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Age Differences in Dynamic Measures of EEG

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Summary: Eighteen older adults and 18 younger adults were compared on two quantitative measures describing changes over time in the spatial distribution of running EEG. EEG was collected from 128 electrodes under resting eyes-open and eyes-closed conditions and during performance of a 13 minute sustained attention task. One EEG measure, the recrudescence rate, represented the number of changes in the location of the highest squared voltage per second. A second EEG measure consisted of the algorithmic complexity of changes in the location of the highest squared voltage over time. Regardless of the task condition, older adults had significantly higher scores than younger adults on both the recrudescence rate and the measure of algorithmic complexity. The implications of the results for neurologically-based theories of performance declines in older adults are discussed.

Key words: EEG; Aging; Algorithmic Complexity; Recrudescence Rate.

Introduction

Older adults perform less well than younger adults on a wide variety of cognitive tasks. These tasks include measures of speed of performance, memory, selective attention, and sustained attention. One proposed explanation for these findings is a task-independent decline in the speed of information processing in older adults (Cerella 1985; Myerson et al. 1990; Salthouse 1985). This model has become know as the generalized slowing hypothesis. Other explanations of age differences in cognitive performance include (a) reduced processing resources available to older adults (e.g., Salthouse 1991) and (b) reduced inhibitory control in the cognitive operations of older adults (Hasher and Zacks 1988). Each of these positions is based on the underlying assumptions that (a) changes in brain activity with increasing age are responsible for age differences in behavior and (b) these changes take the form of decrements in brain activity.

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Several non-invasive methods have been used to study brain activity during cognitive performance. These methods include PET (e.g., Madden et al. 1999), functional MRI, and EEG. The primary advantage of EEG is that samples of brain activity are obtained hundreds of times per second. PET and functional MRI must average signals over periods ranging from seconds to minutes. Traditionally, EEG's advantage in terms of temporal resolution has been outweighed by severe restrictions in spatial resolution. However, recent advances in dense-array electrode systems containing 64 or 128 recording sites have offset this disadvantage to some degree (Potts et al. 1998; Tucker et al. 1994). Because of its high sampling rate, EEG was used in the present study to examine age differences in the rate of change in brain activity.

A large literature exists describing age differences in quantitative measures of EEG activity. Studies using spectral analysis to quantify the percentage of EEG activity within the delta, theta, alpha, and beta frequency bands have yielded inconsistent findings regarding age differences in the brain's electrical activity. For example, a number of investigators have reported higher levels of beta activity in healthy older adults during baseline conditions requiring no mental effort (e.g., Duffy et al. 1984; Marciani et al. 1994). Similarly, Marciani et al. (1994) reported that older adults had lower percentages of theta and alpha activity and higher percentages of beta activity, compared to younger adults, during performance of a mental arithmetic task. In contrast, other studies either report shifts of the power spectrum towards the lower frequencies with increasing age (for a review, see Klass and Brenner 1995) or no age differences at all (e.g., Hartikainen et al. 1992).

The mixed nature of findings regarding age differences in EEG frequency components makes it difficult to link lower levels of cognitive performance observed in older adults to specific patterns of brain electrical activity. One reason for the inconsistent findings regarding age differences in EEG may be that the effects of age are more predominant in the relationships among measurement sites (i.e., functional connectivity) rather than in the pattern of activity at a single location.

Spectral analysis provides information about the dynamics of EEG by quantifying the constituent frequencies present in EEG. However, spectral analysis only describes the patterns of electrical activity at individual electrode sites. An alternative strategy is to examine the distribution of electrical activity across the entire surface of the scalp and to quantify patterns of change in the spatial distribution of EEG. The purpose of the present study was to compare younger and older adults on two such quantitative measures of EEG activity that take into account data from each of 128 electrode sites. These two measure are the recrudescence rate (Pribram et al. 1996) and a measure of algorithmic complexity (Kolmogorov 1965).

