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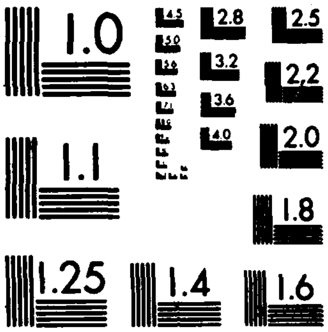
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Final Report for "Levels of Analysis of Complex Auditory Stimuli"

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Summary

The two-year project (AFOSR 84-0324) called for work in several areas of complex auditory pattern perception. Our first annual report summarized research in two of these areas. This report summarizes our efforts in four other areas. The most detailed section of this report covers work on the perception of normal and whispered speech. Using the selective adaptation paradigm, this study examined the representation of stops (/b/) and continuants (/w/). The results supported the existence of a simple acoustic, peripheral level of representation, and a complex acoustic, central level of representation.

Three other lines of research are briefly summarized in this report. First, several experiments tested the putative role of the syllable in the disruption of perception under conditions of signal ear-alternation. No support was found for the syllable playing a role in this effect. Moreover, a similar effect was found for instrumental melodies presented with ear-alternation, suggesting that the effect is a general property of complex auditory pattern perception.

The second brief report covers work on timbre perception. A "trumpet" - "cello" continuum of tokens was synthesized, and used in various speech perception paradigms. The results for these nonlinguistic stimuli were similar to those for speech, suggesting common mechanisms.

The final brief summary reports work on the perceptual restoration of musical

notes. Those experiments were designed to explore possible commonalities in the use of expectations in the perception of complex auditory patterns. The data suggest that music perception does make use of expectations, and that aspects of such perception are analagous to the use of lexical and sentential information in speech.

Introduction

This is the final report of a two-year project entitled "Levels of Analysis of Complex Auditory Stimuli" (AFOSR 84-0324). The project proposal had a stated goal of clarifying the perceptual processing of complex acoustic stimuli, especially speech and music. We believe that through our efforts over the last two years, we have made substantial progress in achieving this goal.

Quantitatively, one can assess the project in terms of the research effort proposed, and the research accomplished. The project proposal included seven studies, with a total of 17 experiments for the two year period. We have collected and analysed data for approximately twenty experiments, from six of the seven studies; another investigator has run a study very much like the seventh proposed one, and reported results in accord with the proposal's prediction.

Our first annual report included a set of experiments (based on two of the studies in the proposal) that were completed during the first 12-month period. That research was reported at the November, 1985 Psychonomic Society meeting, and appeared in the October 1986 issue of <u>Cognitive Psychology</u>. Subsequent research that we have conducted has been, and will be, presented at several professional meetings. One study (on the possible perceptual role of the syllable) was presented at the November 1986 Psychonomic Society meeting. Two other studies (on music restoration, and on musical timbre) were presented at the December 1986 meeting of the Acoustical Society. Our most recently conducted work, on whispered speech, will be presented at the November 1987 meeting of the Acoustical Society, and is being submitted for publication in the Journal of Experimental Psychology: Human Perception and Performance.

As should be clear from the papers and talks generated, we have collected data and found interesting results in several domains. To keep this report manageable, only the work on whispered speech will be reported in detail. Brief summaries of work on the role of the syllable, music restoration, and timbre perception will be included in this report, with detailed writeups to follow (in the first progress report for our current grant, AFOSR 86-0357).

I. Central and peripheral representation of whispered and voiced speech

A basic goal of research on speech perception is to specify the various types of representations of the speech signal, beginning with the vibration pattern on the basilar membrane, and culminating in the understood meaning. Various intermediate levels of analysis have been suggested, such as phones, phonemes, demisyllables, and syllables. The analyses of possible intermediate representations focus on how "encoded" the stimulus is at any point, with greater encoding indicating that the representation is further removed from its initial acoustic form.

A growing body of evidence has emerged that supports the existence of at least two distinct levels of analysis in the early processing of speech. In recent years, investigators have repeatedly invoked a distinction between acoustic and phonetic representations (e.g., Fujisaki and Kawashima, 1969; Pisoni, 1973; Sawusch, 1977). This distinction, however, is by no means uncontroversial: Some researchers regard the acoustic representation as unimportant in speech processing (Liberman, Isenberg, and Rakerd, 1980), while others would dispense with the phonetic (Bailey, 1975; Klatt, 1980a). Additional controversies center on the nature of these representations. For example, Samuel and Newport (1979) argued that the two-level model was correct, but that the levels are better thought of as simple and complex acoustic representations, rather than acoustic and phonetic. Work by Sawusch (1977), and Samuel (1986), among others, suggests that the simpler acoustic representation may be more peripheral, while the more abstract representation may be more central. Samuel (1986) has reviewed much of the literature supporting the distinction between two levels of analysis, and noted the convergence of several theories in this regard (e.g., Eimas and Miller, 1978; Samuel and Newport, 1979; Sawusch, 1977, 1986; Simon and Studdert-Kennedy, 1978; also see Jamieson and Cheesman, 1986).

The present study is intended to explore some of the properties of the two perceptual processing levels postulated on the basis of the research cited above. Samuel and Newport (1979) argued that at these levels, the overall spectral quality of the input (i.e., whether it is primarily noisy or primarily periodic) is an important determinant of its perceptual processing. This claim was based on the results of three selective adaptation experiments. The experiments indicated that if an adaptor and test series differed in spectral quality, labeling shifts did not occur. If spectral quality matched, adaptation effects on speech continua occurred even when the adaptors were nonspeech, and even if there was no spectral overlap of adaptors and test items. Further research by Kat and Samuel (1984) replicated these findings, and demonstrated that the mere presence of a periodic component (voicing) does not matter if there is sufficient aperiodic energy as well.

The present study consists of two experiments that focus on the role of periodicity, and on its representation at peripheral and central levels. These experiments are designed to determine whether the importance of a phoneme's overall spectral quality derives from its psychological representation, or directly from the acoustics of the stimulus. The approach involves using test continua that are either whispered or produced normally, and periodic and noisy adaptors. Consider, for example, a /ba-wa/ test series. Samuel and Newport (1979) found that a periodic nonspeech adaptor changed labeling of this series, and that an aperiodic one did not. A central question addressed in the present study is whether a whispered /ba-wa/ continuum (that is acoustically primarily aperiodic) shows the same pattern. If so, it would indicate that it is the long-term psychological representation of a speech sound that matters, rather than the particular instantiation of the moment. If instead the pattern reverses, with aperiodic adaptors now producing an effect, the labeling shifts would be interpreted as reflecting the encoding of the particular instance. The results should clarify whether the level of processing that is being tapped in demonstrations of the importance of spectral quality is relatively superficial, or if it reflects more fundamental properties of speech perception.

EXPERIMENT 1

Experiment 1 examined the effects of four classes of adapting sounds on the perception of two classes of speech sounds. The latter were (1) a normally-voiced synthetic /ba-wa/ continuum, and (2) a whispered version of the /ba-wa/ continuum, differing from the normal /ba-wa/ series in the energy source (voicing vs aspiration). The four classes of adaptors include periodic speech (/ba/, /wa/) and nonspeech (the "pluck" and "bow" tones used in previous research), and aperiodic counterparts (speech: whispered /ba/ and /wa/; nonspeech: the "abrupt" and "gradual" noises used by Samuel and Newport, 1979, and Kat and Samuel, 1984.

Method

Stimuli

The test items: Two speech continua were constructed with the Klatt cascade/parallel synthesizer (Klatt, 1980b), using the cascade branch of the synthesizer. An eight-step /ba/-/wa/ continuum was generated that varied in rate and duration of the formant transitions. The voiced series was energized by the normal voicing source (AV). The /ba/ endpoint had short, rapid formant transitions: F1, F2, and F3 all reached their steady-state values in 20 ms. The starting frequency for F1 was 297 Hz, for F2 it was 759 Hz, and for F3 it was 2028 Hz. The final values for these three formants were 739, 1267, and 2439 Hz. The onset value for AV was 52 dB, and it reached its full level of 60 dB in 20 ms. The endpoint /wa/ differed from /ba/ in the rate and duration of the formant transitions, and in rise time. The transitions and rise time were 55 msec for this token; all other parameter values were as in the /ba/ stimulus. Six intermediate stimuli were constructed using linear interpolation of the transition duration in five ms steps.

An analagous whispered /ba/-/wa/ series was constructed with identical parameter values other than a switch in the energy source. Rather than exciting the formants with the periodic voicing source, the aperiodic aspiration source (AH) was used. The eight whispered tokens were digitally reduced in amplitude in order to match their perceived loudness to the voiced stimuli.

All stimuli were 300 ms, and all decayed to silence during the last 100 ms. The fundamental frequency for the voiced stimuli was 122 Hz for the first 100 ms of each stimulus, and dropped linearly over the last 200 ms to 90 Hz.

The adaptors. Eight stimuli served as adaptors. Four speech adaptors were used, the /ba/ and /wa/ endpoints of the normal and whispered test series. The remaining four adaptors were the periodic "pluck" and "bow", and the aperiodic "abrupt" noise and "gradual" noise stimuli used by Samuel and Newport (1979) and Kat and Samuel (1984). The pluck and bow are sawtooth wave stimuli with a 440 Hz fundamental; the abrupt and gradual are white noise segments. The particular versions used in this study were 350 ms, approximately matched to the duration of the speech adaptors. The pluck and abrupt stimuli had nominal rise times of 0 ms (with actual times less than 4 ms); the bow and gradual adaptors had rise times of approximately 80 ms. All adaptors gradually decayed to silence.

Procedure

Subjects participated in eight one-hour sessions, with sessions separated by at least 24 hours. Each session included a baseline identification test, and an adaptation test. On both tests, subjects heard the normal and whispered /ba/-/wa/ stimuli, and identified each token as either "B" or "W", using labeled response buttons. The identification test consisted of 18 randomizations of the 16 syllables (eight normal and eight whispered). The first three randomizations were practice, and were not scored. The adaptation test included 15 randomizations of the test items, with an adaptation sequence preceding the labeling of blocks of eight identification stimuli. More specifically, subjects initially heard 45 repetitions (30 sec) of an adaptor, followed by eight randomized syllables to identify, followed by another 45 adaptor repetitions, followed by eight more syllables, etc. There was an additional minute (90 repetitions) of adaptation at the beginning of the adaptation test.

