

ERP Indicators of Learning in Adults

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This study investigated learning-related changes in the brain activity of young adults. A group of 29 undergraduate students (18–24 years) participated in a learning study that included a pretest, a training session, and a posttest. Each trial involved presentation of a complex visual stimulus and its spoken “name.” Auditory event-related potentials (ERPs) were recorded in response to matching and mismatching names. In the pretest, the participants guessed whether the names were matching the figures. During training they learned the names of a set of simple elements making up the complex figures and were required to master a simple rule for combining the visual and auditory stimuli. The posttest included presentation of the combinations learned during training as well as novel pairings of the same elements. Following training the number of correct responses for learned items doubled and the amplitudes of the auditory ERPs to learned and rule transfer stimuli were more positive than brain waves to the not learned or novel items over most of the analysis window. The ERPs further differentiated between a familiarity response (late positive shift) and learning-specific changes (N2–P3 range). Overall, the findings suggest that ERPs can be a useful tool for learning assessment and offer new insights in the study of individual differences associated with the learning process.

Traditional learning assessment techniques based on behavioral observations are not always sensitive to small increments in learning that occur over short periods of time. They also may not be as efficient in determining whether learning has oc-

curred when applied to populations with limited behavioral response capabilities (e.g., infants, very young children, individuals with disabilities, etc.). Furthermore, most behavioral assessments for learning are age specific, and thereby make longitudinal comparisons more difficult. On the other hand, electrophysiological measures, such as recordings of electrical brain activity, are highly sensitive to changes in information processing even when behavioral indicators are not present. Such procedures can use similar testing paradigms across various ages and are well suited for tracking developmental changes.

This article reports results of an investigation of the learning process in adults using event-related potentials (ERPs). The ERP is a portion of the ongoing electroencephalogram (EEG) thought to reflect changes in brain activity over time (Rockstroh, Elbert, Birbaumer, & Lutzenberger, 1982). What distinguishes the ERP from the more traditional EEG measures is that it is time-locked to the onset of a stimulus presented to the participant. This aspect represents a major advantage over other neurophysiological measures because it allows one to evaluate the relation between a specific event and the associated brain activity (Callaway, Tueting, & Koslow, 1978; Rockstroh et al., 1982). This relation can be resolved down to milliseconds or even fractions of a millisecond.

Previous research identified numerous ERP components as reflecting learning differences. The majority of studies that focused on learning appear to have combined it with memory and employed either recognition or recall paradigms (Donaldson & Rugg, 1998; Wilding & Rugg, 1996, 1997) after directed learning (Holamon, Morris, & Retzlaff, 1995; Honda et al., 1996; Hugdahl & Nordby, 1991; van Hooff, Brunia, & Allen, 1996), or incidental learning situations (Noldy, Stelmack, & Campbell, 1990; Paller, Kutas, & Mayes, 1987; Paller, McCarthy, & Wood, 1988). The stimuli typically involved meaningless consonant-vowel syllables (Mäntysalo & Gaillard, 1986), single or paired words and pseudowords (Curran, 1999; Donaldson & Rugg, 1998; Johnson, Pfefferbaum, & Kopell, 1985), artificial language made of nonwords (McCandliss, Posner, & Givón, 1997), as well as pictures (Friedman, 1990; Kazmerski & Friedman, 1997) and faces (Nelson, Thomas, de Haan, & Wewerka, 1998). The results for all stimulus types are generally consistent in finding that ERPs for items correctly recognized as old (i.e., learned stimuli) are characterized by more positive amplitudes and shorter latencies. Such differences usually are most evident over the left hemisphere. Specific ERP components sensitive to the old-new information distinction spanned multiple time ranges and included P2 (McCandliss et al., 1997), N2 (Mäntysalo & Gaillard, 1986), P3 (Johnson et al., 1985; Kazmerski & Friedman, 1997; Mäntysalo & Gaillard, 1986; Rose, Verleger, & Wascher, 2001), N400 (left temporo-parietal or frontal maximum), and a late slow wave between 400 msec and 800 msec following stimulus onset (Allan & Rugg, 1997; Curran, 1999; Kazmerski & Friedman, 1997; Johnson, Kreiter, Russo, & Zhu, 1998; Paller et al., 1988).

However, during the course of human development much of one's learning involves not the mere acquisition of specific facts or skills but also mastery of a great variety of rules. To address such concerns, a separate line of behavioral research focused on learning in terms of rule acquisition and was most commonly associated with language development in young children. Foss (1968) utilized a paradigm based in the concept of the miniature learning system (MLS), initially introduced by Esper (1925). Esper devised a matrix of stimuli that varied in content, color, shape, and so on, that could be used to study the acquisition of rules. Foss (1968) tested participants on an association task between color, syllable, and shape. The association difficulty level differed between the two groups of participants, and those who had less complex associations to memorize also made more correct responses to the stimuli. However, improvement was noted in both groups. Foss concluded that learning occurred through mastering simple information first, and then using it to acquire new, more elaborate rules.

