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Tests of the Neural Noise Hypothesis of Age-Related Cognitive Change[1]

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Three predictions were derived from the assumption that with increased age there is a decrease in the effective signal-to-noise ratio of neural representations of visually presented stimuli. Although the results from manipulations designed to examine the internal consistency of the predictions were quite positive, the predicted age differences failed to appear in two of the three dependent measures. Because the same pattern was found in two independent studies and estimates of measurement reliability and statistical power were moderately high, it was concluded that at least some versions of the neural-noise hypothesis of cognitive changes with age may be untenable and that more effort should be devoted to devising experimentally testable implications of the hypothesis.

Key Words: Signal-to-noise ratio, Cognition, Perceptual thresholds

ONE of the few hypotheses proposed to account for age-related decrements in several aspects of information processing is that with increased age there is an increase in the level of neural noise (e.g., Crossman & Szafran, 1956; Gregory, 1957; Welford, 1965). This neural noise increase may be caused by attenuated signal strength due to cortical cell loss, by accentuated background activity due to weak inhibition, or by a variety of other factors. Regardless of the reason, however, a nervous system with an effectively lower signal-to-noise ratio than another nervous system will tend to have higher sensory thresholds (because the external signal-to-noise ratio must compensate for the lower internal signal-to-noise ratio) and generally slower rates of information processing (because of the need to accumulate a greater number of information samples to reach the same criterion level of signal-to-noise). Despite the broad explanatory potential of the neural noise hypothesis, there is currently very little empirical evidence that can be considered directly relevant to this perspective.

The experiments in the current project, therefore, were designed to attempt to provide an experimental test of one version of the neural noise hypothesis. The major assumption underlying the present experiments was that stimulus representations in the nervous system of older adults are "noisier", and generally more variable, than those in the nervous system of young adults. Our research strategy was to begin with this assumption that the functional stimulus representation is more variable in older adults than in young adults and then to attempt to test predictions derived from this perspective. Figure 1a illustrates the basic premise. For concreteness, these distributions can be considered to reflect the internal excitation (vertical axis) across space (horizontal axis) of a single punctate stimulus such as a brief flash of light.

(Binary classification tasks are used in the current project, and thus it might be more appropriate to portray two overlapping distributions rather than a single distribution. If it is assumed, however, that the two stimulus distributions are identical and that the absolute distance between the means along some similarity axis is the same for young and old adults, the critical determinant of speed and accuracy will be the variability of each distribution. Illustrations of a single distribution for each age group are therefore sufficient for the present purposes, and have the added advantage of being much simpler to represent than multiple distributions.)

One prediction from the hypothesis that the stimulus representations are more variable in older adults is that a greater number of samples (or time because each sample is assumed to require a finite time) will be needed for the representation to reach a criterion level of excitation compared to young adults. This reasoning is illustrated in Figure 1b. Note that more samples are required in order for the representations of older adults to attain the criterion assumed to be necessary for the emission of an overt response. The principle of enhancing the ef-

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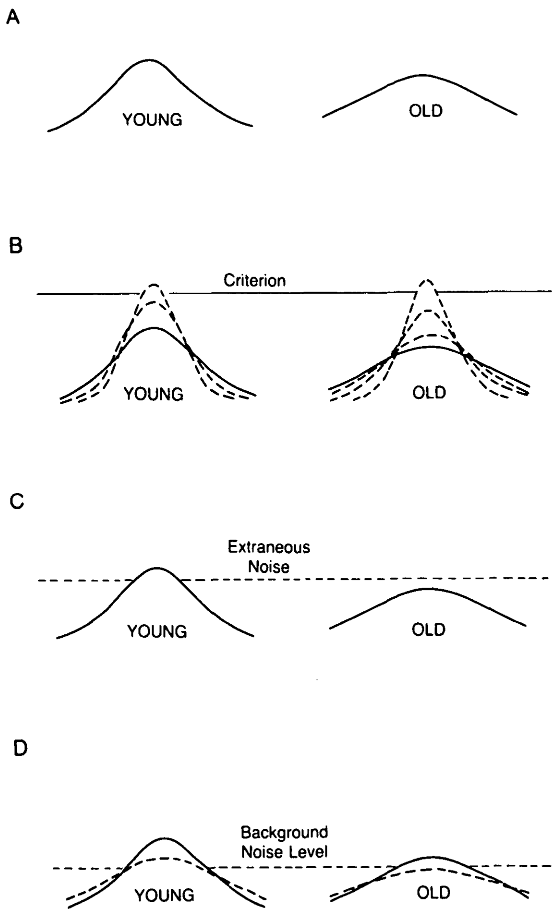