Adaptors were presented at a rate of 1.5 repetitions per second, and subjects were allowed up to 4.5 seconds to respond to each identification stimulus. They were encouraged to respond accurately and quickly. When all subjects had responded, or 4.5 seconds had elapsed, the next stimulus was presented after a one second wait.

Subjects were run in groups of three; four such groups were run. Two latin squares were used to counterbalance the order of adaptation conditions. For the first four sessions (involving speech adaptors), the latin square revolved around the order /ba/, whispered /wa/, /wa/, and whispered /ba/. In the final four sessions (involving nonspeech adaptors), the latin square revolved around the order pluck, gradual, bow, and abrupt.

Subjects

Twelve paid subjects participated in the eight sessions. All were native English speakers with no known hearing problems. One of the subjects failed to label the syllables consistently, and was not included in any of the analyses to be reported.

Results and Discussion

Insert Figure 1 About Here

Insert Figure 2 About Here

Insert Table 1 About Here

For each subject, the average percentage of "B" responses was calculated for each test stimulus, both on the baseline and adaptation tests. The group labeling functions for the voiced adaptors are shown in Figure 1; comparable data for the whispered adaptors are shown in Figure 2. For statistical tests of adaptation effects, a boundary shift measure was calculated by subtracting average "B" report after adaptation from such report before adaptation; only test items near the phoneme boundary (items 3-6) were used in these calculations. Using this measure, Table 1 presents the mean adaptation shifts for all of the conditions of Experiment 1. The Table also indicates which shifts were significant by two-tailed t-tests.

Not surprisingly, speech adaptors were all reliably effective when paired with the continua from which they were drawn. Three of the four cross-series adaptation conditions (whispered adaptor on voiced continuum or vice-versa) also yielded significant shifts. The exception was the non-effect of a whispered /ba/ adaptor with voiced test items. This failure of adaptation probably reflects two factors. First, the voiced test series was perceptually less labile than the whispered continuum - shifts were generally smaller. Second, there is apparently a substantial asymmetry in the efficacy of /ba/ and /wa/ as adaptors. Across voiced and whispered stimuli, the average shift of 11.6% for /ba/ adaptors was only 36% as large as the 32.1% average for /wa/. This asymmetry is evident in all four comparisons of /ba/ and /wa/ formed by the crossing of periodicity of adaptor and test series.

Insert Figure 3 About Here

Insert Figure 4 About Here

The results for the nonspeech adaptation conditions are shown in Figures 3 and 4, and summarized in Table 1. A central question addressed in Experiment 1 involves the effect (or non-effect) of the pluck adaptor. Recall that previous research had found that an adaptor similar to the one used here significantly reduced /ba/ report (Diehl, 1976; Samuel and Newport, 1979). For the voiced test items, the 3% effect found in Experiment 1 is comparable to shifts found in earlier research, but did not reach significance. Fortunately, the critical prediction of this study involved the effect of the pluck adaptor on the whispered /ba/-/wa/ syllables: Does the periodic nonspeech sound work at a straightforward acoustic level, or is the effect on a more abstract representation? The significant reduction of /ba/ report indicates that the effect is on a more abstract representation, since the periodic pluck shares features with the underlying (voiced) representation of the whispered /ba/, but not with its aperiodic surface realization. The larger effect on the whispered stimuli than on the voiced ones presumably is another reflection of the greater lability of the whispered syllables.

The results for the other nonspeech adaptors were, as expected, small and nonsignificant. In previous research, (Samuel and Newport, 1979), the bow, abrupt and gradual adaptors had been ineffective on a voiced /ba-wa/ test series; the present results replicate this. The results for the whispered stimuli were also nonsignificant, although there were trends in the appropriate direction for the two aperiodic adaptors. These trends could reflect the operation of low-level acoustic adaptation, given the shared aperiodicity and onset characteristics of the adaptors and whispered test syllables.

In sum, Experiment 1 yielded two very interesting results. First and foremost, the efficacy of the pluck adaptor on the whispered /ba-wa/ stimuli demonstrates that the effect is occuring at an abstract level of representation. Second, there is a marked asymmetry in the effects of adaptation with /ba/ and with

/wa/: The effects for /ba/ are much smaller than those for /wa/, and they appear to more sensitive to matching the adaptor and test series. Experiment 2 provides a test of the replicability of the first point, and examines whether the second can be traced to differences in the central and peripheral representations of /ba/ and /wa/.

EXPERIMENT 2

The success of the periodic nonspeech adaptor in changing the identification of whispered /ba/--/wa/ syllables demonstrates that such shifts can occur in the absence of substantial spectral similarity. Recall that this effect was predicted on the assumption that /b/ and /w/ are underlyingly periodic, and that it is at this more abstract level that the pluck is causing labeling shifts. In terms of the two-level model discussed in the Introduction, these effects would be traced to the complex acoustic, or central, level. The fact that the adaptor was nonlinguistic indicates that this level is not speech-specific.

A number of investigators have compared ipsilateral and contralateral presentation of adaptors and test items to separate peripheral from central effects (e.g., Ades, 1974; Eimas, Cooper, and Corbit, 1973; Ganong, 1978; Jamieson and Cheesman, 1986; Ohde, 1982; Samuel, 1986; Sawusch, 1977). The rationale for this manipulation is that central effects are assumed to occur at a level beyond the point at which information from the two ears is combined. As such, adaptation effects found under contralateral testing conditions are inferred to reflect central processing. In contrast, effects under ipsilateral conditions should be due to both central and peripheral mechanisms (assuming the existence of both). The prediction for the pluck adaptor in this paradigm should be clear: If the effect observed in Experiment 1 really is due to central mechanisms, contralateral testing should be equivalent to ipsilateral testing. Moreover, because the adaptation is hypothesized to occur at an abstract level, the effect should be no different for whispered and normal /ba/--/wa/ test items.

This same-ear versus different-ear methodology can also be profitably applied to an analysis of possible differences in the representation of voiced stops and continuants. The relatively large shifts found with /w/ adaptation could reflect effects at both central and peripheral levels of representation. The smaller shifts found for the /b/ conditions might be due to the absence of an effect at one of these levels. The /b/-like effect for the pluck adaptor, just postulated to be centrally mediated, suggests that an adaptable central representation for /b/ is called for. On the other hand, Jamieson and Cheesman (1986) have recently argued that the peripheral level is the primary locus for adaptation of voiced stops. Experiment 2 uses the same-ear/cross-ear methodology, along with the nonspeech adaptor and voiced/whispered stimulus distinction, to try to clarify the representation of stops and continuants.

Method

Stimuli

The same two test series (voiced /ba/--/wa/ and whispered /ba/--/wa/) that were used in Experiment 1 were used in Experiment 2. Five adaptors were used: the endpoints of each test series, and the nonspeech pluck.

Procedure

Subjects participated in ten one-hour sessions of the same form used in Experiment 1. Four groups of subjects were run. For two of these groups, the order of adaptors over the first five days was /ba/, /wa/, pluck, whispered /ba/, and whispered /wa/; this order was reversed for the last five sessions. For one of these groups, the test items and adaptors were presented ipsilaterally for the first five sessions, and contralaterally for the last five. For the second group, the five ipsilateral conditions followed the five contralateral ones. The remaining two groups followed a similar counterbalancing procedure. Their first five sessions followed the adaptor order whispered /wa/, whispered /ba/, pluck, /wa/, and /ba/. Test items were presented to the left ear for subjects in the first two groups, and to the right ear for the other two..

Subjects

Twelve subjects from the same population as those in Experiment 1 participated in Experiment 2. One subject's data were not included in the analysis due to his failure to label the syllables consistently, and another subject's data were lost due to computer error.

Results and Discussion

As in Experiment 1, for all subjects the percentage of stimuli labeled "B" was calculated for each token in each condition. As before, the measure of adaptation is the difference in proportion of stimuli labeled "B" before and after adaptation using the center four items of the eight-item continuum. Separate analyses of variance were conducted on these scores for the pluck adaptation conditions, the /wa/ adaptation conditions, and the /ba/ adaptation conditions.

Insert Figure 5 About Here

Insert Table 2 About Here

The results for the pluck adaptor are illustrated in Figure 5. A two-factor analysis of variance was conducted on the pluck data, examining the effects of laterality (ipsilateral versus contralateral adaptation) and test continuum periodicity (voiced versus whispered). Collapsing across these factors, the grand mean shift was 7.7%, $F(1,9) = 7.59$, $p<.03$. As Figure 5 shows, there were no notable effects of laterality or periodicity (both $F<1$); there was also no interaction of these factors, $F(1,9) = 1.00$, n.s. Thus, the results nicely replicate those of Experiment 1, and confirm the abstract nature of the affected representation: A central representation that is relatively insensitive to the acoustic details of a stimulus (e.g., its periodicity) would produce exactly this pattern of results.

Insert Figure 6 About Here

Insert Figure 7 About Here

The results for the /wa/ adaptors also paint a consistent picture. These data were examined with a three-way analysis of variance, testing the effects of adaptor periodicity (voiced /wa/ versus whispered /wa/), continuum periodicity (voiced versus whispered test items), and laterality (ipsilateral versus contralateral adaptation). As is clear in Figures 6 and 7, the continuants produced large labeling shifts; the mean change of 24.1% was quite reliable, F(1,9) = 141.44, p<.001. There was no main effect of periodicity, either of test series (F<1), or of adaptor, F(1,9) = 1.32, n.s. There was, however, a robust effect of laterality: Same-ear adaptation produced shifts twice as large as those caused by cross-ear adaptation, F(1,9) = 58.44, p<.001. By the logic of the laterality manipulation, this difference indicates a roughly equal mix of central and peripheral effects for continuants.

None of the two-way interactions approached significance, with all F's < 1. However, the three-way interaction was reliable, F(1,9) = 9.27, p<.02. The basis for this interaction is apparent both in theory and in Table 2: Matching the periodicity of adaptor and test series (a two-way interaction) makes a difference with ipsilateral adaptation, but is irrelevant in the contralateral case. Recall that contralateral testing is assumed to tap central, abstract representations. Such representations should be relatively insensitive to acoustic details, such as whether a /wa/ was voiced or whispered. Ipsilateral testing, in contrast, is assumed to include a peripheral component that Samuel and Newport (1979) likened to a "neural spectrogram". Therefore, under ipsilateral conditions, acoustically matching adaptor and test items should make a difference, and it does.