Palermo and Eberhart (1968) further examined the effect of rule complexity on learning by testing a group of adolescents on a matrix of number–word associations with regular and irregular patterns, similar to the structure of the English language verb category. The participants were instructed to match the correct pattern of the combinations. During each of the two testing sessions, participants received more examples of one pattern than the other. The results indicated that participants accurately matched up the combinations of the stimuli that they experienced more frequently during their training period regardless of the overall complexity of the pattern. The authors suggested that frequent exposure makes stimuli more familiar and leads participants to learning the rule that governs them. In a subsequent study, Palermo and Parrish (1971) found that the total number of exposures to a rule application presented during training is more important to learning than the variety of the examples provided. Rules were learned with the same accuracy whether the same example was presented multiple times or a variety of examples were presented once each.

More recently, McCandliss et al. (1997) examined the changes in brain activity associated with rule acquisition. In their study, participants mastered an artificial language made of nonwords. Following 50 hr of learning the “meaning” of various nonwords, specific changes were noted in the 280- to 360-msec window after stimulus onset where responses to the learned nonwords began to elicit P2 components resembling responses to standard English words. Responses to the not-learned nonwords remained unchanged over time (McCandliss et al., 1997).

This study defined learning as acquisition and later recall of discrete stimuli as well as the ability to apply the learned rule for arranging them into new combinations of the same items. It was hypothesized that learning would result in more positive ERPs in response to the learned stimulus combinations compared to brain waves elicited by the same items prior to training. Second, the differences would be larger over the left hemisphere. Third, it was expected that new combinations of

the learned components (i.e., rule transfer items) would be associated with different ERPs compared to those recorded in response to stimuli experienced before training. Fourth, ERPs elicited by novel stimuli in the posttest were predicted to be similar to the brain waves recorded prior to training but different from the ERPs associated with the learned and rule transfer stimuli.

METHOD

Participants

Twenty-nine adults (10 men), age 18 to 24 years, from the University of Louisville undergraduate Introductory Psychology participant pool (M age = 20.21 years, SD = 1.74 years) participated in the study for partial course credit. All participants had normal or corrected-to-normal vision and a mean full-scale IQ of 105.69 ± 7.58 points as determined by Shipley Institute of Living Scale (Zachary, 1986). Twenty-seven participants were right-handed (M = 0.67, SD = 0.26) and 2 participants were left-handed (M = -0.61, SD = .15) as determined by the Edinburgh Handedness Inventory (Oldfield, 1971). Data from an additional 8 participants were excluded from the analyses due to equipment failure (n = 3), failure to pass a neurological wellness screening (n = 2), or poor quality of ERP data (n = 3).

Stimuli

Nine pairs of labels and colorful cartoon figures served as stimuli, three pairs used for the pretest session and six additional pairs used in the posttest. The labels consisted of short first and last names digitally recorded by a female native English speaker using the SoundEdit® program for the Macintosh (v. 16). Both first and last names were one-syllable (three or four letters) long. First and last names within a pair were separated by a 70-msec silence period. Labels were presented auditory at 75 dB SPL through a speaker positioned 1 m above the center of the participant's head.

The cartoon figures were made of simple geometric shapes (e.g., circle, rectangle, etc.) and resembled a human (head, body, hands, and feet). The figures were presented on a white background in the center of a 17-in. computer monitor positioned 1 m in front of the participant. All shapes utilized a variety of random colors and occupied approximately two thirds of the viewable screen area (see Figure 1).

The assignment of labels to figures was pseudorandom with the first name always associated with the top portion of the figure (head) and the last name corresponding to the lower portion (body). The stimuli were selected from a larger set based on ratings of ease of pronunciation for the names and lack of specific object

Stimuli

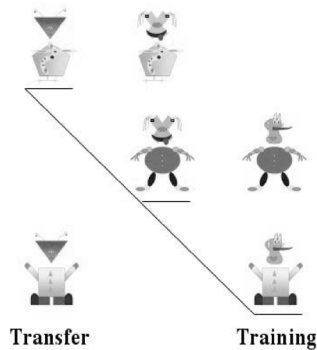


FIGURE 1 Diagram of stimuli used in training (underlined diagonal set) as well as the transfer stimuli (remaining stimuli).

associations for the shapes obtained prior to the study from a separate group of 10 participants.