The recrudescence rate as a measure of the rate of change in EEG voltage animations

Relatively recent technology has made it possible for many labs to represent the spatial distribution of EEG through voltage maps that use data from a limited number of electrode sites to extrapolate voltages over the entire surface of the scalp. When voltage maps at successive measurement epochs are presented as running animations, it is clear that the observed pattern (a) is highly complex and (b) changes at a rapid rate. In order to compare the patterns in various records with each other, it is necessary to quantify one or more aspects of these complex patterns.

Using running animations of EEG voltage maps as a starting point, Pribram et al. (1996) proposed a number of techniques for quantifying the complex patterns of change observed in these maps. One strategy was simply to track changes in the location of a single feature of the running animation. The feature selected was the highest squared voltage among all electrode sites at each successive measurement epoch. The rate of change in the location of this feature was quantified by calculating the number of changes per second in the location of the highest squared voltage. Pribram et al. (1996) referred to this measure as the recrudescence rate. The term recrudescence implies a change in location of a particular feature without an action at one site causing the appearance of that feature at another site. The authors found that the recrudescence rate was higher during performance of a mental arithmetic task than during a resting baseline.

Algorithmic complexity as a means of quantifying the complexity of patterns of change in the location of the highest squared voltage

The recrudescence rate provides information about the rate of change over time in the location of a single feature of an EEG voltage animation, the highest squared voltage. However, this measure does not contain information about the degree of complexity in the sequence of electrode sites containing the highest squared voltage or the degree to which there is redundancy in this sequence. Information about the path of successive locations of the highest squared voltage can be represented by (a) assigning an abstract symbol to each electrode location, (b) determining the electrode site containing the highest squared voltage at each measurement epoch, and then (c) constructing a time series consisting of the symbols corresponding to each measurement epoch. A measure of the algorithmic complexity (Jimenez-Montano 1984; Kolmogorov 1965) of this time series was used to quantify the degree of complexity present in this symbol string representing successive locations of the highest squared voltage.

Mathematically, algorithmic complexity can be thought of as a data compression routine that defines the degree of complexity present in a string of symbols in terms of the number of bits of information needed to represent the symbol string after compression. Random sequences of symbols cannot be compressed to a significant degree. However, symbol strings that contain substrings that repeat themselves one or more times (consistent with the presence of a hierarchically structured redundant pattern) can be compressed to a significant degree.

Algorithmic complexity complements the recrudescence rate because it captures information about the pattern of changes in the location of the highest squared voltage, not just the rate of change in its location. The computational routine used to calculate algorithmic complexity in this paper has been used previously to describe the complexity of neural spike trains under different experimental conditions (Rapp et al. 1994) and the complexity of variations in heart rate (Storella et al. 1996). Additional information about the mathematical definition of algorithmic complexity is provided in the Methods section of this paper.

Purpose of the present study

The goal of the study was to compare younger and older adults on EEG measures of recrudescence rate and algorithmic complexity. EEG records from a 128 electrode system were obtained from 18 younger and 18 older adults before, during, and after performance of a 13 minute continuous performance task. On the basis of the generalized slowing hypothesis, it was predicted that the EEG of older adults would have lower recrudescence rates and lower levels of algorithmic complexity than younger adults.

Method

Participants

Eighteen healthy older subjects (10 males and 8 females) and 18 healthy younger adults (7 males and 11 females) served as research participants in this study. Older adults had a mean age of 71.55 years (SD = 6.82) and a mean of 16.17 years of education (SD = 2.23). Younger adults had a mean age of 21.78 years (SD = 3.35) and a mean of 14.39 years of education (SD = 1.42). The cognitive status of all participants was assessed using the Mini Mental State Examination (MMSE) Questionnaire (Folstein, et al. 1975). No MMSE scores for healthy older or younger adults fell in the impaired range (i.e., below a score of 26). No subjects had a previous history of learning disabilities, head injury, or coronary heart disease, and none were currently taking psychotropic medications. Three older adults were taking medication for hypertension and one older adult was taking medication for treatment of diabetes.