Insert Figure 8 About Here

Insert Figure 9 About Here

The results for the /ba/ adaptation conditions are shown in Figures 8 and 9. Although the overall shift of 8.6% was quite reliable ($F(1,9) = 24.60$, $p<.001$), the pattern of results was rather odd in some respects. The data were analyzed with the same three factors used for the /wa/ conditions. As in all of the other analyses, there was no effect of test series periodicity, $F<1$. There was a noticeable but nonsignificant trend for the whispered adaptor to be more effective than the voiced one, $F(1,9) = 3.34$, $p>.10$. The most bizarre aspect of the data was the significant effect of laterality, in the wrong direction; contralateral conditions actually yielded bigger shifts than ipsilateral, $F(1,9) = 5.76$, $p<.05$. Examination of Table 2 reveals that this was due to the total lack of an effect for both ipsilateral conditions of voiced /ba/, and a similarly small effect for one of the ipsilateral whispered /ba/ conditions.

This pattern led to significant interactions of adaptor periodicity with continuum periodicity ($F(1,9) = 9.68$, $p<.02$), and of laterality with continuum periodicity, $F(1,9) = 8.00$, $p<.02$. There was no three way interaction, $F(1,9) = 1.50$, n.s.

Given that no plausible theory could account for larger contralateral effects than ipsilateral ones, we hypothesized that the null ipsilateral effects were a fluke. To test this assumption, we re-ran the voiced /ba/ conditions with a new group of twelve subjects. These subjects were run under identical conditions to those in the main experiment, but for only two sessions. Ear of test items, and order of ipsilateral/contralateral conditions were counterbalenced over four groups of subjects.

Insert Figure 10 About Here

The results for the new subjects are shown in Figure 10, and are summarized in the bottom row of Table 2. As is clear in the Figure, the data are much more sensible than before, confirming the aberrant nature of the previous results. A two-factor analysis of variance was conducted on the data from the new subjects, examining the effects of laterality and test series periodicity. The overall shift of 14.6% was reliable, $F(1,10) = 13.41$, $p<.005$. Neither laterality ($F<1$) nor continuum periodicity ($F(1,10) = 1.77$, n.s.) had an effect, and their interaction did not reach significance, $F(1,10) = 2.62$, n.s. Individual tests of the four conditions shown in Figure 10 confirmed that all were significant (smallest $F(1,10) = 5.78$, $p < .04$).

General Discussion

Several issues have been addressed in the two experiments of the present study. These issues revolve around the levels of representation of voiced and whispered stops and continuants. At a general level, the pattern of results supports the simple intuition of native speakers that whispered speech is fundamentally similar to its voiced counterpart: Across all of the various manipulations used in the two experiments, the voiced and whispered stimuli behaved similarly. This result is less intuitive than it might at first appear if the gross differences in spectral compositon for voiced and whispered productions are considered.

The results of the present study suggest that the perceptual similarity of acoustically discrepant tokens may be mediated by an abstract level of representation. Recall that there is a converging body of evidence that supports the existence of two discernable levels of representation. In terms of this two-level theory, the similarity of voiced and whispered speech may be traced to the "complex acoustic", or central level (Samuel and Newport, 1979; Sawusch, 1977).

A critical piece of evidence for this claim is the significant adaptation effect of the pluck on the whispered /ba/-/wa/ continuum found in both experiments. Previous work (Diehl, 1976; Samuel and Newport, 1979) has shown that this nonspeech sound induces changes in identification of a normal (voiced) /ba/-/wa/ series. In addition, Samuel and Newport showed that the pluck was ineffective on an aperiodic /ča/-/ša/ continuum that, like /ba/-/wa/, varied in rise time. These and other results led to the conclusion that /b/ is represented as a periodic sound with an abrupt onset; the pluck matches these properties, and thereby acts like /b/ in the adaptation paradigm.

Within this context, the efficacy of the pluck on the whispered /ba/-wa/ series has three important implications. First, a whispered /b/, though acoustically aperiodic, is psychologically periodic; it really is a /b/. Second, the adapting effect of the pluck is occuring at this abstract level, rather than in the "neural spectrogram" of the simple acoustic level. These two conclusions follow from the reliable adaptation effect despite the acoustic mismatch of the pluck to the whispered speech. Finally, the complex acoustic level being affected cannot be speech-specific, or "phonetic", as it has often been called. This follows from the simple fact that the pluck is clearly a nonspeech sound,, yet it is affecting (and thus being processed by) this level of representation. These results converge with successful adaptation results that Samuel and Newport reported using a filtering manipulation to preempt acoustic overlap of nonspeech adaptor and speech syllables.

The results with the pluck adaptor in Experiment 2 provide further evidence for these conclusions. The adaptation effect using the pluck sound was unaffected by either the periodicity of the test items, or by the laterality manipulation. The equivalence of contralateral adaptation to ipsilateral adaptation provides strong support for the claim that these effects may be traced to a central, complex acoustic level of representation.

Insert Table 3 About Here

The pattern of adaptation effects found with the /b/ and /w/ adaptors also can be used to test the utility of distinguishing between simple acoustic and complex acoustic levels of representation. To examine this issue, it is helpful to organize the various conditions of Experiments 1 and 2 in terms of three factors: (1) whether the adaptor was a stop (/b/) or a continuant (/w/); (2) whether the adaptation would only affect central mechanisms (contralateral), or both central and peripheral (binaural/ipsilateral); and (3) whether the adaptor came from the same series as the test items (matched periodicity), or from the other series (mismatched periodicity). Table 3 summarizes the results of the two experiments in terms of these factors.

Consider first the pattern of adaptation as a function of laterality. In the contralateral conditions, neither the type of adaptor (stop versus continuant) nor the match/mismatch of adaptor and test series made any difference; the shifts only range from 13.3% to 17.4%. This pattern is consistent with the view that contralateral testing taps central mechanisms that are removed from the acoustic details, and that are comparable for stops and continuants. The pattern is quite different when adaptation is conducted under either binaural or ipsilateral monaural conditions. As the Table shows, these conditions show big effects of adaptor type -- /w/ adaptors average 32.1% shifts versus only 11.8% for adaptation with /b/. Similarly, within-series effects (26.4%) are noticeably bigger than between-series (17.5%). These differences support the view that these testing conditions tap an additional peripheral component that is sensitive to the acoustics -- the simple acoustic level. Moreover, the difference between /b/ and /w/ effects suggests that continuants have a more substantial peripheral representation, or at least one that is more susceptible to adaptation. This point will be considered further shortly.

Looking at Table 3 in terms of the type of adaptor, rather than in terms of laterality, leads to the same conclusions. For stops, laterality condition does not matter; contralateral effects (14.7%) were actually slightly larger than binaural/ipsilateral (11.8%). Again, this suggests that primarily central representations were affected, with little or no contribution of peripheral adaptation. The results for the continuants clearly contrast with those for the stops; binaural/ipsilateral effects (32.1%) were twice as large as contralateral ones (16.0%). As noted previously, continuants show roughly equal effects of adaptation at the simple acoustic (peripheral) and complex acoustic (central) level.

The conclusion that /b/ is primarily centrally represented is at odds with a recent study by Jamieson and Cheesman (1986). These investigators also used the same-ear/different-ear methodology, and found that voiced stops (on a voice onset time continuum) displayed weak cross-ear effects. As such, they concluded that voiced stops were represented primarily peripherally. The conflicting conclusions may be reconciled with two assumptions: (1) The Jamieson and Cheesman study underestimates a central component for /b/; (2) The present study underestimates a peripheral component for /b/.

Jamieson and Cheesman tested both /ba/-/pa/ and /da/-/ta/ continua, and found small but consistent effects with contralateral adaptation with the voiced tokens. Due to the details of their testing procedure, the data presented for /ba/-/pa/ cannot accurately be compared to the results of the present study. The /da/-/ta/ results are broken down in a way that makes this comparison possible, and these results include a reasonably robust, if not overwhelming, effect for contralateral /da/. Overall, the data suggest more of a central component than a simple gloss might suggest.

An important difference between the Jamieson and Cheesman study and the present one lies in the details of the speech synthesis. The /b/ in their study had 40 ms formant transitions, whereas the /b/ endpoint here had 20 ms transitions. These short transitions were used because transition duration and rise time are not independent in the Klatt (1980b) synthesizer, and a short rise time was needed in order to provide a test of the pluck adaptor. It is possible that the brevity of the transitions minimized the contribution of peripheral-level adaptation. If such adaptation depends on some function of stimulus energy, the short transitions would be relatively ineffective. This would lead to an underestimate of simple acoustic effects for /ba/. It could also contribute to the instability of adaptation effects found with /b/ in Experiment 2.

The possible role of stimulus energy in determining the size of peripherally-based adaptation has not been studied extensively, and deserves further study. This factor might help to account for variations in adaptor efficacy across voiced and voiceless adaptors (see Eimas, Cooper, and Corbit, 1973; Jamieson and Cheesman, 1986; Kat and Samuel, 1984).

The present study has used a combination of techniques to investigate the levels of representation of voiced and whispered stops and continuants. By combining nonspeech adaptors, variation of test continuum and adaptor periodicity, and laterality of adaptation, the two experiments have developed a cohesive description of two levels of representation. These results converge with a growing body of evidence supporting a distinction between simple acoustic and complex acoustic representations. In addition, the results provide data on the commonalities of whispered and normal speech. These commonalities arise at the complex acoustic level, following different (i.e, periodicity-specific) processing at the simple acoustic level. The techniques employed here appear to provide powerful tools for investigating the various representations of the speech signal as it goes from a vibration pattern on the basilar membrane to a linguistic structure.

II. A direct test of the syllable's perceptual role

In many models of speech perception, a sublexical level of processing beyond the two explored in the whispered speech research has been proposed -- the syllable. Several lines of research have supported the syllable's role in the chain of processing. First, Massaro (1972) presented listeners with speech stimuli followed by a masking sound, and found that recognition of the stimulus reached an asymptote with about 250 msec of processing. This time interval is of approximately syllabic size. Second, Savin and Bever (1970) found that subjects were faster to report the occurrence of a syllable target (e.g., "pon") than the occurrence of a phonemic one (e.g., "p") (but see Foss and Swinney, 1973). Third, in a developmental study, Liberman, Shankweiler, Fischer, and Carter (1974) found that children demonstrated metalinguistic access to the syllabic level before the phonemic one. Fourth, in the selective adaptation paradigm, Ades (1974) showed that adaptation effects do not occur if the adaptor and test items are mismatched in syllabic position (initial versus final); Samuel, Kat, and Tartter (1984) have extended this position-specificity to intervocalic consonants.