Procedure

Each participant was tested individually in a sound-isolated room. The brain waves were obtained using a high-density array of 128 Ag/AgCl electrodes (Geodesic Sensor Net, EGI, Inc.). Prior to placement, the net was soaked in warm potassium chloride solution (KCl) that served as a conductor for electrical currents from the scalp to the electrodes embedded in soft sponges of the net. During recording, all electrodes were referenced to vertex. All impedances were at or below 40 k Ω as indicated by measurements taken immediately before and after the ERP acquisition session. The filters were set at .1–30 Hz. Data were sampled every 4 msec (sampling rate = 250 Hz).

The experimental procedure included three main blocks: pretest, training, and posttest. During the pretest period, participants were instructed to view three figure–label pairs (not learned set) presented one a time, guess whether the spoken label matched the figure or not, and indicate their judgment by pressing a corresponding key on a response pad. The experimenter explained that each figure had only one correct label but gave no information on the rules for pairing them. No feedback was provided. The assignment of the buttons to match and not match responses was counterbalanced across participants. Each stimulus pair was presented 10 times in matching and 10 times in not matching (same label paired with a different figure) pairs, resulting in 60 trials. Each label was paired with one matching and one mismatching figure.

During the training stage, the participants studied the same three labels and figures printed on 4×6 in. white cards. First, the experimenter explained the principle of assigning each first name to the head of the figure and the last name to the body of the figure. Next, the participant was given an opportunity to study which label went with which figure part. Overall, the study set included six picture components (three heads and three bodies) and six labels (three first names and three last names). At that time feedback was provided for each response. To control for the amount of learning, all participants practiced until they could correctly name all six figure parts (training lasted 5–8 min). No participants had to be excluded due to a failure to master the study set.

In the posttest block, each participant again was asked to make match–mismatch judgments for nine pairs of labels and figures: three learned pairs, three pairs made of the same components but arranged in different groups (e.g., a head and first name from one figure paired with the body and last name of another) designed to test the participant's ability to transfer the learned rule to a new instance of the same components (rule transfer set), and three novel pairs of figures and labels that previously had not been seen or heard. All stimulus pairs were presented in random order. Each figure and label pair was presented eight times in matching and eight times in not matching conditions for a total of 144 trials. Similar to the pretest session, within each stimulus type, all auditory labels were paired once with a matching and once with a mismatching figure. Assignment of the stimulus pairs to the learned, transfer, or novel conditions varied across participants.

For the pre- and posttest blocks, each trial began with a presentation of a fixation point for 500 msec centered on the screen, followed by a figure presented for 1,000 msec followed by the spoken label (while the picture remained on the screen for an additional 2,500 msec). The stimulus was then replaced by a question mark presented in the center of the screen for 2,000 msec to serve as the response prompt. The intertrial intervals varied randomly from 1.5 to 2.5 sec to prevent habituation.

Auditory ERPs were recorded in response to each stimulus label during pretest and posttest blocks only. The brain wave data recording was controlled by the Net Station v.2.0 software package (EGI, Inc.). The E-prime software package (Psychological Software Tools, v. 1, Service Pack 2) controlled stimulus presentation and behavioral data collection.

RESULTS

Behavioral Data

Reaction time and accuracy data for each participant were submitted to separate repeated measures mixed design analyses of variance (ANOVAs) involving sex (2: female, male) \times stimulus type (4: to-be-learned, learned, rule transfer, and novel) \times match condition (2: match, mismatch).

The analysis of reaction time data resulted in a stimulus type main effect, $F(3, 66) = 7.416, p < .001$. Specifically, to-be-learned items elicited the longest reaction time as compared to other stimuli and there were no significant differences in the reaction time for the learned, rule transfer, and novel items ($p > .3$). All other main effects and interactions were not significant.

The analysis involving accuracy as a dependent measure resulted in the main effect of stimulus type, $F(3, 66) = 40.921, p < .0005$; Figure 2). As expected, the number of correct responses to learned items increased after training from 32% to 88% as a result of learning, $t(23) = -8.856, p < .0005$. Further, rule transfer items elicited more correct responses (81%) than the to-be-learned items (32%) in the pretest, $t(23) = -7.667, p < .0005$, and the novel items (47%) in the posttest, $t(23) = 5.582, p < .0005$.

