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Relation of backward masking and frequency discrimination to reading and language among 5-12 year old children

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Psychoacoustic adaptive threshold estimation procedures were implemented as "computer games" to measure, with no experimenter intervention, backward detection masking and frequency discrimination in 54 children aged 5–12 years. Assessments of the subjects' pure-tone hearing thresholds, language abilities, and reading skills were also made. Thresholds were successfully obtained for backward masked pure tone detection, and for pure tone frequency discrimination (unmasked and backward masked). Receptive language ability was significantly correlated with backward masking and reading skills were significantly correlated with backward masking and frequency discrimination, consistent with an auditory processing deficit hypothesis in reading and language impairments.

The origin of language and reading difficulties has long been an issue of controversy, in parallel with competing theories of reading and language acquisition and of the skills thought to underly competent linguistic and reading performance. Because of the primarily auditory nature of linguistic input, deficits in auditory processing may reasonably be expected to result in deficient linguistic representations, an argument most clearly applicable in the domain of phonology and consistent with our current understanding of reading difficulties as often stemming primarily from phonological impairments. The relation of language impairments to reading difficulties and the possible overlap of the corresponding diagnostic categories is well documented (Bishop & Adams, 1990; Catts, 1993; Kamhi & Catts, 1986; Kamhi, Catts, Mauer, Apel, & Gentry, 1988; Scarborough, 1990).

Specifically language impaired (SLI) children (variably termed "language-learning impaired," "dysphasic," or suffering from "developmental aphasia," "language impairments" or "specific language disorders") have been found to differ, as a group, from normal children in several nonverbal auditory tasks including simple and complex tone sequencing (Ludlow, Cudahy, Bassich, & Brown, 1983; Robin, Tomblin, Kearney, & Hug, 1989; Tallal & Piercy, 1973; Tallal, Stark, Kallman, & Mellits, 1981), gap detection (Ludlow et al., 1983), and masked pure tone detection (Wright et al., 1997; Helzer, Champlin, & Gillam, 1996 only in learning the task). See Leonard (1998) for a recent review and discussion (an early review can be found in Lubert, 1981).

Poor reading has also been associated with deficient nonverbal auditory processing. Findings include, for adults, impairments in modulation detection (Witton et al., 1998), tone sequencing (Protopapas, Ahissar, & Merzenich, 1997), processing of rapid sound sequences (Hari & Kiesilä, 1996), frequency discrimination (McAnally & Stein, 1996; Protopapas et al., 1997; Watson & Miller, 1993), and binaural unmasking (McAnally & Stein, 1996); for children, impairments in auditory fusion (McCroskey & Kidder, 1980), frequency discrimination (De Weirdt, 1988), and tone sequencing (Reed, 1980; Tallal, 1980). See Farmer and Klein (1995) for a review and discussion of some of the nonverbal auditory processing findings with respect to the temporal dimension.

If the auditory perceptual deficit hypothesis for reading and language problems is correct, one might expect to find that auditory perceptual performance is related to the reading and language ability even in children with no impairments or difficulties. This prediction was tested in a group of normally developing children with normal hearing attending a private school in Sunnyvale, CA. Due to time contstraints only a restricted set of tests could be administered to each child, selected to be most representative of the respective skills measured.

Method

Subjects. In the present study 54 schoolchildren (24 girls and 30 boys) ranging in age between 5;1 and 12;0 years (mean age 7.7±1.7 years) were tested. All children's pure tone hearing thresholds were measured and were found to be within the normal range except for two children with elevated hearing thresholds whose data were excluded from the analyses reported below.

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The techniques described herein constitute proprietary technology of Scientific Learning Corp., Berkeley, CA. Patent pending.