Apparatus

EEG data were collected with a 128-channel Geodesic Sensor Net, Version 1.0 (Tucker 1993). The net contains 128 electrodes wrapped in electrolytic sponges. Each sponge is set inside a plastic casing. The plastic casings holding the electrodes are connected by monofilament lines to form a geodesic pattern. The distance between neighboring electrodes is 2.8 cm. A reference electrode and common electrodes are located at vertex and the bridge of the nose, respectively. Surface impedance is lowered by soaking the sponges in a solution of KCl. Typical surface impedances are 15-20 KOhm.

EEG data were amplified through an Electrical-Geodesics Net Amps Dense Sensor Array Amp 128, Version 1.1 and interfaced with a Macintosh Power PC 8100. The Net Amps have input impedance of 200 MOhms, bandwidth of 0.01 Hz to 400 Hz, and a programmable low-pass filter configurable from 40-400 Hz (Tucker 1993). The sampling rate was 500 samples per second. Internal amp settings were controlled by data acquisition software developed by Electrical-Geodesics Incorporated, Version 1.0. Data analysis was conducted using MATLAB, Version 4.1.1 software on a Silicon Graphics workstation computer.

Materials

Continuous performance task. The Intermediate Visual and Auditory (IVA) Continuous Performance Test is an "integrated 13 minute auditory and visual continuous performance test designed to assess two major factors: Response Control and Attention" (Sanford 1995). This test presents participants with either "1"s or "2"s visually or audibly through speakers located beside the screen. Participants are instructed to press a mouse button every time they either see or hear a "1" and to do nothing when they see or hear a "2". Equal numbers of "1"s and "2"s and equal numbers of visual and auditory stimuli are presented. Five hundred stimuli were presented to participants over a thirteen minute period, or approximately one stimulus every 1.5 seconds.

The task provides information about the ability to maintain attention on a single task over an extended period of time. Performance and reaction time were evaluated by a button press on a computer mouse in response to either a randomly presented visual or auditory cue. Response control measures include prudence (a measure of impulsivity and response inhibition based on the number of responses to the non-target stimulus "2"), consistency (a measure of the variability of RTs on correct trials computed by dividing the RT at the 25th percentile by the RT at the 75th percentile and multiplying by 100), and stamina (based on a comparison of RTs obtained at the beginning and end of the task). Attention measures included vigilance (based on the number of trials on which participants failed to respond in the target stimulus "1"), focus (a measure of the variability of performance based on the dividing the standard deviation of RTs by the mean RT), and speed (the mean reaction time for correct trials). The IVA analysis software provides separate scores for responses on auditory and visual trials for each of the six types of measures described above. Only raw scores (unscaled for age or gender) for each of the resulting 12 dependent measures were used in statistical analyses of IVA performance. For all measures, higher scores indicate better performance.

Procedure

All participants were provided with verbal and written descriptions of the study and given the opportunity to ask questions about their participation as research subjects. After giving their informed consent, participants were seated in a comfortable reclining chair while the sensor net was applied. After head circumference and reference points were obtained, a sensor net that had been bathed in an electrolyte solution containing KCl was positioned on the surface of the scalp. The electrodes were manipulated against the scalp with finger pressure until all 128 electrodes were under the 40 KOhm impedance level. The investigator then left the participant in a dimly lit, sound attenuated room for data collection.

Two separate one minute EEG pre-task resting baseline samples were obtained. The first baseline recording was obtained with eyes open, the second with eyes closed. During the recordings, visual inspection was used to exclude artifacts due to eye movement or any other noticeable muscle activity. After the baselines were recorded, another series of running EEG data was collected while subjects performed the Intermediate Visual and Auditory (IVA) Continuous Performance Test (Sanford 1995). One minute samples of running EEG were collected during the first, seventh, and twelfth minutes of performance. After the task was completed, separate one minute post-task resting baselines with eyes open and eyes closed were obtained. Finally, participants were debriefed and given a chance to ask questions about the experimental protocol and the research questions addressed in the study.