Probably the most widely cited study supporting the role of the syllable in speech perception is one by Huggins (1964). Huggins presented listeners with speech that alternated between the ears, and found that an ear-alternation rate of approximately four switches per second was maximally disruptive. Note that this rate corresponds to the time course found by Massaro, and would on average interrupt each syllable once. Interestingly, when Huggins increased the speech rate, the maximally disruptive switching rate increased correspondingly, suggesting once again that interrupting each syllable disrupts comprehension. The only problem in interpreting this otherwise excellent study is that the inference of a syllabic role is indirect: The switching was done at a regular rate, with no correlation to what the syllabic pattern actually was.

A more direct test of the syllable's role in this phenomenon was reported by Huggins (1967). This test involved presenting a passage with various ear-switching conditions that were directly related to the syllabic structure of the passage. In particular, Huggins compared performance when all syllables were disrupted to performance when none were disrupted, with alternation rate matched. This test actually found no effect of syllabic structure. Perhaps because this study was not as comprehensive and impressive as the Huggins (1964) study, this failure to support the syllable's role has disappeared from the literature.

The series of experiments we have conducted had three goals. First, we wished to replicate the basic effect of Huggins (1964). Second, we wished to test the syllable's role directly, using a set of materials substantial enough to be convincing whichever way the results turned out. Finally, assuming the syllable does not play a critical role, despite its wide citation, we decided to test whether the ear disruption effect is speech-specific, or is instead a general property of the perception of complex auditory signals.

The results of our work in this domain can be summarized succintly. First, the basic ear-alternation effect is reasonably robust: We had to degrade the passages slightly (by adding white noise) to bring our subjects' performance off the ceiling, but once that was done, we found a pattern over various alternation rates that was consistent with Huggins (1964); we also replicated the effect of playback rate.

Our direct test of the syllable's role, like that of Huggins (1967), involved presenting passages with equal average alternation rates, but with differing syllabic disruption (all, none, or random). Unlike Huggins (1967), we used a wide set of materials (twelve passages versus one), and two levels of overall difficulty. Simply put, there was absolutely no hint of a syllabic role, confirming Huggins (1967), and disconfirming the widely-cited conclusion of Huggins (1964).

Given the irrelevance of the syllable, we decided to test whether similar disruption occurs for other complex acoustic signals. We have run one large study testing recognition of familiar melodies. The data indicate that there seems to be a similar disruption of perception at about the same alternation rate as with speech. However, there was no corresponding effect of playback rate. We plan one more experiment, using a more sensitive technique to determine how similar the speech and music domains are with respect to the ear-alternation effect.

III. Perception of timbre: similar to speech?

In the two-level model explored in the whispered speech work, a critical result was the success of the nonspeech "pluck" in shifting listeners' identification of speech syllables. This result strongly reinforces Samuel and Newport's (1979) claim that the second, central, level of representation is best characterized as "complex acoustic", rather than "phonetic", since a phonetic level must by definition be speech specific. An implication of this analysis is that sounds in additon to speech should be represented at this level; recognition of complex acoustic patterns in general should be mediated by these representations.

If this is so, then we might expect to find nonspeech sounds that produce patterns of performance similar to those found for speech. In fact, a number of investigators have reported speech-like results for nonspeech stimuli in domains such as categorical perception (e.g. Burns and Ward, 1978; Miller, Wier, Pastore, Kelly, and Dooling, 1976). The experiments conducted in the present line of research were intended to provide a principled set of studies that examine a nonspeech domain across a range of phenomena typically studied for speech.

A nonspeech domain that seems to share many of the structural properties of speech is timbre. In particular, timbre is a multidimensional domain, and the families of instruments differentiated by timbre can be compared to the families of phonemes. Thus, just as there are high vowels and low vowels, or stops and fricatives, there are horns and strings, or percussion and woodwind. The research summarized in this section involved synthesizing a "horn"-"string" (actually "trumpet"-"cello") continuum, and using this continuum in various paradigms that have been extensively used in speech research. The goal is to see whether the patterns found for speech are found for stimuli varying in timbre.

We have collected data on the timbre continuum in four speech paradigms, and the results can be summarized as follows:

(1). Categorical perception: This phenomenon has been a hallmark of speech research. It is defined by the relationship between identification of stimuli, and their discrimination. In theory, categorical perception is present when subjects can discriminate stimuli only as well as they can identify them; discrimination can be predicted from identification. In practice, fully categorical perception is rarely, if ever, observed. However, some stimuli, notably stop consonants, show rather categorical results. Other consonants, and vowels, show moderate levels of categorical perception.

Our results for the timbre continuum are comparable to the moderate levels of categorical perception found with many speech sounds. Subjects produced clean identification functions ("horn" versus "string"), and the (ABX) discrimination functions had peaks at the category boundaries, with troughs within categories. The discrimination function predicted on the basis of identification paralleled the observed discrimination very nicely, but actual discrimination systematically exceeded the predicted. This indicates that subjects were using both categorical and noncategorical information.

(2). Selective adaptation: In our first annual reprot, we reviewed much of the literature and controversy regarding selective adaptation, and put forth a strong case for its utility. The results of this technique with the timbre stimuli were quite consistent with those for speech: Repeated presentation of the horn reduced horn report, and repeated presentation of the string reduced string report.

(3). Paired contrast: The annual report also reviewed the paired contrast paradigm, and its relationship to selective adaptation. It was argued there that despite claims to the contrary (e.g., Diehl, 1981), the two paradigms are dissociable. The results for the timbre stimuli support this contention: Despite the reliable adaptation effects just reported, no shifts in labeling were found in the paired contrast paradigm. A plausible, but as yet untested inference is that the observed adaptation effects in this domain are occurring at the simple acoustic level of representation (see Samuel, 1986 for a discussion of this analysis).

(4) Duplex perception: In "duplex perception" experiments (Rand, 1974), synthetic speech syllables are broken into two pieces, and the pieces are presented dichotically. One piece includes the second and/or third formant transition(s), and the other includes the rest of the syllable. Under these conditions, listeners report hearing the appropriate full syllable in the ear with the bulk of the syllable, and a nonspeech chirp in the other (e.g., Rand, 1974; Liberman, Isenberg, and Rakerd, 1980). This "duplex percept" of speech and nonspeech simultaneously has led a number of researchers to suggest that an "auditory" mode and a "speech mode" of perception are involved (Liberman, Isenberg, and Rakerd, 1980; Repp, Milburn, and Ashkenas, 1983).

The timbre stimuli provide a test of the position advanced by these theorists. If such stimuli can produce duplex perception, then an alternative model that does not invoke a "speech mode" is needed. At this point, we have generated a number of synthesis versions, and collected data on their perception. This work is still in progress. The data in hand are mixed — the timbre stimuli appear to produce the duplex percept, but the synthesis versions to date have not provided a very robust effect. We plan to pursue alternative synthesis versions, to see whether these nonspeech stimuli can produce a robust duplex effect.

IV. Music Restoration

A final line of research to be reported is an extension to the domain of music of the phonemic restoration effect (Warren, 1970). Warren replaced part of an utterance with a cough, and found that listeners could not detect the replacement; they appeared to have restored the missing speech. Samuel (1981) introduced a methodology for studying the illusion that has been used in the music restoration work. Stimulus items are constructed in pairs: a replacement item is comparable to Warren's stimuli — a portion of the waveform is replaced with an extraneous sound (white noise). An added item is constructed by adding the white noise to the same portion of the waveform that is replaced in the matching item. To the extent that listeners are perceptually restoring the missing sound in replacement items, they should sound like added items (intact with an extraneous noise). By using signal detection analyses, a bias-free measure of how much replacement items sound like intact ones is computed (d'), and is the measure of the perceptual strength of the effect; a bias parameter (Beta) is also computed that reflects postperceptual bias toward calling a stimulus intact.

The work on music restoration is the basis of a dissertation by Lucinda DeWitt. The only prior work on this phenomenon is essentially a pilot study by Sasaki (1980) that suggested that music might produce restoration. The goals of the research are to establish whether music restoration really works, and if so, to explore what factors affect the illusion. In addition, we are interested in the relationship of music restoration and phonemic restoration : Are similar patterns found, and is there reason to posit a unitary mechanism for speech and music restoration?

We have run a half dozen experiments in this domain, and several more are planned. The first experiment was a comparison of restoration in words, in melodies, and in a control condition. The word items were standard phonemic restoration stimuli like those used by Samuel (1981). The melodies were simple familiar tunes played on a piano. One note in each melody was either replaced by noise, or had noise added to it. The control condition was the added or replaced version of the critical note from each melody; subjects judged whether the item was a note plus noise, or just noise. The results indicated that (1) music restoration is real - there was more perceptual restoration in melodies than in control notes; and (2) phonemic restoration is a stronger effect than music restoration, at least under these testing conditions.

Several followup experiments have explored the role of listener knowledge / note predictability, using manipulations such as melody familiarity and priming. These experiments generally showed better discriminability of added from replaced stimuli with increasing listener knowledge, a result that is contrary to that found with words, but consistent with the results for sentential predictability (Samuel, 1981). Our latest experiments have looked for an analog to the lexical effects found with speech. We have recently tested scales, rather than melodies, and these stimuli appear to behave in the desired fashion. In particular, giving listeners a longer stretch of a scale (leading up to a note) seems to boost expectation of that note sufficiently to induce stronger perceptual restoration. We are currently working on chord stimuli to see if they exhibit similar word-like behavior. Overall, the work with music is providing interesting comparisons of the role of expectation in the perception of complex acoustic patterns.