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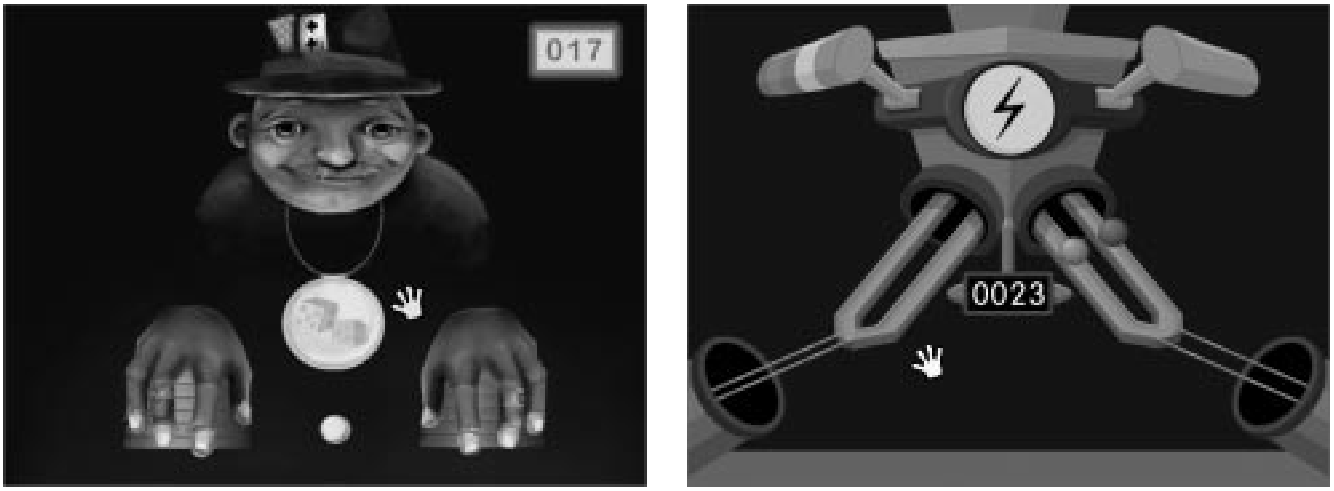

Figure 1. Screen shots of the graphical interfaces in the implementation of the psychoacoustic threshold estimation tasks as "computer games." *Left:* The "magician," implementing a two-alternative forced choice detection task. Each trial is initiated by a mouse click on the magician's medallion upon which the little ball disappears and then each cup lights up (left first and then right) coinciding with a selection interval (in the backward masking task conveniently also marked auditorily by the presence of masking noise). The child has to use the mouse cursor (indicated by the open hand icon) to click on the cup containing the ball, i.e., select the interval in which a tone occurred preceding the noise masker. The ball is revealed, the magician winks, and the score is increased with every correct response. *Right:* The "gumball machine," implementing a same-different discrimination task. A trial is initiated by a mouse click on the circle with the thunderbolt, upon which the two sounds to be compared are presented. The child then uses the mouse cursor (the open hand icon) to click on one of the two levers. The right lever is orange colored and represents the "same" response; the left lever is multicolored and represents the "different" response. Upon "pulling a lever," two balls roll out of the machine on the selected side. The two balls are of the same color if the two sounds were the same or of different colors if the two sounds were different. When two balls of the same color meet at the rolling ramp, they merge forming a larger ball, which will be collected on the right ("same" response) side due to the wide rail but fall out on the left ("different" response) side due to the narrow rail. Conversely, two balls of different colors do not merge and are successfully collected on the left but not on the right side. Sound effects accompany the events of rolling, collection, and loss, and the score is increased with every correct response.

Language and reading assessment. Language skills were assessed using the receptive language scales from the Clinical Evaluation of Language Fundamentals–Third Edition (CELF-3; Semel, Wiig, & Secord, 1995): Sentence Structure (for the younger childern only), Semantic Relationships (for the older children only), Concepts and Directions, and Word Classes. Scores on the three age-appropriate of these four scales combine to form the age-standardized CELF-3 "Receptive Language Quotient." Reading ability was measured using the Word Identification, Word Attack, and Passage Comprehension scales from the Woodcock Reading Mastery Tests–Revised (Woodcock, 1987) and the Spelling subtest from the Wide Range Achievement Test 3 (WRAT-3; Wilkinson, 1993). In all these tests, raw scores are converted to age-standardized scores with a mean of 100 and a standard deviation of 15, termed "standard scores."