Design

Independent variables.

A 2 (Age Group) X 7 (Task Condition) design was used in analyses of dependent variables in this study. Age group was a between-subjects independent variable and consisted of two levels (healthy younger and older adults). Task condition was a within-subjects factor and consisted of seven levels (pre-task eyes-open and eyes-closed conditions, three task conditions, and post-task eyes-open and eyes-closed conditions).

Dependent variables obtained from EEG.

The EEG dependent variables examined in this study were (a) the recrudescence rate and (b) the algorithmic complexity for the symbol string of electrode sites containing the highest squared voltage.

Recrudescence rate.

A MATLAB routine first determined the electrode location at each measurement epoch that contained the highest squared voltage. The program then determined the number of times per second that a change in the location of the highest squared voltage occurred (Pribram et al. 1996).

Algorithmic complexity.

The algorithm to compute the measure of complexity used in this study was originally described by Kolmogorov (1965) and further developed by Jimenez-Montano (1984). The algorithm consists of a data compression routine that takes a sequence of abstract symbols and determines the degree to which the symbol sequence contains segments that repeat themselves, and thus contain redundant information. Using this type of strategy, the less complex and more redundant the symbol sequence, the more the program is able to minimize the resulting compressed symbol sequence. For example, perhaps a sample symbol string consists of the following sequence of symbols [1 3 2 7 3 1 3 7 2 7 3]. The data compression routine searches for a pattern that repeats itself within this string of abstract symbols. In this case, the substring [2 7 3] is repeated twice. A new symbol is then assigned to represent each example of the repeating sequence. For example, the symbol [A] might be used to represent the substring [2 7 3]. A new and shorter symbol string is then generated by replacing each example of the repeating sub-string with the single new symbol. In this example, replacing every example of a [2 7 3] with the new symbol [A] results in a new string that is considerably shorter than the original, [1 3 A 1 3 7 A]. The algorithm repeats this procedure until there are no more repetitions present within the latest version of the complete symbol sequence. For example, substituting the second new symbol [B] for the substring [1 3] results in a further reduction of the number of bits of information required to represent the original symbol string, [B A B 7 A]. The measure of complexity generated by the program is based on the number of substitutions needed to eliminate any repetitions (or redundancies) in the final version of the symbol string and thus to fully compress the original symbol string.

In the present study, each symbol within the symbol sequence represents one of the 93 electrode sites closest to vertex (the routine used in this study is unable to use more than 93 different symbols, so 35 peripheral electrodes were omitted from the analysis). At each measurement epoch (occurring at two msec intervals), the location of the highest squared voltage was identified, and the symbol corresponding to that location was added to the string. The completed symbol string thus consisted of information about changes in the location of the highest squared voltage. The numerical value generated by the algorithm represents the degree to which redundant (repeating) sequences of locations of the highest squared voltage are observed.

Dependent variables based on IVA performance.

Twelve measures provided by the IVA analysis software were used as dependent variables in this study: Prudence-Auditory, Prudence-Visual, Consistency-Auditory, Consistency-Visual, Stamina-Auditory, Stamina-Visual, Focus-Auditory, Focus-Visual, Vigilance-Auditory, Vigilance-Visual, Speed-Auditory and Speed-Visual. These measures are described in the Materials section of this paper.

Results

Effects of age and task condition on EEG measures

The MANOVA routine from SPSS was used to conduct a 2 × 7 mixed-model ANOVA for each of the two EEG dependent variables described above. An alpha level of .05 was used for all tests of statistical significance.