Figure 1. (A) Hypothesized distribution of internal neural activity for a single stimulus in young and old adults. (B) Illustration of necessity of obtaining more information samples to achieve the same criterion level of excitation with initially more variable representations. (C) Illustration that less variable representations with higher signal-to-noise ratios are still discriminable at levels of extraneous noise that completely mask more variable representations. (D) Illustration that distortions of a representation with a high signal-to-noise ratio are still discriminable from the background noise level even when distortions of the lower signal-to-noise ratio representation blend into the background noise level.

fective signal-to-noise ratio by aggregating samples is the same as that employed in statistics when one increases the size of one's sample to increase the power of detecting a significant difference between two distributions. Because larger sample sizes generally require added time, the well-documented age differences in reaction time and other speeded activities (see Salthouse, in press, for a review) might be explained by a mechanism such as a reduced signal-to-noise ratio with increased age.

A second prediction from the basic premise that increased age is associated with greater variability of stimulus representations is that older adults should be less able than young adults to tolerate additional noise in the stimulus display. Because the stimulus representation in older adults is assumed to be very close to the level of background activity with no extra noise in the display, even a small amount of added noise will reduce the effective signal-to-noise ratio to a level that is no longer distinguishable from the normal background activity. Because the stimulus representation in young adults is postulated to have a fairly high signal-to-noise ratio, substantial increases in extraneous noise presumably could be handled without reducing discriminability to the background level. Figure 1c illustrates this argument; note that the stimulus representation for young adults is postulated to be distinguishable at a level of extraneous noise that completely masks the representation of older adults. The finding that there are pronounced age differences in tests of identifying targets embedded in larger contexts (e.g., Axelrod & Cohen, 1961; Eisner, 1972; Lee & Pollack, 1978) might be explained by this type of mechanism.

A third prediction from the differential variability assumption portrayed in Figure 1a is that older adults should be less able than young adults to tolerate distortion in the stimulus patterns. The reasoning is similar to that used with the addition of extraneous noise except that the distortion is assumed to reduce the strength of the signal rather than to increase the level of noise. That is, a distorted stimulus necessarily produces a weaker signal than the prototype from which it is derived, and therefore the representation of that distortion will be closer to the level of background activity than the representation of the prototype. Figure 1d illustrates this reasoning for the postulated internal distributions in young and old adults. Because in older adults the prototype representation is variable and weak relative to the background noise level, the even more variable and weaker representations of the distorted stimuli will be very difficult to distinguish from the background activity. It can therefore be expected that older adults will make many errors when classifying distorted versions of prototype stimuli. Young adults should have little difficulty classifying the distortions because their prototype representations are less variable and stronger relative to the noise level, and consequently even the less salient representations of the distorted stimuli should be easily distinguished from the background level. The well-documented inferiority in performance of older adults compared with young adults in tests of incomplete figure identification (e.g., Danziger & Salthouse, 1978; Eisner, 1972; Verville & Cameron, 1946) might be attributable to an age-related reduction in the strength (and consequently the association potential) of partial figure segments.

Three tasks were designed to test these predictions from the reduced signal-to-noise hypothesis. All involved a choice between two stimulus patterns. The first task was a choice reaction time procedure in which participants simply pressed a left key as rapidly as possible when one stimulus appeared and pressed a right key as rapidly as possible when the other stimulus appeared. The dependent variable was the mean reaction time over the last 25 trials for which accuracy was at least 90%.

The second task involved subjects attempting to make the stimulus classification when the stimuli were embedded in extraneous noise. The stimulus patterns and the noise consisted of dots in a matrix, and across trials the number of dots added to the display was varied. A Parameter Estimation by Sequential Testing (PEST) adaptive-threshold procedure (Taylor & Creelman, 1967) was used to determine the number of noise dots that led to an accuracy of 75%. The average of two independent thresholds determined in the same block of trials served as the dependent measure.