Psychoacoustic assessment. Psychoacoustic measures were necessarily restricted to those that could be obtained within an hour of testing and without experimenter supervision. To elicit the children's interest and maintain their attention, they were programmed to appear as "computer games" with engaging graphical interfaces (Figure 1). All thresholds were estimated using an adaptive staircase procedure with variable asymmetric step size based on the Accelerated Stochastic Approximation method (Kesten, 1958, cited in Treutwein, 1995, p. 2509) with the following modifications: (a) The number of reversals was increased by 1.0 and not by 2.0 in the denominator of the formula for the determination of the step size, and (b) reversals were discarded to accelerate threshold approximation in the case of too many consecutive correct or incorrect responses. Testing was terminated based on number of reversals (10 for the detection and 8 for the discrimination tasks) and the threshold was defined as the arithmetic mean of the reversal points excluding the first two. This method was found to be exceptionally reliable in producing stable thresholds in one or two sessions from untrained subjects including children and adults (in contrast to more modern, and theoretically much faster to converge, maximum likelihood methods, which were found to be unstable when used with untrained and occasionally inattentive subjects).

Of the many auditory processing tasks that have been reported in the literature to correlate with language and reading skills we selected two simple complementary tasks and their combination. Specifically, we measured brief pure tone detection under backward masking, which was recently found by Wright et al. (1997) to be impaired for SLI children, and long pure tone frequency discrimination, which has been found (Protopapas et al., 1997) to be difficult for adult poor readers. These two tests are particularly informative as they assess temporal integration and spectral resolution in a form relatively uncontaminated from each other and with minimal cognitive requirements.

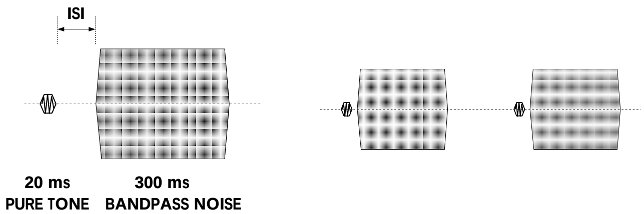

Figure 2. Illustration of the temporal relations between auditory components of the backward masking and frequency salience tasks (not to scale). *Left:* A single 20 ms pure tone followed by a 300 ms bandpass noise masker. Both are ramped in amplitude to prevent audible artifacts. *Right:* A succession of two tone-noise pairs as used in the frequency salience task. The ISI between each tone and the ensuing noise is the same for the two pairs.

Measuring the detection threshold for brief backward masked pure tones (henceforth termed "backward masking") closely followed the method of Wright et al. (1997), with the addition of a set of training sessions preceding actual testing (threshold estimation) sessions. In each trial, two bandpass (600-1400 Hz) approximately 60 dB SPL 300 ms long noise bursts were presented, 750 ms apart, one of which was immediately preceded (0 ms ISI) by a 20 ms 1 kHz pure tone (2.5 ms sine-squared ramped on each side) of adaptively varying amplitude (see Figure 2, left). Each noise burst coincided with the "lighting up" of a brightly colored cup in a magician's hand on the screen (see Figure 1)—this way there was a spatial and a primary visual (color) correlate of temporal order to ensure that children would not have to remember the order of the stimuli but only to click with the mouse on the cup under which the tone occurred, thus removing a possible confound of order memory with detection performance. Each correct response was visually rewarded (with a ball being uncovered under the chosen cup, a friendly wink, and a score indicator advancing. Training to the task included recorded verbal instructions at the beginning of the game along with a visual demonstration, as well as preliminary threshold estimation sessions first without any masking noise and then with a 230 ms ISI between tone and masker. Finally, the desired detection threshold at 0 ms ISI was estimated three times. The mean of the latter two measurements is referred below as the "backward masking threshold" unless otherwise specified.

The frequency discrimination threshold was measured for 250 ms long pure tone pairs at approximately 70 dB SPL separated by 750 ms, with frequencies in the range of 600-1400 Hz. The two tones were of the same frequency in 40% of the trials (and not 50% in order to reduce the total number of trials) and differed by an adaptively varying amount in the remaining trials. The child was to indicate whether the two tones were the same or different by clicking on ("pulling") one of two levers to let two colored balls roll down to be collected (in the case of a correct response) or lost (in the case of an incorrect response; see Figure 1, right). There was no training to this task; however, it was used as training for the more difficult task of backward masked frequency discrimination which followed. Two threshold estimation sessions were administered to each child, referred to below individually as first and second measurement.