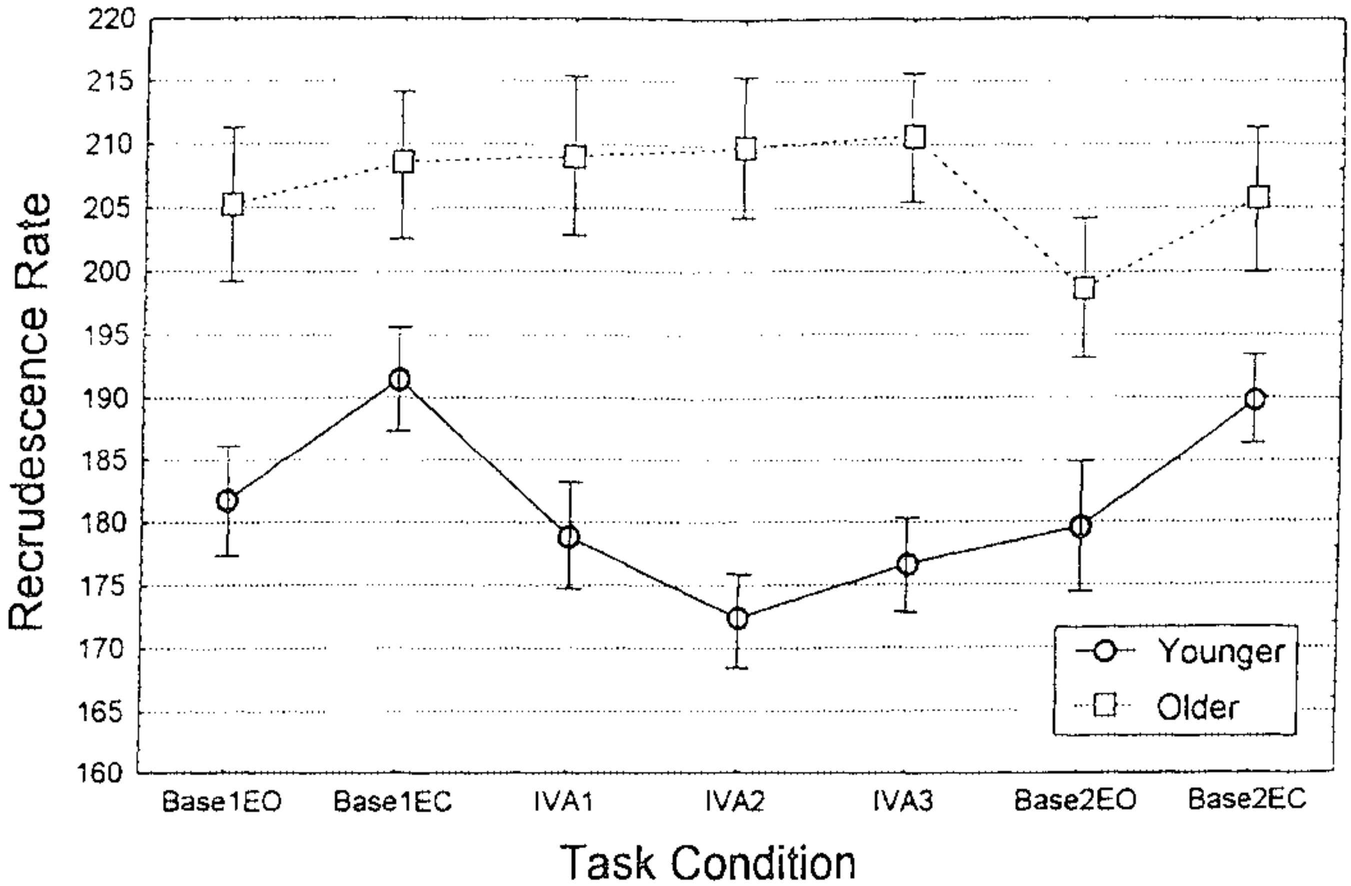

Figure 1. Recrudescence rates of younger and older adults during different task conditions. Error bars represent standard errors of the mean.

Comparisons of healthy older and younger adults on recrudescence rates.