The third task involved subjects attempting to make the stimulus classification with distorted versions of the stimuli. The distortions were created by perturbing the positions of the dots comprising each stimulus pattern, and the amount of distortion (perturbation of original dot position) was varied systematically across trials. A PEST adaptive-threshold procedure was used to determine the amount of distortion that led to an accuracy of 75%. The average of two independent thresholds determined in the same block of trials was used as the dependent variable.

To summarize, the predictions with respect to the age differences on these tasks were as follows. First, older adults should have slower reaction times because they have to integrate for a longer period of time to achieve the criterion level of activation (Figure 1b) needed to produce an accurate response. Second, older adults should have smaller noise thresholds because they are able to tolerate less extraneous noise (Figure 1c). Third, older adults should have smaller distortion thresholds because the less salient representations of distorted stimuli will tend to be indistinguishable from the background activity (Figure 1d).

EXPERIMENT 1

Before attempting to test the predictions concerning age differences, the assumptions about the qualitative effects of the distortion and extraneous noise manipulations were evaluated in a small sample of highly practiced young adults. Four young adults participated in the three tasks with varying levels of distortion or extraneous noise. That is, the reaction time task was performed at six levels of distortion and at six levels of extraneous noise, the noise threshold task was performed at six levels of stimulus distortion, and the distortion threshold task was performed at six levels of extraneous noise. The data from this experiment are of interest to determine whether the results are qualitatively consistent with the expectations outlined above. Predictions were that reaction time should increase with additional extraneous noise and with more distortion in the to-be-classified stimuli and that both noise threshold and distortion threshold should decrease with added distortion (for the noise threshold task) or with added noise (for the distortion threshold task). In effect these manipulations can be considered attempts to simulate the hypothesized effects of aging in a sample of young adults.

METHOD

Participants. — Three men and one woman, aged 22 to 36, participated in one practice session and eight experimental sessions. Two of the participants were highly practiced in these types of tasks and two were experimentally naive.

Apparatus. — A PDP-11/03 laboratory computer was used to present stimuli on a Hewlett-Packard 1311A Display Monitor and to record responses from a response panel containing two touch telephone keyboards. Temporal measurement was to a precision of 1 ms.

Procedure. — The stimuli in each task were based on 13 dots arranged in either an × or a + pattern. In all tasks a key on the left keyboard was to be pressed when a + appeared, and a key on the right keyboard was to be pressed when an × appeared. A speeded response was requested in the reaction time task, but participants could respond at their own pace in the two threshold tasks.

The reaction time task involved the presentation of the × or + stimulus until a key on one of the keyboards was pressed. Fast but accurate responding was emphasized in this task. Two independent and randomly intermixed trial sequences were administered. The accuracy for the preceding 25 trials on a given sequence was determined after each trial, and the sequence terminated when the accuracy reached 90%. The mean reaction time for the last 25 trials of the sequence at this criterion level of accuracy was then computed, and, after both sequences had terminated, the mean of the two means served as the dependent variable for that block of trials.

The noise threshold task consisted of the 1-s presentation of either the × or + stimulus pattern simultaneous with the presentation of a variable number of randomly located noise dots. The positions of these extraneous dots were determined independently on each trial and had no systematic relationship either to the positions of the stimulus dots on that trial or to the positions of the noise dots on prior trials. Two independent and randomly intermixed trial sequences were administered. In each sequence the number of noise dots was adjusted depending upon the accuracy of the preceding 20 trials on that sequence. If the accuracy exceeded 75% the number of dots was increased, and if it was less than 75% the number of dots was reduced. With each shift in the direction of the change in number of dots the amount of change was reduced by one half until the sequence terminated when the number of dots added or subtracted was four and accuracy was between 70% and 80% for the preceding 20 trials. The number of dots at the point of termination defined the threshold for that trial sequence, and the average of the two thresholds served as the dependent variable for that block of trials.