In addition to the two simple tasks, it was desirable to obtain a measure of a "combination task," in which backward masking was applied in a recognition context, i.e., where it was requred that two masked brief tones not be merely detected, but actively compared to each other on the basis of their frequency. This task, termed "frequency salience," resembled the frequency discrimination task in that the frequencies of two tones had to be compared, in the graphical interface, and in the proportion of trials in which the two tones were identical (40%). It resembled the tone detection task in the duration of tones and masker noise and in the spectral content of the masker noise. It was unique in that the frequency of each tone was either 900 Hz and 1100 Hz and the adaptively varying parameter was the ISI between each tone and the ensuing noise masker. In sum, in each trial two brief (20 ms) tones were presented at approximately 70 dB SPL, each of a frequency either 900 Hz or 1100 Hz and followed by a bandpass (600-1400 Hz) 300 ms long 60 dB SPL noise masker at an adaptively varied ISI (see Figure 2, right). Two threshold estimation sessions were administered to each child, referred to below individually as first and second measurement.

Results

CELF-3 receptive language quotients ranged between 75 and 143 (mean 110 ± 16) and reading standard scores ranged as follows: For Word Identification, between 93 and 175 (mean 127 ± 19); for Word Attack, between 95 and 148 (mean 121 ± 11); for Passage Comprehension between 89 and 143 (mean 116 ± 12); and for Spelling between 90 and 155 (mean 123 ± 17). Hence it is evident that the children tested were in general in the high average range or better with respect to their reading and language skills.

Valid psychoacoustic thresholds were obtained from the majority of children, and more for the backward masking task than for the frequency discrimination and frequency salience tasks (Table 1). After excluding sessions with an insufficient number of reversals or with "at-floor" performance, threshold validity was further determined as follows: for the backward masking measurements by visually examining the plotted progression of the adaptively varying parameter and excluding sessions lacking evidence for convergence (i.e., widely distant reversals or an upward sloping trend in the last few reversals). For the frequency discrimination and frequency salience measurements, an objective criterion of at least 75% correct responses to "same" trials (i.e., trials in which the two tones were of the same frequency) was adopted instead of the subjective visual examination (resulting, nevertheless, in the same sessions being rejected). The relatively small percentage of children with valid frequency salience thresholds indicates the difficulty of the task, as most of the excluded data points were because of poor performance resulting in a "floor" threshold estimation, i.e., an ISI of 500 ms, or in a low percentage of "same" trails correctly responded to (or both).

Table 1
Valid (V), invalid (I), and total (T) number of thresholds obtained in each age group for each psychoacoustic measure. BM230: Backward masked pure tone detection with a 230 ms ISI between the tone to be detected and the ensuing noise masker (used in the training part of the backward masking sequence). BM0: Backward masked pure tone detection with a 0 ms ISI; three successive measures were taken, numbered here 1 (considered "training" to the task), 2, and 3. FRDIS: Frequency discrimination of 250 ms long pure tones, two measurements (1 and 2). FRS: Frequency salience (ISI required for frequency discrimination of backward masked brief pure tones), two measurements (1 and 2). See text for criteria determining threshold validity.

	Age group																				
	<6			6-7			7-8			8-9			9-10			>10			Total		
Measure	V	I	T	V	I	T	V	I	T	V	I	T	V	I	T	V	I	T	V	I	T
BM230	4	3	7	9	2	11	17	1	18	4	1	5	4	0	4	7	0	7	45	7	52
BM0.1	5	2	7	10	1	11	15	3	18	5	0	5	4	0	4	7	0	7	46	6	52
BM0.2	4	3	7	10	1	11	17	1	18	5	0	5	2	1	3	6	1	7	44	7	51
BM0.3	5	2	7	11	0	11	17	1	18	4	1	5	3	0	3	7	0	7	47	4	51
FRDIS1	5	2	7	9	2	11	13	2	15	5	0	5	3	0	3	7	0	7	42	6	48
FRDIS2	6	1	7	8	3	11	13	1	14	4	1	5	3	0	3	7	0	7	41	6	47
FRS1	4	3	7	5	6	11	7	7	14	3	2	5	3	0	3	6	1	7	28	19	47
FRS2	6	1	7	5	6	11	7	7	14	3	1	4	3	0	3	5	2	7	30	16	46

Threshold validity (i.e., number of cases with valid vs. invalid thresholds) did not vary significantly with age for any of the three tasks (by χ^2 tests separately for each measure). In the following analyses only the valid thresholds are taken into account. The term "correlation" refers to Pearson's r coefficient of correlation.