A significant Age Group × Task Condition interaction was observed, $F(6, 204) = 2.79$, $p = .013$, $eta^2 = .11$ (see figure 1). No significant effect of task condition for older adults was observed. The simple effect of task condition for younger adults was significant, $F(6,102) = 2.68$, $p = .019$, $eta^2 = .19$. Simple comparisons regarding the effect of task condition for younger adults indicated that (a) recrudescence rates were significantly higher in the baseline eyes-open condition than in the baseline eyes-closed condition and that (b) recrudescence rates were significantly lower in the three task conditions than in the baseline eyes-open conditions. The presence of a significant main effect for age group indicated that older adults had significantly higher recrudescence rates than younger adults across all task conditions, $F(1,34) = 20.19$, $p < .001$. No significant main effect of task condition was observed, $p > .05$.

Comparisons of healthy older and younger adults on algorithmic complexity.

The presence of a significant main effect for age group, $F(1,34) = 16.27$, $p < .001$, $eta^2 = .32$, indicates that younger subjects displayed lower levels of algorithmic complexity in the pattern of change in the location of the highest squared voltage than did older adults (see figure 2). No main effect for task condition was observed. The Age Group by Task Condition interaction did not reach statistical significance, $p > .05$.

Comparison of younger and older adults on subtests from the IVA Continuous Performance Task

A multivariate analysis of variance was conducted comparing younger and older adults on the following twelve subtests from the IVA Continuous Performance Task: Vigilance-Auditory, Vigilance-Visual, Focus Auditory, Focus-Visual, Prudence-Auditory, Prudence-Visual, Consistency-Auditory, Consistency-Visual, Stam-