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Table 1

Adaptor	Voiced Series	Whispered Series
voiced /ba/	-14.2*	-8.7*
voiced /wa/	+29.6*	+25.9*
whispered /ba/	-4.3	-19.1*
whispered /wa/	+33.2*	+39.5*
pluck	-3.0	-10.9*
bow	+1.6	-0.5
abrupt	-0.2	-5.6
gradual	+4.3	+4.4

Note: Values shown are the percentage changes in labeling the middle four items fo the eight-item continua. Means marked with an asterisk reflect shifts significant at the .05 level or beyond (critical value for $t(10) = 2.228$)

TABLE 2

	Ipsilateral		Contralateral	
	Voiced Series	Whispered Series	Voiced Series	Whispered Series
Adaptor				
pluck	-5.0	-8.2	-10.1	7.6
whispered /wa/	+25.2	+33.9	+17.1	+13.3
voiced /wa/	+39.9	+29.8	+15.8	+17.7
whispered /ba/	-0.5	-13.5	-16.0	-12.8
voiced /ba/ I	-0.7	0.9	-17.0	-9.6
voiced /ba/ II	-21.6	-12.2	-13.7	-16.2

Note: Values shown are the percentage changes in labeling the middle four items of the eight-item continuum.
The "voiced /ba/ I" data are from the original group of subjects, and the "voiced /ba/II" data are from the additional subjects (see text).

TABLE 3

	STOP ADAPTOR		CONTINUANT ADAPTOR		
	Ipsilateral or Binaural	Contralateral	Ipsilateral or Binaural	Contralateral	$\lvert\bar{X}\rvert$
Same series	-17.1	-13.3	+35.7	+14.5	20.2
Across series	- 6.4	-16.1	+28.5	+17.4	17.1
$\bar{X}$	-11.8	-14.7	+32.1	+16.0	

Note: Values shown are the percentage changes in labeling the middle four items of the eight-item continua. Contralateral data come for Experiment 2, and Binaural/Ipsilateral data come from Experiments 1 and 2. The voiced /ba/ data from the additonal group of 12 subjects in Experiment 2 were used for this Table, rather than the apparently aberrent results.

Figure Captions

Figure 1: Indentification of the test syllables (percentage "BA") before and after adaptation with voiced /ba/ (top two panels) and voiced /wa/ (bottom two panels).

2: Indentification of the test syllables (percentage "BA") before and after adaptation with whispered /ba/ (top two panels) and whispered /wa/ (bottom two panels).

3: Indentification of the test syllables (percentage "BA") before and after adaptation with pluck (top two panels) and bow (bottom two panels).

4: Indentification of the test syllables (percentage "BA") before and after adaptation with abrupt (top two panels) and gradual (bottom two panels).

5: Indentification of the test syllables (percentage "BA") before and after adaptation with pluck, with ipsilateral presentation of adaptor and test items (top two panels), or contralateral presentation (bottom two panels).

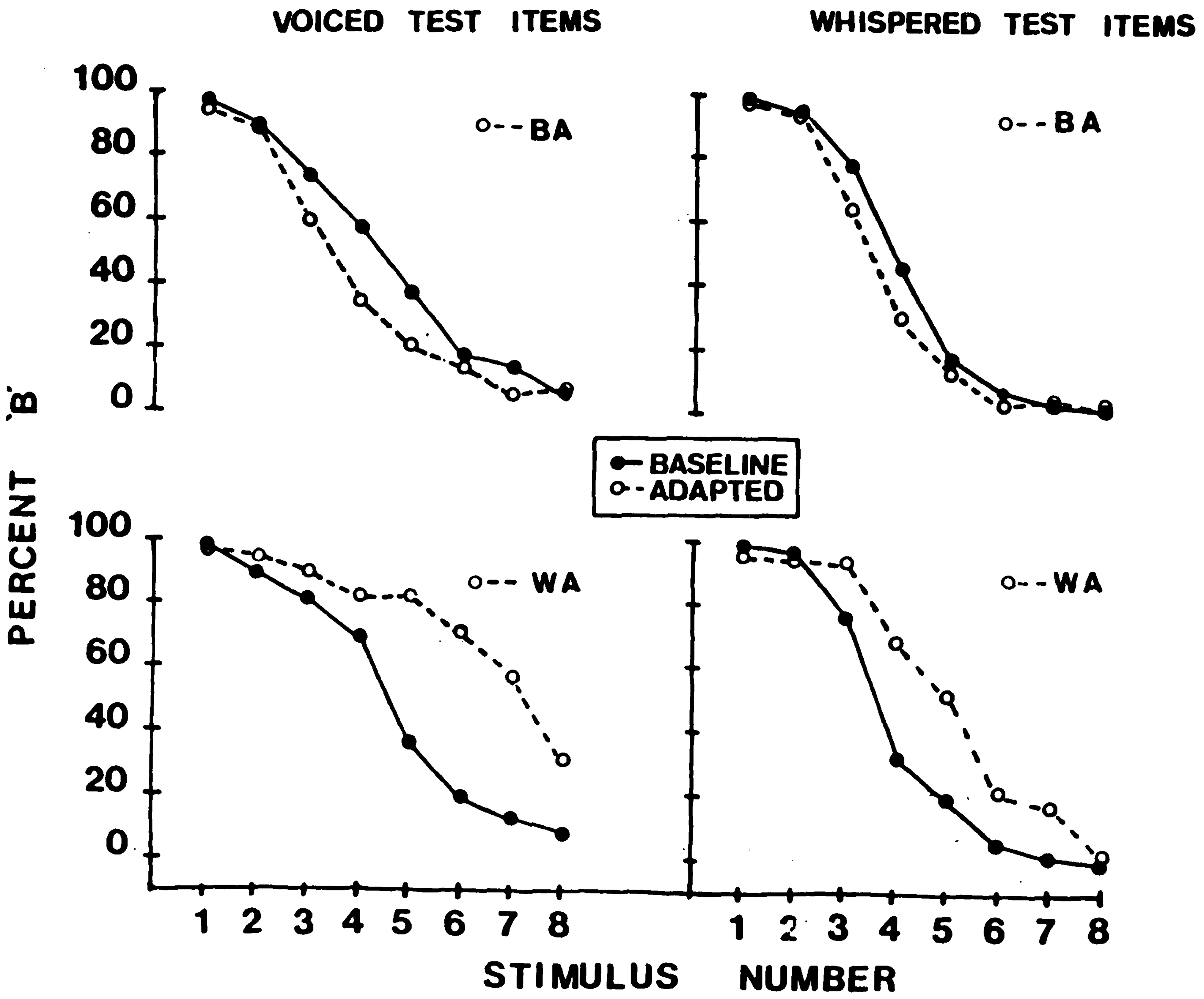
6: Indentification of the test syllables (percentage "BA") before and after adaptation with whispered /wa/, with ipsilateral presentation of adaptor and test items (top two panels), or contralateral presentation (bottom two panels).

7: Indentification of the test syllables (percentage "BA") before and after adaptation with voiced /wa/, with ipsilateral presentation of adaptor and test items (top two panels), or contralateral presentation (bottom two panels).

8: Indentification of the test syllables (percentage "BA") before and after adaptation with whispered /ba/, with ipsilateral presentation of adaptor and test items (top two panels), or contralateral presentation (bottom two panels).

9: Indentification of the test syllables (percentage "BA") before and after adaptation with voiced /ba/, with ipsilateral presentation of adaptor and test items (top two panels), or contralateral presentation (bottom two panels).