Table 2 shows the correlations between the psychoacoustic thresholds and age for all measures. Backward masking thresholds were not significantly correlated with age, except for the first measurement at 0 ms ISI, and did not vary significantly ($F<1$) in one-way ANOVA by age groups. Frequency discrimination and frequency salience, however, were significantly correlated with age and approached (frequency discrimination) or reached (frequency salience) significance when compared via one-way analysis of variance across age groups.

Table 2
Relation of the psychoacoustic measures to age: (a) correlation coefficients (and corresponding levels of significance) between the psychoacoustic measures and the age of the subjects in years; (b) one-way analyses of variance (and levels of significance) of psychoacoustic measures across the six age groups (as shown in Table 1). See caption of Table 1 for an explanation of the measure abbreviations.

	Correlation		ANOVA	
Measure	r	p	F	p
BM230	−.23	.14	0.67	.65
BM0.1	−.42	.004	4.02	.005
BM0.2	−.17	.29	0.30	.91
BM0.3	−.13	.38	0.66	.66
FRDIS1	−.35	.025	2.14	.08
FRDIS2	−.37	.018	2.29	.07
FRS1	−.60	.001	3.46	.02
FRS2	−.69	<.0005	5.70	.002

As seen in table 3, language scores were correlated with backward masking but not with frequency discrimination. Specifically, backward masking thresholds were significantly correlated with the raw scores on the CELF-3 subscales Concepts and Directions and Word Classes, with the standard scores on the CELF-3 subscales Concepts and Directions and Sentence Structure, and with the CELF-3 Receptive Language Quotient. Frequency discrimination thresholds were not significantly negatively correlated with any CELF-3 scores (the positive correlation with Sentence Structure raw score is discussed later). Frequency salience thresholds, however, were significantly correlated with the raw scores, before controlling for the effect of age, on the CELF-3 subscales Concepts and Directions and Word Classes ($r=-0.55$, $p=0.02$, and $r=-0.50$, $p=0.03$, respectively; not shown in the table), in the same pattern as the backward masking thresholds. It is possible that this reflects the backward masking component on frequncy discrimination in this task (frequency salience) but a stronger interpretation is not at present possible because performance on frequency salience is age-dependent (whereas on backward masking is not, at least in this population) and the correlations between frequency salience and the corresponding age-partialled CELF-3 scores were not statistically significant (see Table 3).

The correlation coefficients between reading scores and psychoacoustic measures are shown in Table 4. Backward masking was correlated with Word Identification scores, both raw (controlling for age) and standard. Frequency salience thresholds were significantly correlated with the raw scores in all three Woodcock Reading Mastery scales before partialling out the effect of age (Word Identification: $r=-0.67$, $p=0.002$; Word Attack: $r=-0.51$, $p=0.030$; Passage Comprehension: $r=-0.55$, $p=0.02$; Spelling: $r=-0.63$, $p=0.005$) but only with Word Identification after controlling for age.

Frequency salience was also significantly *positively* correlated with Passage Comprehension standard scores, as was frequency discrimination with Word Attack standard scores

Table 3
Correlation coefficients between psychoacoustic measures and language scores from the CELF-3. Correlations with raw scores are partial, controlling for age. Psychoacoustic measures: *BM230: Backward masked pure tone detection with a 230 ms ISI between tone and masker. BM0: Backward masked pure tone detection with 0 ms ISI, mean of second and third threshold. FRDIS: Frequency discrimination of 250 ms tones, mean of two thresholds. FRS: Frequency salience, mean of two thresholds.* CELF-3 scores: *SS: Sentence structure; C&D: Concepts and directions; WC: Word classes; SR: Semantic relationships; RLQ: Receptive language quotient.*