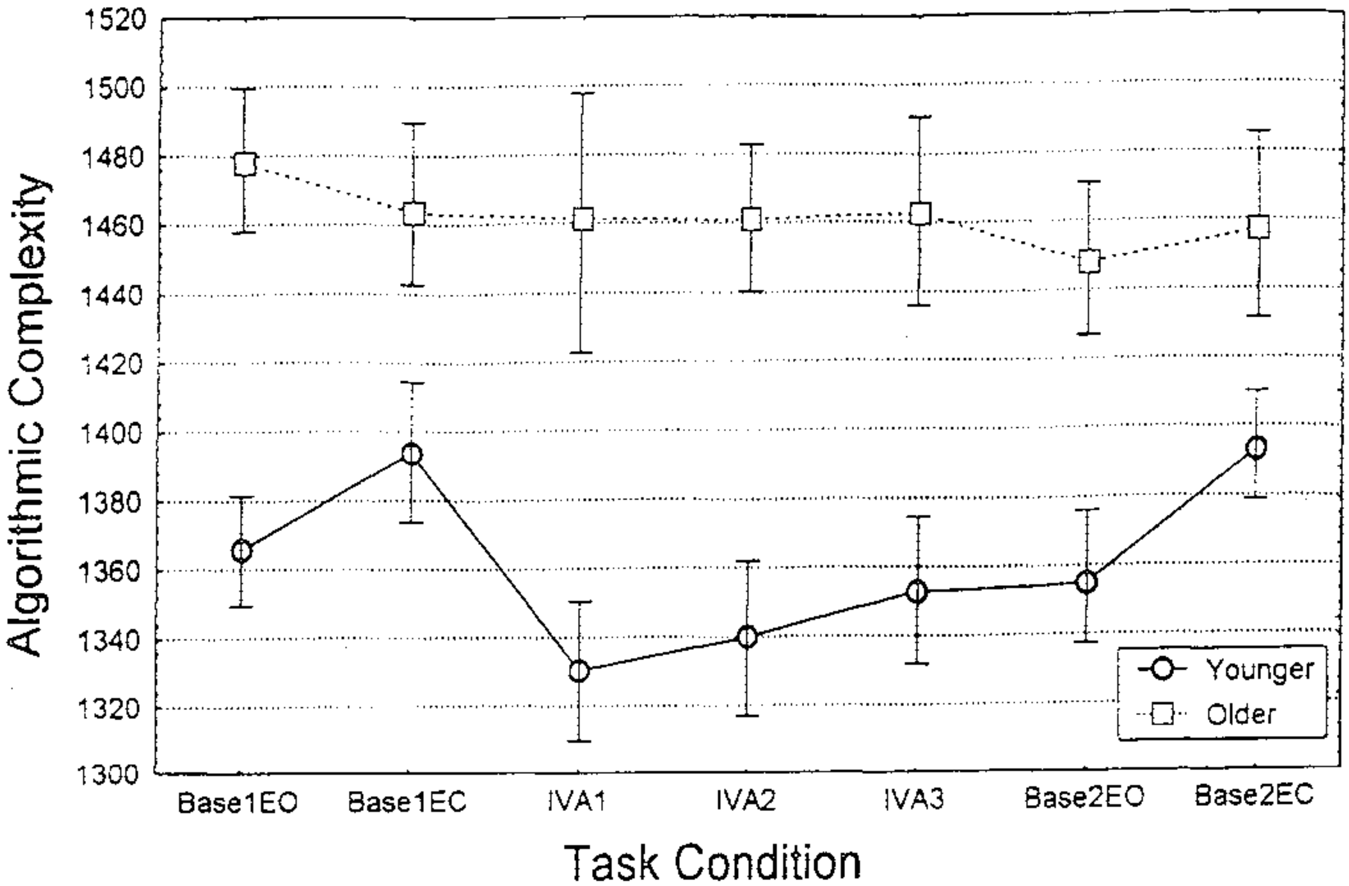

Figure 2. Algorithmic complexity of patterns of change in the location of the highest squared voltage for younger and older adults during different task conditions. Error bars represent standard errors of the mean.

ina-Auditory, Stamina-Visual, Speed-Auditory, and Speed-Visual. Means and standard deviations for IVA subtests are presented in table I.

A significant multivariate effect for age group was observed, $F(7,22) = 2.85$, $p = .016$, $eta^2 = .608$. Univariate analyses showed that older adults performed significantly better than younger adults on the Focus-Visual ($F(1,34) = 23.93$, $p < .001$, $eta^2 = .42$) and Consistency-Visual measures ($F(1,34) = 16.58$, $p < .001$, $eta^2 = .334$), reflecting greater variability in reaction times from the beginning to the end of the task in younger adults. Younger adults performed significantly better than older adults on the Speed-Auditory measure, ($F(1,34) = 4.30$, $p = .046$, $eta^2 = .112$), reflecting faster reaction times for younger adults on auditory trials. Significant effects of age group were not observed for the nine other IVA measures.

Pearson correlations between recrudescence rate and IVA measures

Scores from the IVA were correlated with the average of the three recrudescence rates obtained during performance of the IVA. Higher recrudescence rates were associated with significantly higher scores on both the Focus-Auditory measure ($r(34) = .467$, $p = .004$) and the Consistency-Visual measure ($r(34) = .584$, $p < .001$). No other correlations between the recrudescence rate and IVA measures reached significance at the .05 level.

Pearson correlations between algorithmic complexity and IVA measures

Scores from the IVA were correlated with the average of the three measures of algorithmic complexity obtained during performance of the IVA. Higher levels of algorithmic complexity were associated with significantly higher scores on the Consistency-Visual measure ($r(34) = .418$, $p = .011$). No other correlations between algorithmic complexity and IVA measures reached significance at the .05 level.

Discussion

The primary goal of this study was to determine whether age differences exist in the distribution of EEG

Table I. Means and Standard Deviations of IVA Measures for Younger and Older Adults. Values in parentheses represent standard deviations. Scores for Speed-Auditory and Speed-Visual are measured in milliseconds.