10: Indentification of the test syllables (percentage "BA") before and after adaptation with voiced /ba/, with ipsilateral presentation of adaptor and test items (top two panels), or contralateral presentation (bottom two panels), with a new group of subjects.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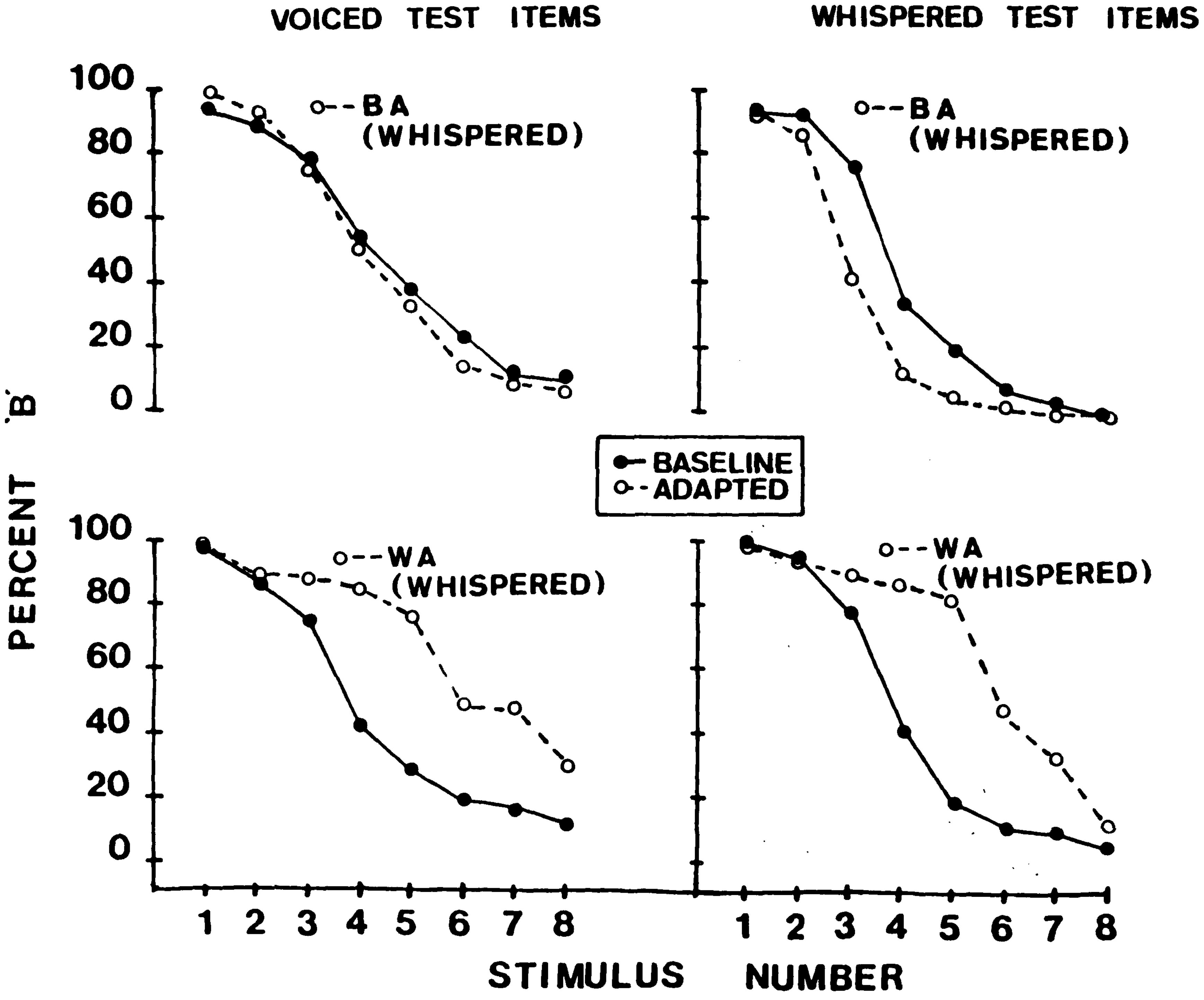
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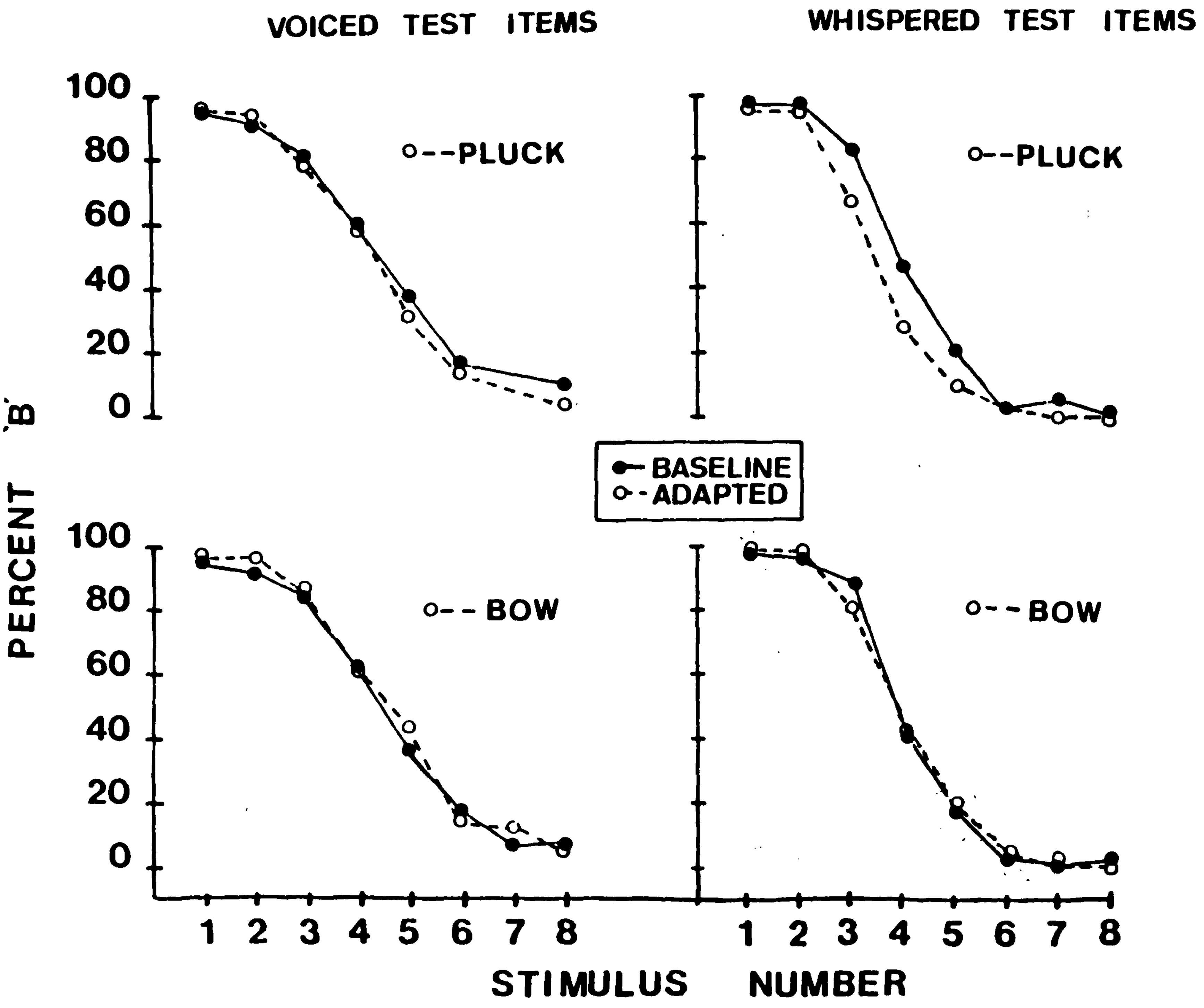