	With Raw Scores				With Standard Scores				
Measure	SS	C&D	WC	SR	SS	C&D	WC	SR	RLQ
BM230	−.17	−.37*	−.29	.73*	−.34	−.37*	−.18	.45	−.28
BM0	−.22	−.47**	−.36*	.09	−.35*	−.48**	−.29	.12	−.42**
FRDIS	.72**	−.03	−.11	.33	−.01	−.23	.04	.35	−.07
FRS	.26	−.32	−.27	.58	−.27	−.31	.12	.35	−.13

* $p < 0.05$; ** $p < 0.01$;

Table 4
Correlation coefficients between psychoacoustic measures and reading scores from the Woodcock Reading Mastery Test – Revised (WRM) and the Wide Range Achievement Test 3 (WRAT). Correlations with raw scores are partial, controlling for age. Psychoacoustic measures: *BM230: Backward masked pure tone detection with a 230 ms ISI between tone and masker. BM0: Backward masked pure tone detection with 0 ms ISI, mean of second and third threshold. FRDIS: Frequency discrimination of 250 ms tones, mean of two thresholds. FRS: Frequency salience, mean of two thresholds.* Reading scores: *WI: Word Identification; WA: Word Attack; PC: Passage Comprehension (from the WRM). Sp: Spelling (from the WRAT).*

	With Raw Scores				With Standard Scores			
Measure	WI	WA	PC	Sp	WI	WA	PC	Sp
BM230	−.15	−.08	−.18	−.07	.18	.11	.07	.02
BM0	−.30	−.19	−.37*	−.28	−.26	−.10	−.33*	−.28
FRDIS	−.00	−.20	−.06	−.02	.25	.32*	.00	.14
FRS	−.49*	−.30	−.26	−.44	.43	.34	.45*	.12

* $p < 0.05$; ** $p < 0.01$;

and with CELF-3 Sentence Structure raw scores (controlling for age). That is, children with higher reading (or language) scores performed worse (obtained higher thresholds) in frequency discrimination. This is a spurious result, explained by the *decreasing* trend in standard scores with age for our population, in conjunction with the age-dependency of the frequency discrimination and frequency salience tasks. For example, the correlation of age with Passage Comprehension standard score is −0.58, with Word Attack standard score −0.51, and with Sentence Structure standard score −0.52 (all $p < 0.0005$). In other words, these spurious correlations indicate simply that the younger children in the sample tested were on average more advanced in their language and reading skills relative to the general population than were the older children, perhaps due to early intensive educational programs, and should not be interpreted as indicating meaningful population trends with respect to the relationship between acoustic processing and language.

Discussion and Conclusion

Psychoacoustic performance in temporal integration and, to a much lesser extent, in spectral resolution has been found to be significantly correlated to reading and language measures in children with normally (average or better) developing language and reading skills. This finding strengthens the hypothesis that deficits in auditory perception may be causally related to language and reading impairments without denying that other factors, not directly related to acoustic processing, may also be involved in the development of linguistic skills. One potentially very important factor, in particular, that has not been taken into account in the present study is general mental ability, or intelligence. Although the relationship between indices of intelligence and language and reading skills is a complicated one and the time course of this relationship still not understood (Naglieri, 1996; Shaywitz et al., 1995; Stanovich, 1994), it is important to disentangle, to the extent possible, the contributions of distinct causal factors to language and reading development and to failures thereof.

It must be noted that the task found to correlate best with language and reading scores was tone detection under backward masking, which is known to be difficult for SLI children (Wright et al., 1997) and has not been found to correlate with nonverbal intelligence in adults (Raz, Willerman, & Yama, 1987), in contrast to frequency discrimination, backward recognition masking, and stimulus sequencing, which have been associated with “general mental speed” or “cognitive ability” (i.e., IQ scores; Deary, 1994; Raz & Willerman, 1985; Raz et al., 1987; Vickers, Pietsch, & Hemingway, 1995; Watson, 1991) It is concluded that the relationships between psychoacoustic performance, intelligence, reading, and language merit further investigation in normal as well as in impaired populations in order to understand more fully normal development as well as to identify and possibly ameliorate as early as possible the primary deficits underlying language and reading impairments.

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