	Age Group	
IVA Measure	Younger Adults	Older Adults
Prudence-Auditory	97.83 (2.14)	96.89 (3.08)
Prudence-Visual	95.89 (4.71)	96.16 (4.88)
Consistency-Auditory	73.06 (6.49)	73.94 (6.27)
Consistency-Visual	71.33 (3.12)	76.38 (4.96)
Stamina-Auditory	100.94 (8.86)	98.53 (9.38)
Stamina-Visual	100.06 (9.54)	101.72 (9.53)
Focus-Auditory	71.11 (7.22)	72.05 (11.41)
Focus-Visual	73.44 (3.42)	78.16 (3.41)
Vigilance-Auditory	99.44 (1.41)	93.94 (2.25)
Vigilance-Visual	99.67 (0.76)	98.94 (2.38)
Speed-Auditory	466.22 (50.53)	526.78 (113.12)
Speed-Visual	330.38 (40.58)	361.00 (59.36)

across the surface of the scalp. The results of the study showed that older adults displayed significantly more rapid changes in the location of a single feature of EEG voltage animations (i.e., the highest squared voltage) than did younger adults. Analyses using a measure of algorithmic complexity indicated that changes in the location of this single feature were significantly more complex in older adults than in younger adults.

The study also provided an opportunity to observe recrudescence rates collected from participants in (a) different subject populations and (b) different task conditions. The study by Pribram et al. (1996) was designed only to describe and demonstrate the recrudescence rate as a possible method for quantifying EEG activity. The present study demonstrates the utility of the recrudescence rate as an individual difference variable that can discriminate between different task conditions and subject populations. The algorithmic complexity of patterns of change in the location of the highest squared voltage discriminated between younger and older adults but not between task conditions.

Overall, analyses involving measures from the IVA Continuous Performance Task indicated only modest performance differences between younger and older adults. Younger adults displayed significantly faster reaction times to auditory stimuli than older adults while older adults performed better than younger adults on two IVA measures based on the standard deviations of reaction times: Focus scores for visual trials and Consistency scores for visual trials. This pattern of results indicates that the responses of older adults are significantly slower, but less variable than those of younger adults across the 13 minute task. No age differences were observed in other IVA measures, including those measures of attention based on either the number of errors of omission (failing to respond to a target stimulus) or commission (responding to a non-target stimulus).

Correlational analyses indicated that significant correlations between the recrudescence rate and measures of task performance were obtained for only two measures of IVA performance: Consistency-Visual and Focus-Auditory. Scores for EEG algorithmic complexity were correlated with only the Consistency-Visual measure from the IVA. These findings indicate that both the recrudescence rate and the algorithmic complexity are largely insensitive to performance measures assessing speed, vigilance, and response inhibition. Further studies are needed to determine whether these EEG measures are sensitive to performance differences in tasks requiring other components of information processing, such as memory or selective attention.

Because the relationships between EEG and behavioral measures are correlational in nature, the interpretation of age differences in recrudescence rate and algorithmic complexity should be approached with caution. The data presented in this paper show that an EEG measure of the rate of change over time in the brain's electrical activity, the recrudescence rate, was consistently faster in older adults than in younger adults. This finding, at face value, seems inconsistent with a generalized slowing interpretation of brain/behavior changes that occur in normal aging. One possible explanation for this apparent inconsistency is that faster recrudescence rates and higher levels of algorithmic complexity in the EEG records of older adults reflect a decrease in the coordination of processing activities among cortical areas. This decrease in coordination might, in turn, be caused by an age-related slowing in the speed of information processing. Further work utilizing measures of shared variance among electrode sites may help to clarify the effects of aging on the spatially complex patterns of change observed in dense-array EEG recordings.

In summary, the present study provides evidence that two quantitative measures of EEG activity based on patterns of change among electrode locations successfully discriminate between two subject populations: younger and older adults. In addition, the recrudescence rate discriminated between task conditions, particularly between eyes-open and eyes-closed conditions. Further research is needed to determine the specific task conditions under which higher and lower scores on these measures are obtained and to determine the types of tasks where levels of performance are related to these quantitative measures of EEG activity.

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