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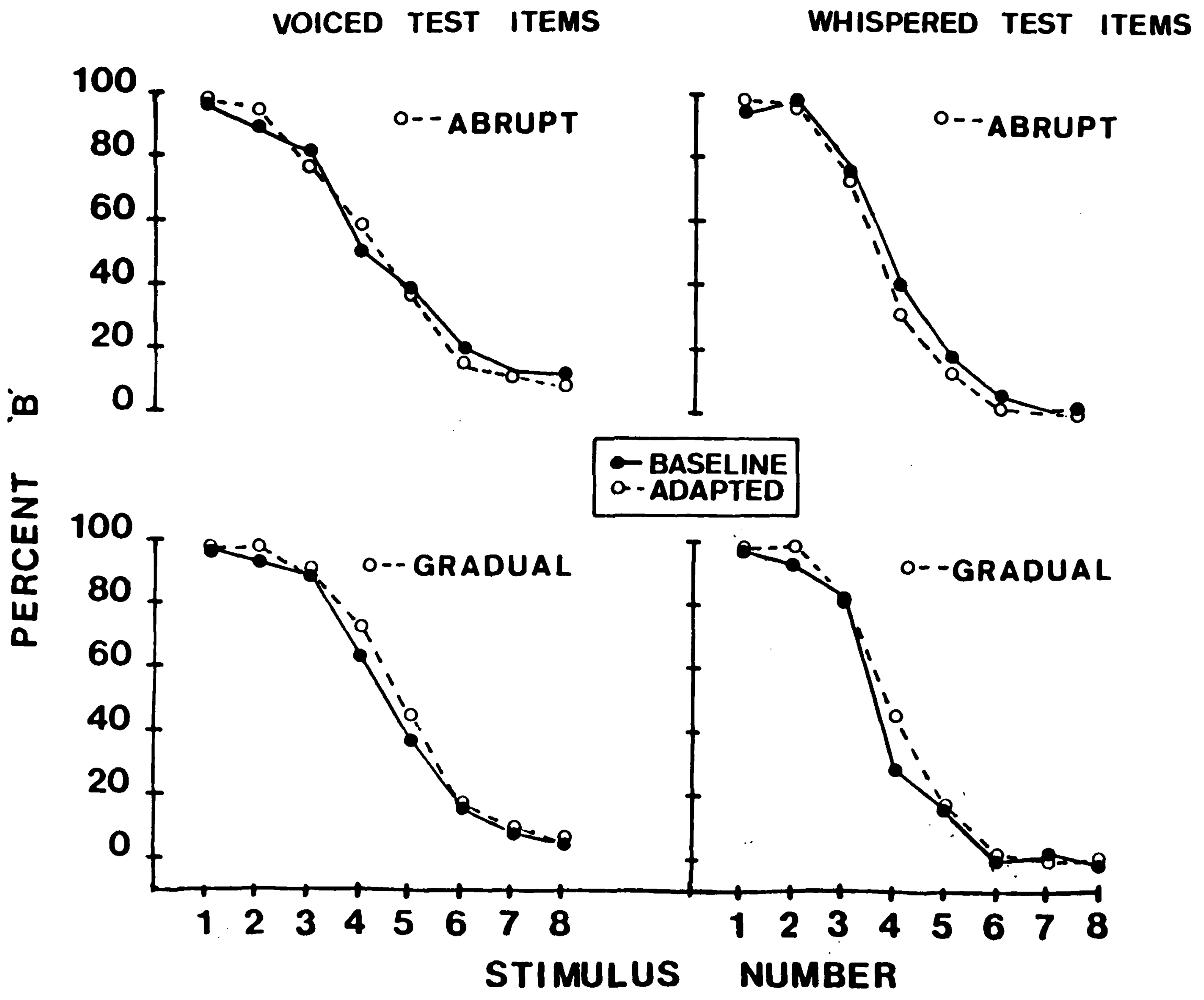
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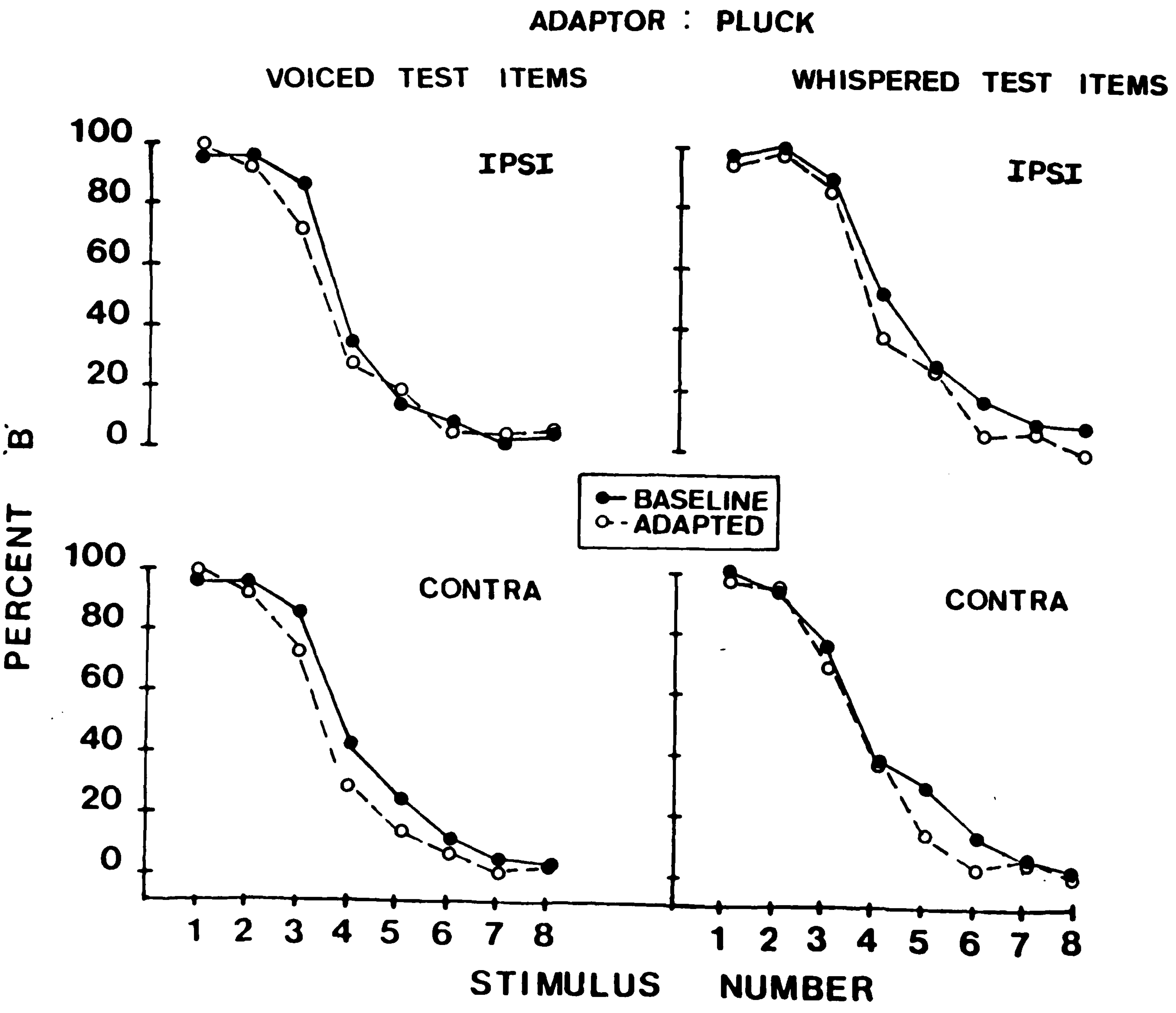
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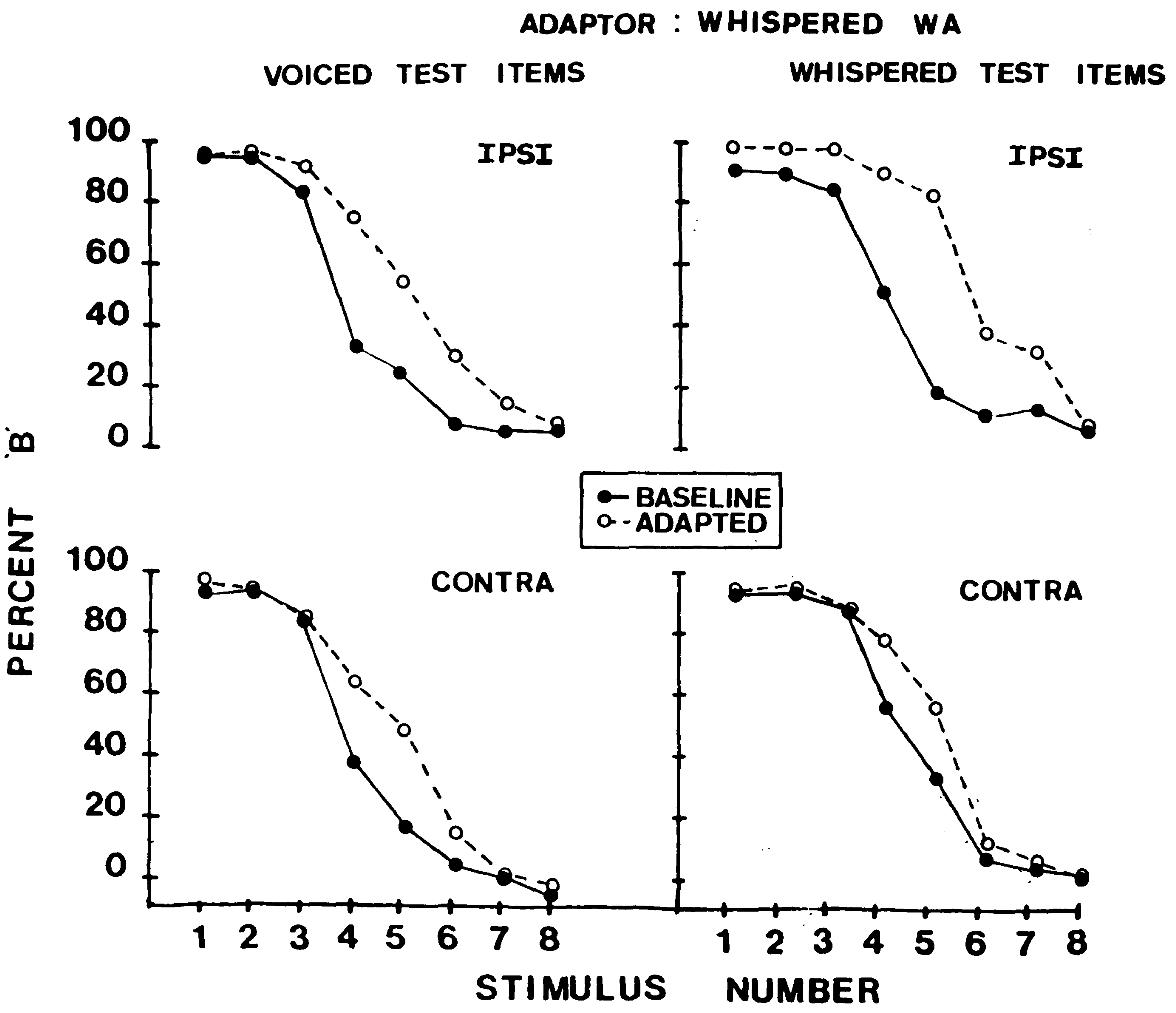
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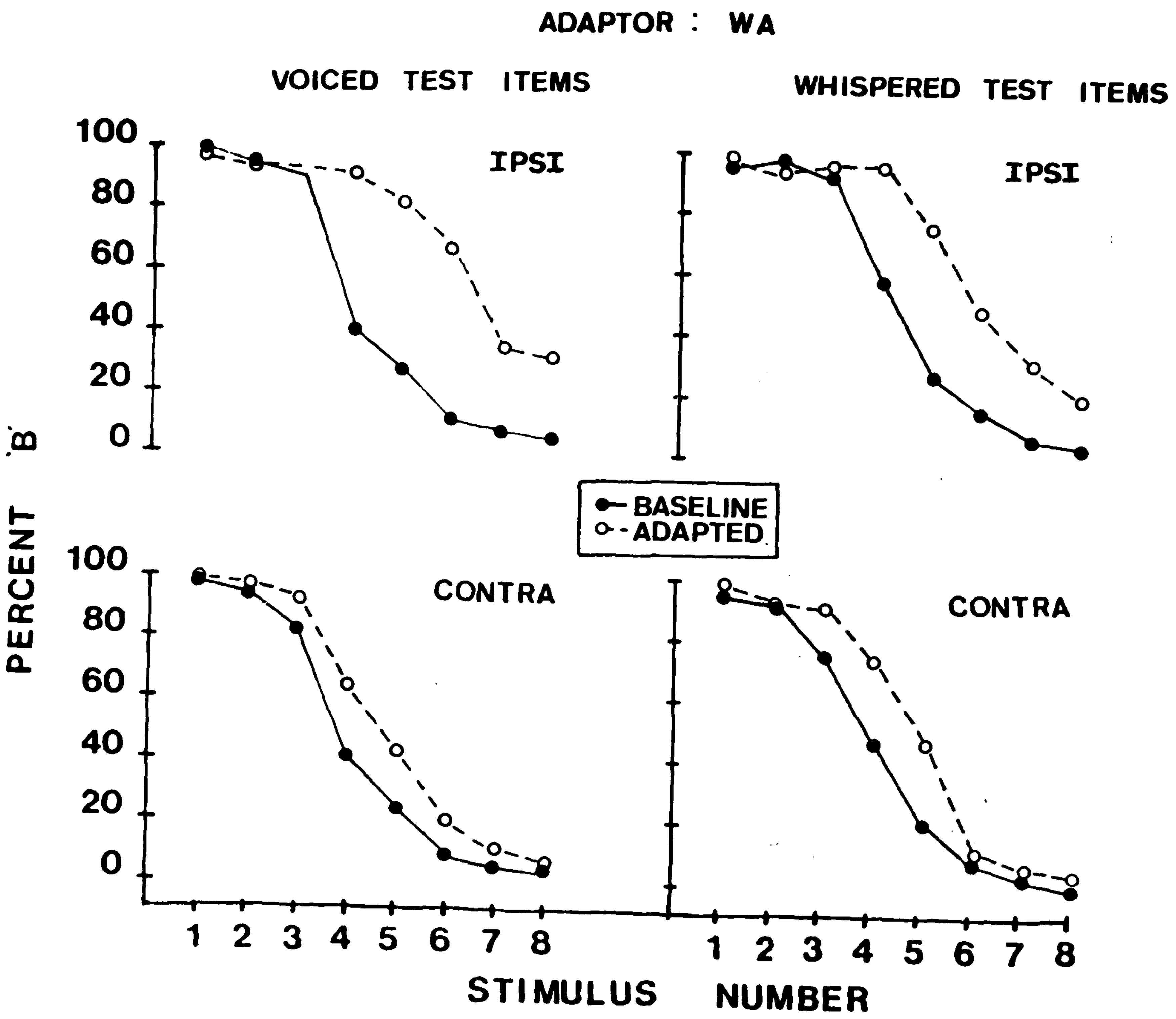
