent with the results of Voyer and Boudreau (2003), we found nonsignificant correlations of laterality indices between the auditory and visual versions of these tasks.

Penner et al (2009) suggest that the increase in working memory load in dichotic listening tasks leads to an amplification of the structural properties of the auditory system. An alternative possibility is that the right-ear advantage reflects "speech related output mechanisms" (i.e., processes related to motor planning, motor-sequencing abilities, perceptual-motor skills, etc.).

Table 2. Pearson Product Correlations between Total Scores, Summed across Spans and Sides

Variable	Auditory recognition	Auditory reproduction	Visual recognition
Auditory reproduction	0.62**	—	—
Visual recognition	0.50**	0.32	—
Visual reproduction	0.67**	0.56**	0.65**

**p < 0.01

Table 3. Pearson Product Correlations between Laterality Indices Summed across Spans

Variable	Auditory recognition	Auditory reproduction	Visual recognition
Auditory reproduction	0.47**	—	—
Visual recognition	−0.28	−0.28	—
Visual reproduction	−0.27	−0.17	0.16

$^{**}p < 0.01$

This later interpretation is consistent with the results of the present study, where the right-ear advantage was present when using verbal reproduction but not when recognition was required. It is also in marked contrast to common interpretations of dichotic speech perception that emphasizes "encoding processes." Furthermore, it is notable that in all other studies we have discussed, reproduction using free recall was the methodology utilized.

Correlations between the dependent variables averaged over ears and digit spans were generally positive and significant. This suggests that common factors are involved in the overall performances of the auditory and visual recognition and reproduction tasks. With the laterality index, only auditory recognition and reproduction were significantly correlated. This indicates that a consistent modality specific laterality factor is obtained only with the auditory tests. While the right-ear advantage is highly dependent on the use of reproduction as a form of response selection, there is consistency in laterality effects across the auditory tasks. Thus, a perceptually based asymmetry might best be evaluated with tasks that do not involve reproduction, although more research is needed to confirm this observation.

Ceiling effects occur when tests are very easy and a substantial proportion of individuals obtain maximum or near-maximum scores (Uttl, 2005). This results in a reduction of the true range of scores and produces undesirable effects on variability dependent test statistics such as reliability, validity, and correlations with other tests (Uttl, 2005). While use of multiple-digit pairs, reproduction mediated response selection, and random presentation of different digit spans are methodological tactics used to increase difficulty and to minimize ceiling effects, they also make performances on these tasks susceptible to supramodal factors (i.e., abilities that are not of a perceptual nature) including increased demands on working memory. To the extent that working memory requires the use of supramodal resources, a key involvement of this process is *not* a desirable property for a test of auditory processing, which should emphasize instead the assessment of perceptual abilities. In this context, it is notable that Maerlender et al (2004) report that results obtained on the dichotic-digits task is related to performance on the digit span subtest of the Wechsler Intelligence Scale for Children (WISC). Our findings of correlations between all scores summed across spans and sides (Table 2) also suggest that a general individual difference factor is operating. This observation could be related to memory span or other supramodal influences. Thus, we contend that if the intent of the investigator/clinician is to study perceptual disorders, then manipulations that involve these types of supramodal factors should be avoided.

Mechanisms underlying increased task difficulty based on reproduction mediated response selection are not entirely understood. However, like dichotic listening, asymmetries in selected motor-task performances are also age dependent and may be related to maturation of the corpus callosum (Roeder et al, 2008). Furthermore, neuroimaging studies may provide some insight into the brain mechanisms involved in these procedures. For example, Habib and Nyberg (2007) suggest that recognition procedures may allow access to weaker memory representations than recall. In contrast, Salami et al (2010) suggest that recall involves a proportionally greater activation of a modality-independent conceptual network. What is overtly apparent is that in studies of perception, the use of reproduction as the response mode complicates the interpretation of results.

Bellis et al (2008) compared performances on small samples of normal adults, normal children, and children diagnosed with central auditory processing disorder

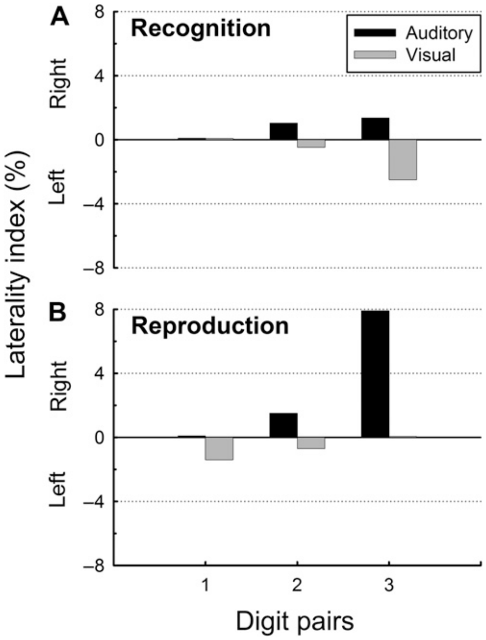

Figure 5. *A:* Laterality indices as a function of modality and number of digit pairs for the recognition response mode; *B:* Laterality indices as a function of modality and number of digit pairs for the reproduction response mode.