The distortion threshold task consisted of the 1-s presentation of a distorted version of either the × or the + prototype pattern. The distortions were created by allowing each dot in the prototype pattern to vary in both the horizontal and vertical dimensions according to a normal distribution. Locations of the dots were determined independently on every trial, and the only systematic relationship between dot positions on different distortions was that due to the fact that each distortion resembled the prototype from which it was derived. Two independent and randomly intermixed trial sequences were administered. In each sequence the standard deviation of the normal distribution was varied depending upon the accuracy of the preceding 20 trials on that sequence. If the accuracy exceeded 75% the variability was increased, and if the accuracy was less than 75% the variability was reduced. With each shift in the direction of the change in variability the amount of change was reduced by one half until the sequence terminated when the change was 1 standard deviation and accuracy was between 70% and 80% for the preceding 20 trials. The standard deviation at the point of termination defined the threshold for that trial sequence, and the average of the two thresholds served as the dependent variable for that block of trials.

In the present experiment four task combinations were created by measuring: (a) reaction time while manipulating amount of extraneous noise, (b) reaction time while manipulating level of stimulus distortion, (c) distortion threshold while manipulating amount of extraneous noise, and (d) noise threshold while manipulating level of stimulus distortion. The six levels of noise consisted of 0, 30, 60, 90, 120, and 150 extraneous dots in the stimulus display, and the six levels of distortion consisted of 0, 2, 4, 6, 8, and 10 standard deviation units.

Each task combination was performed on two separate sessions, and within each session there were two trial blocks at each level of noise or distortion. A different counterbalanced order of task combinations across sessions was used for each participant.

Results and Discussion

The average results across the four participants are displayed in Figure 2. Each data point in these illustrations is based on an average of over 640 trials (i.e., two thresholds based on a minimum of 20 trials in each trial block, two blocks per session, two sessions per participant, and 4 participants). The pooled standard deviations across participants, conditions, and sessions are indicated by the vertical bars in each panel. Each individual participant produced the same trend of approximately monotonic changes in the dependent variable with increases in noise or distortion. The important point for current purposes is that the patterns are all consistent with the predictions derived earlier. Reaction time increases with a manipulation assumed to simulate heightened background activity (extraneous noise) and with a manipulation assumed to simulate attenuated signal strength (stimulus distortion). The amount of stimulus distortion that can be tolerated when classifying stimuli is reduced when the simulated noise level is high, and the amount of extraneous noise that can be tolerated is reduced when the simulated signal strength is low.

EXPERIMENT 2

The findings of Experiment 1 clearly support the qualitative arguments about the relationship be-

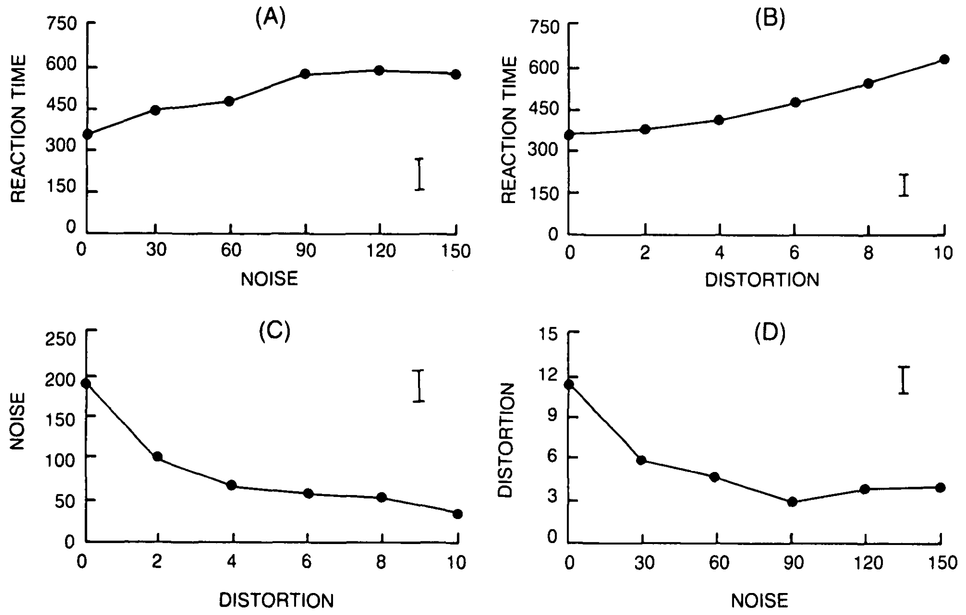

Figure 2. (A) Reaction time as a function of level of extraneous noise. (B) Reaction time as a function of amount of stimulus distortion. (C) Noise threshold as a function of amount of stimulus distortion. (D) Distortion threshold as a function of amount of extraneous noise.