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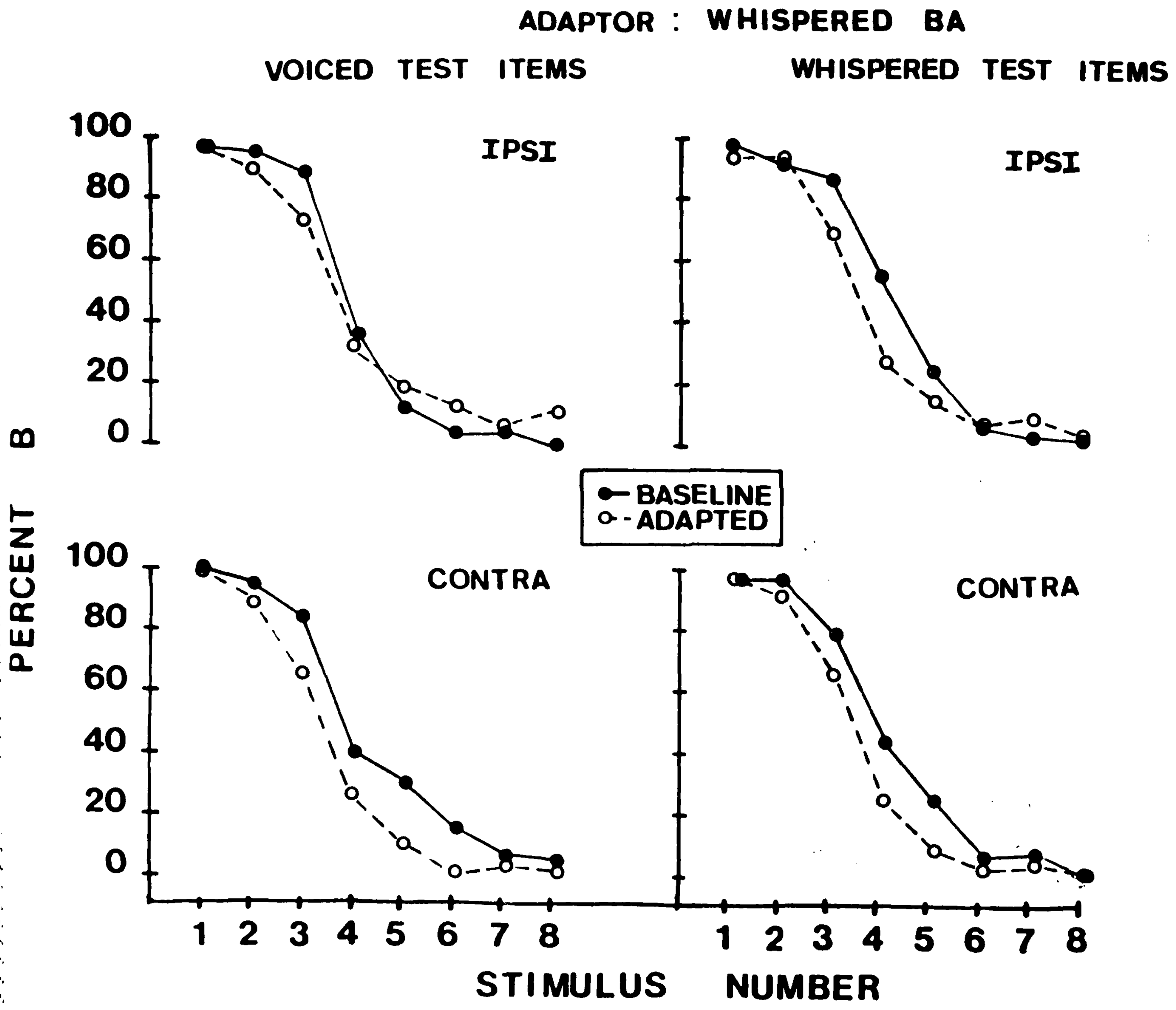
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WHISPERED TEST ITEMS
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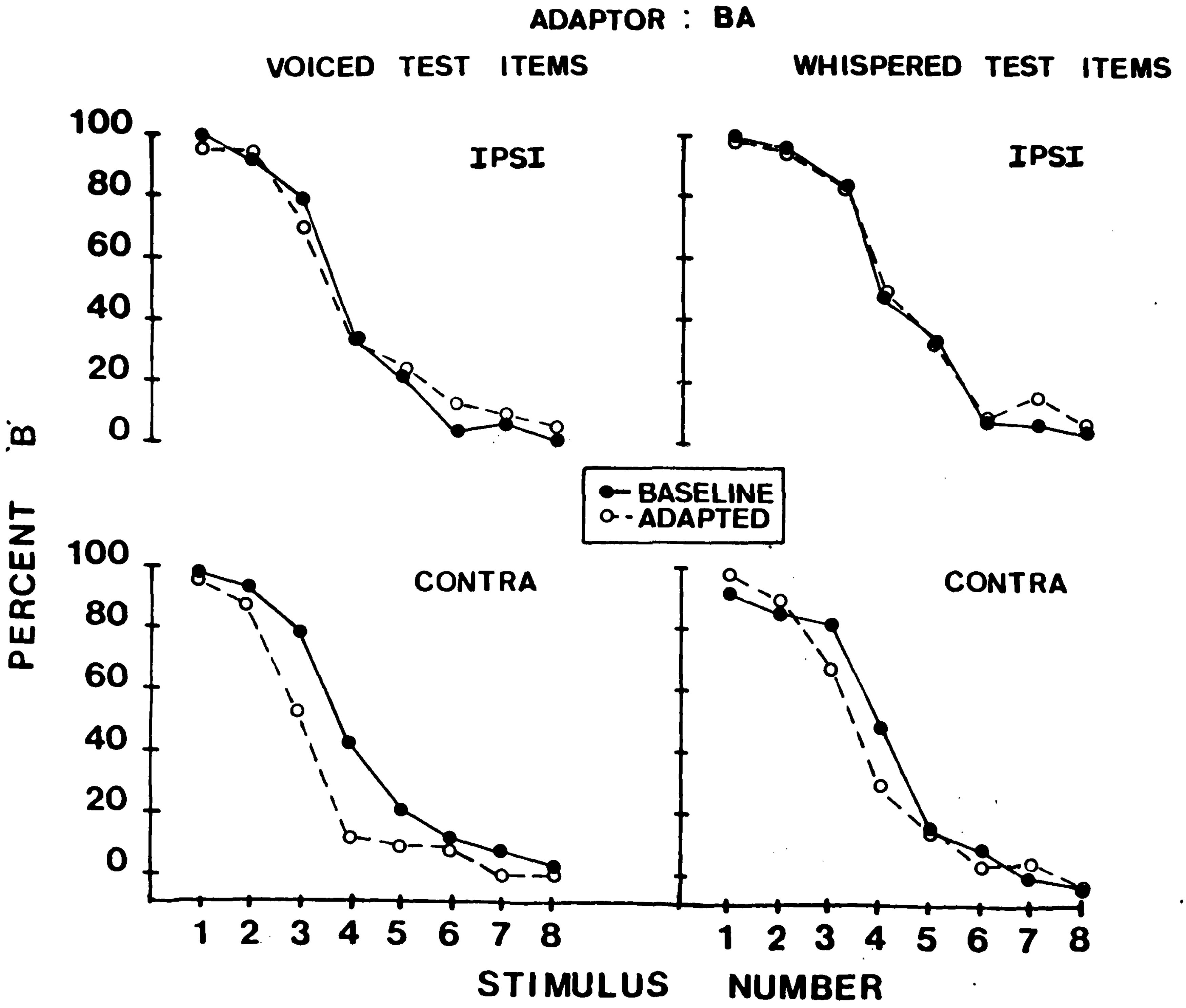
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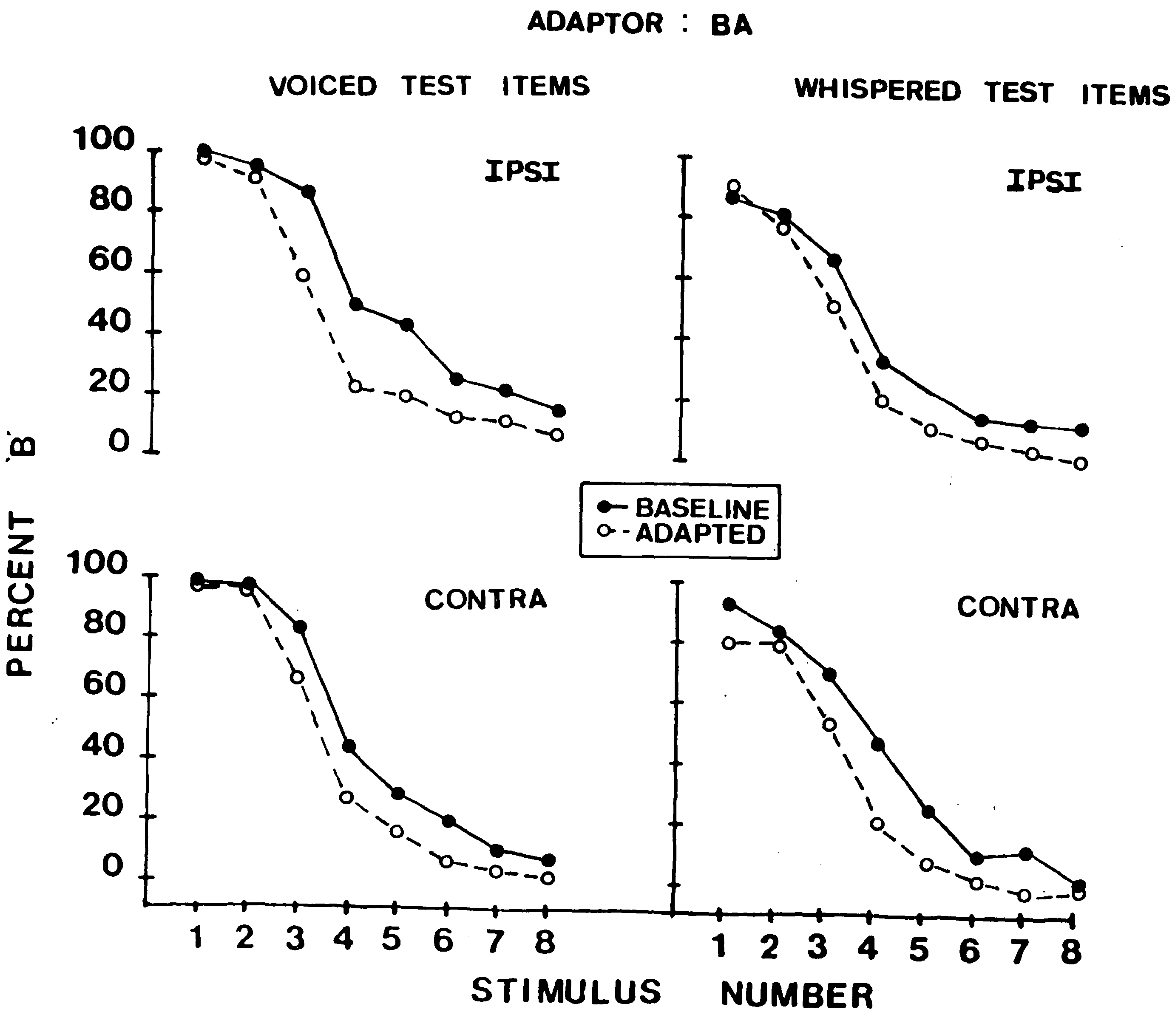
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END

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