(CAPD) based on a dichotic digits tests and its visual analog. These tasks made use of multiple-digit pairs and reproduction as the response mode. Normal children performed significantly better than children with "presumed" CAPD in both auditory and visual tasks. Bellis et al (2008) conclude that their results "do not support the concept of complete modality-specificity in children diagnosed with CAPD." They assert that this result is consistent with the position of Musiek et al (2005) that "complete" modularity of central auditory function is neurophysiologically untenable.

Several points are relevant here. First, describing our position as advocating "complete modality specificity" is inaccurate. Neither of the two senior authors (DJM or ATC) has ever used this description. Instead, it has been stated that it is sufficient to demonstrate "relative" modality specificity where the point-of-emphasis is the realization that auditory-perceptual disorders, if present, should involve the auditory modality to a disproportionate degree (McFarland and Cacace, 1995). Furthermore, arguing that the auditory system is not modular *undermines* the concept of auditory-perceptual disorders. For if these disorders are not modality specific (i.e., modular), then why characterize them as being auditory? Indeed, what is clear from current dogma is the fact that modality specificity continues to be a useful construct in many areas of cognitive and neural science (see McFarland and Cacace, 2009, for a review).

While Bellis et al (2008) imply that modality specificity is not a useful concept, there are other explanations for their results. As indicated by the present results, the dichotic tests used for diagnosis and evaluation of children with presumed CAPD may involve factors that are not of a perceptual nature by virtue of their use of multiple-digit pairs and application of reproduction mediated response selection. Thus, rather than calling into question the concept of modality specificity, it may be more appropriate to examine the nature of the tests and methodologies used by Bellis et al (2008).

At this juncture, it is also instructive to ask: what should a test of dichotic perception be like? To the extent that the dichotic listening task represents a central-masking paradigm, the procedure employed by Hugdahl et al (2008) appears more desirable than using multiple-digit pairs. These investigators manipulated task difficulty of single digits by varying interaural intensity differences. This approach allowed the investigators to vary task difficulty along a continuous sensory dimension without increasing memory load. Consequently, modality-specific effects are more likely to be manifest when task performance is not limited by supramodal abilities. Furthermore, while the right-ear advantage observed in dichotic listening tasks is thought to be a complex interaction between the types of stimulus material used, structure within afferent auditory pathways, resource allocation of attention, and working memory (Hugdahl, 1995), the fact that these effects occur predominantly during "reproduction" suggests that this list is incomplete and that commonly used interpretations of dichotic listening need to be revisited.

As we have emphasized throughout, tests of perception should minimize motor demands on participants and be structured to emphasize recognition in the context of a forced-choice paradigm. The additional requirement to verbally reproduce items, as in multiple-item sequences where free recall is used, affects performance and adds unwanted complexity to the task. Along these lines, McFarland and Cacace (1995) found that when participants were asked to "reproduce" sequences of multiple element binary frequency patterns, the recency effect of terminal items was eliminated. In contrast, the recency effect was present when a recognition paradigm was used. This effect indicates that the use of reproduction as a form of response selection in tasks purported to assess sensory processes adds potential sources of variance to the data that are associated with recall rather than with perceptual processes. Therefore, to avoid difficulties with interpretation and minimize complexity of the task, the forced choice recognition paradigm is advocated to replace this traditional format.

While no research endeavor is perfect, further improvements are possible in this area. For example, if we assume that isolating the eyes for presentation of individual visual stimuli to each hemifield is better than presenting stimuli to the left and right sides of a visual fixation point, then future experiments should take this alternative approach into consideration. Lastly, in the context of assessing for disorders of auditory processing, no single test or experiment is beyond alternative explanations. However, if APD is to be a useful construct, then it should be possible to provide evidence for the relative independence among different sensory modalities.

In conclusion, it is our position that tests of auditory perception should employ methodologies typical of those used in contemporary psychophysics. We advocate the use of recognition-based response-selection tasks structured in a forced-choice paradigm such that supramodal memory demands and motor processes are minimized. The observation that reproduction mediated response selection affected performance in the auditory modality to a greater extent than in the visual modality shows that the right-ear advantage observed in a dichotic-digits task is highly susceptible to and influenced by this type of methodology. This effect implicates asymmetries in "output mechanisms," an interpretation which differs markedly from models of dichotic speech perception that emphasizes "encoding processes" and structural properties of afferent auditory pathways.

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