tween manipulations thought to influence the relative signal-to-noise ratio and specific dependent variables. In the second experiment, samples of young and older adults were administered the three basic tasks to determine whether age differences are present in each of the performance measures. As noted earlier, the increased neural noise hypothesis predicts that older adults will have longer reaction times and lower distortion and noise thresholds than young adults.

METHOD

Participants. — Twenty college students (aged 18 to 26 years, $M = 19.6$) and 20 older adults (aged 61 to 76 years, $M = 68.5$) participated in a single experimental session. There were 5 men in the young group and 8 men in the older group. The mean raw score on the digit symbol substitution test from the Wechsler Adult Intelligence Scale was 63.6 for young adults and 46.1 for the older adults, $t(38) = 5.63, p < .001$.

Apparatus and procedure. — The apparatus and the procedure for the three basic tasks (reaction time, noise threshold, and distortion threshold) were identical to that described in Experiment 1. Unlike Experiment 1, however, all tasks were performed in isolation; there was no extraneous noise in the distortion threshold or reaction time tasks, and only prototype stimulus patterns were presented in the noise threshold and reaction time tasks. All participants received the same fixed order of tasks consisting of two trial blocks of the reaction time task, two trial blocks of the noise threshold task, four trial blocks of the distortion threshold task, two trial blocks of the noise threshold task, and, finally, two trial blocks of the reaction time task.

RESULTS AND DISCUSSION

For each participant a single dependent measure for each task was derived by averaging the eight available values (two from each of four trial blocks). Age differences on these measures were then examined with separate t tests for each variable. The means and t test results are displayed in Table 1. Notice that the age differences were significant for the reaction time measure but not for either the noise threshold or distortion threshold measures. Analyses of variance with age and trial block as factors were conducted on the threshold measures to examine the effects of practice on the age trends. Neither of the main effects nor their interaction were significant ($p < .01$) with the noise or distortion threshold measure.

Table 1. Summary Statistics for the Dependent Measures in the Three Tasks.

	Reaction time	Noise threshold	Distortion threshold
	Experiment 2		
Young	423 (38)	102 (28)	7.4 (1.8)
Old	522 (84)	90 (26)	7.4 (2.3)
$t(38)$	−4.81*	1.48	−0.02
Power	—	.92	.86
	Experiment 3		
Dissimilar stimuli			
Young	424 (57)	141 (61)	15.9 (5.1)
Old	534 (122)	107 (49)	13.6 (4.9)
$t(38)$	−3.64*	1.95	1.41
Power	—	.63	.81
Similar stimuli			
Young	413 (42)	57 (18)	5.6 (1.5)
Old	526 (60)	56 (22)	5.0 (0.9)
$t(38)$	−6.93*	0.27	1.42
Power	—	.68	.96

*$p < .01$.

Whenever null results are obtained it is desirable to assess the reliability of the dependent variables to ensure that they have been measured consistently. One index of reliability can be derived in the present context by computing a correlation coefficient between the average of the value from Trial Blocks 1 and 4 and the average of the values from trial Blocks 2 and 3. The correlations for young adults were .46 for reaction time, .80 for noise threshold, and .79 for distortion threshold; corresponding values for the older adults were .94, .73, and .65. These relatively high correlations indicate that the absence of age differences with the noise and distortion threshold cannot be attributed to low reliability of the measures.

Despite the adequate measurement reliability, it is still possible that large within-group variability weakened the statistical power of the significance test. In order to investigate this possibility, computations were carried out to determine the probability of detecting a difference equivalent to 25% less than the young group mean (the approximate value of the percentage difference observed with the reaction time variable) with an alpha level (one-tailed) of .05. These probabilities, displayed in the fourth row of Table 1, are moderately large; therefore weak power is unlikely to be a major factor contributing to the null results.

EXPERIMENT 3

Before accepting the conclusion that there really are no age differences in the threshold for noise or distortion, it was considered desirable to attempt to replicate the previous findings with independent samples of young and old adults. A manipulation of the similarity of the stimuli was also included in order to verify that stimuli with more distinctive representations can be classified at greater levels of noise and distortion than stimuli with similar representations. In addition, the Gestalt Figure Completion Test (French et al., 1963) was administered to determine whether the samples of young and old adults differed in a common test of distorted picture perception.

Method

Participants. — Twenty college students (age 18 to 27 years, $M = 18.7$) and 20 older adults (aged 60 to 74 years, $M = 67.6$) participated in a single experimental session. There were 5 men in the young group and 9 men in the older group. The mean score on the digit symbol substitution test from the Wechsler Adult Intelligence Scale was 64.2 for young adults and 47.6 for older adults, $t(38) = 5.31, p < .01$.

Apparatus and procedure. — The apparatus and procedure for the three basic tasks were identical to that described earlier with two important exceptions. First, only a single trial block in each task was presented with each of two stimulus sets rather than four blocks with a single stimulus set as in Experiment 2. This necessarily reduced the reliability of the measures, from a median within-task correlation of .76 in Experiment 2 (for the correlation between the average of Blocks 1 and 4 and the average of Blocks 2 and 3) to .31 in the present experiment (for the correlation between the similar and dissimilar stimulus sets), but the requirement of presenting two different stimulus sets precluded extensive measurement.

The similar stimulus set had 8 out of 14 dots in common between the two patterns, which were also in the same orientation relative to one another. The dissimilar stimulus set had only 1 out of 15 dots in common between the two patterns and were rotated 90° relative to one another. (For purposes of comparison, the × and + stimuli from the previous experiment had only 1 out of 13 dots in common but were actually the same patterns merely rotated 45° with respect to one another.) The order of presenting the stimulus sets was balanced across the participants in each age group.

The second difference in procedure from the previous experiment was the use of response-terminated stimulus displays in the threshold tasks instead of a fixed 1-s presentation. Perhaps the relatively brief stimulus durations in the previous experiment led to less-than-optimal performance for all participants, with the consequence that age differences were obscured by an effective measurement floor. If this interpretation is correct, allowing participants to observe the stimuli as long as they desired in the noise threshold and distortion threshold tasks should increase the overall level of performance and result in more pronounced age differences.

Results and Discussion

The data from each task were first subjected to analyses of variance with age as a between-subjects factor and stimulus set as a within-subjects factor. The only significant ($p < .01$) effects were age with the reaction time measure, $F(1,38) = 27.48$, $\omega^2 = .294$; and stimulus set with both noise threshold, $F(1,38) = 54.93$, $\omega^2 = .366$, and distortion threshold, $F(1,38) = 151.26$, $\omega^2 = .528$. The remaining, nonsignificant effects all had ω^2 values less than .02. The means of the three dependent measures for each stimulus set are displayed in the bottom panel of Table 1 for both young and old adults. As can be seen, the results are comparable to those of the preceding experiment. Older adults were significantly slower in reaction time but not significantly different in either noise threshold or distortion threshold. Stimulus similarity had the expected effect on the two threshold measures (i.e., less tolerance for extraneous noise and distortion with more similar patterns, but the reaction times were equivalent with the two stimulus sets).

Older adults identified an average of 9.6 items correctly in the Gestalt Completion Test, compared with an average of 15.9 for the young adults, $t(38) = 5.21$, $p < .01$. The correlations between performance on the Gestalt Completion Test and the experimental measures ranged from −.28 to +.48 across age groups, tasks, and stimulus sets. Only the correlation with the noise threshold for the dissimilar stimuli (+.48) was significant for the young adults, and the correlation with the noise threshold for the similar stimuli (+.45) was significant for the older adults.

GENERAL DISCUSSION

Several predictions about age differences in two novel experimental tasks were generated from the assumption that with increased age there is an increase in the amount of noise or variability associated with internal stimulus representations. Experiment 1 demonstrated that the reasoning was plausible in that manipulations of the amount of background noise or of the intactness of the stimuli led to longer reaction times and lower thresholds of tolerance for distortion and noise. It was also found in Experiment 3 that increasing the similarity between the two members of a stimulus set led to the expected reductions in noise threshold and distortion threshold, although inexplicably there were no differences in reaction time between the similar and dissimilar stimulus sets.

The results just mentioned, along with the arguments outlined in the introduction, establish the credibility of the experimental hypotheses about the existence of age differences in measures of noise and detection threshold. Indeed, based on the trend for age differences to be evident in a great variety of perceptual-motor measures, we expected the biggest challenge would be to establish that the predicted age differences originated for the reasons we proposed rather than for an assortment of other reasons. It was surprising, therefore, to discover that young and old adults performed equivalently on the noise threshold and distortion threshold tasks. Moreover, this equivalence cannot be attributed to unusual samples of young and old adults because quite typical age differences were found in Experiments 2 and 3 in the digit symbol and reaction time measures, and pronounced age differences were also obtained in the scores on the Gestalt Completion Test in Experiment 3. In addition, the threshold measures were found to have respectable reliability, particularly in Experiment 2, and the statistical power was demonstrated to be adequate.

Why, then, were there no age differences in the measures of noise threshold and distortion threshold? There are obviously many possible answers to this question, but we currently favor three that may be operating singly or in combination. The first possibility is that the two groups of adults used somewhat different mixtures of strategies, with the older adults using the more successful strategy more frequently to compensate (probably unintentionally) for a real age-related deficit. Unfortunately, there presently is no evidence available to support this interpretation. A strategy difference might have been reflected in the time taken to produce a response in the threshold conditions relative to one's reaction time, but analyses of those ratios failed to yield significant age effects in either Experiment 2 or 3. Despite the absence of systematic information on the nature of the different types of strategies actually used in the tasks, however, perhaps an age difference of this type did exist but was not detectable with the methods employed.

A second interpretation of the absence of age differences in the noise and distortion threshold measures is that the tasks were too simple to have placed much of a cognitive demand upon the individuals in either age group. That is, because the tasks merely involved a binary choice between elementary stimuli, the demands may not have been sufficiently conceptual or cognitive to have revealed what age differences do exist. According to this interpretation, the substantial age differences in embedded figure tests (Axelrod & Cohen, 1961; Eisner, 1972; Lee & Pollack, 1978) and incomplete figure tests (Danziger & Salthouse, 1978; Eisner, 1972; Verville & Cameron, 1946) occur because the tasks require cognitive resources that are in lower supply with increased age but are not required in great amounts by the current noise threshold and distortion threshold tasks. Another way of expressing this view is that the critical determinant of age differences may be the number of cognitive operations required for a task and not the difficulty of a single operation (cf. the complexity/difficulty distinction of Navon, 1984). The current manipulations may have successfully increased the difficulty of the discrimination task, but complexity may have remained invariant.

Of course, stating that tasks with conceptual requirements are more resource limited than tasks with only perceptual requirements does not provide an explanation, but some distinction of this type seems mandated by the different trends evident between the simple and complex perceptual tasks. The challenge from this perspective is to identify exactly what these resources are, to explain how their availability contributes to superior performance on these specific tasks, and to devise a means of quantifying their amount in individuals of varying ages.

A third interpretation of the null results with the threshold measures is that the manipulations of background noise and stimulus distortion do not accurately simulate the internal determinants of signal-to-noise ratio. That is, although the general reasoning represented in Figure 1 may be correct, externally induced variations may not have the same effects as naturally occurring processes within the nervous system. Attributing the failure of the predictions to inappropriate simulation of the relevant mechanisms is, however, not a very satisfactory alternative unless there is some indication of the specific dimensions that are unrealistic. It is not yet clear what manipulations might be more successful in mimicking the hypothesized signal-to-noise reduction with age, or in what respects a simulation must be faithful to the postulated processes.

Regardless of the specific interpretation, the results of Experiments 2 and 3 are inconsistent with the predictions derived from the assumption that stimulus representations are noisier and more variable with increased age. At the very least, therefore, the neural-noise hypothesis should be re-examined and attempts made to formulate and test more of the implications of this perspective.

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