ERP Data

Auditory ERP data (in response to the spoken labels for the visual stimuli) for all participants were segmented into epochs including a 100-msec prestimulus base-

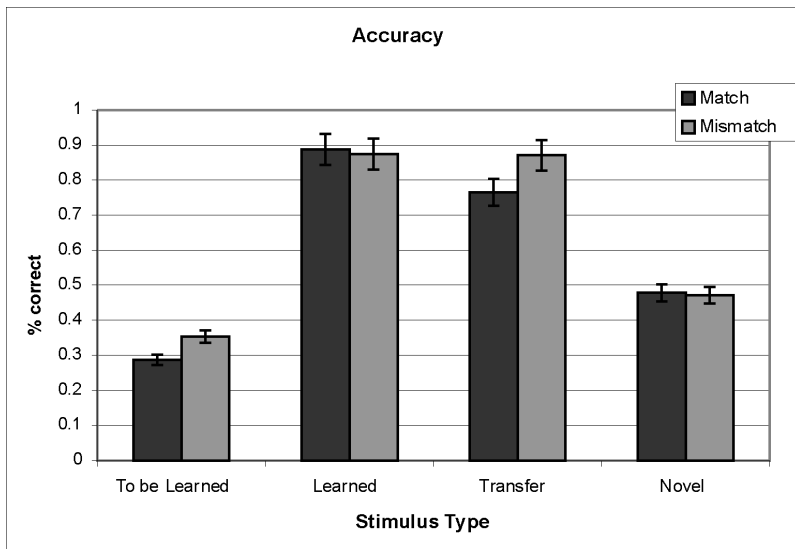


FIGURE 2 Bar graph indicating accuracy rate in correctly identifying which names go with which stimuli. Accuracy rates are lowest for the untrained stimuli prior to training and the novel, untrained stimuli presented following training. No differences are noted in accuracy rates for match versus mismatch conditions for the trained and transfer stimulus sets. Although there appears to be a difference in accuracy for to-be-learned and novel items, in reality, given the small number of possible correct responses, this difference is less than one response. Both types of the stimuli elicited correct responses at chance level.

line and a 900-msec poststimulus interval. All data were rereferenced offline after data collection from the vertex (Cz) to the average of all electrodes (Junghoefler, Elbert, Tucker, & Braun, 1999). Next, artifact rejection was carried out to eliminate ERPs contaminated by movement and eye artifacts from further analysis. Rejection rates were comparable across stimulus conditions. The segmented data were then averaged individually for each participant. Data from electrodes identified as bad (poor signal quality on 10% or more of the trials) were replaced using spherical spline interpolation. For a data set to be included in the analyses, a total of no more than 12 channels (10% of the array) could be considered bad and no two interpolated electrodes could be immediately adjacent to one another. Averaged data were baseline-corrected by subtracting the average microvolt value across the 100-msec prestimulus interval from the poststimulus segment. Next, for each participant and condition, data from the 128 electrodes were clustered into 10 regions by averaging the data for electrodes within five anatomical regions in each hemisphere: frontal, central, parietal, occipital, and temporal (see Figure 3). This approach represented a modification of the clusters initially proposed by Curran

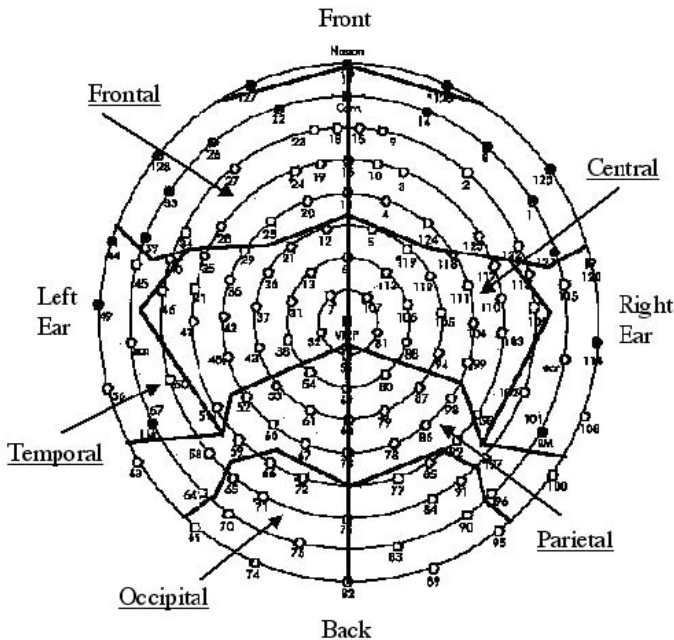


FIGURE 3 Map of electrode distribution for the 128-channel Geodesic Sensor Net (EGI, Inc.) and the electrode clusters used for the analysis procedure in adult learning experiment. Midline electrodes (identified by the vertical line in the center of the plot) were excluded from the analysis.

(1999) that did not reflect the anatomical boundaries. The purpose of the clustering procedure was to reduce the number of variables to increase statistical power instead of recruiting an unreasonably large number of participants.

Clustered data for all participants and stimulus conditions (a total of 2,320 ERPs representing 10 electrode clusters \times 4 stimulus types \times 2 conditions \times 29 participants) were submitted to a single temporal principal component analysis (PCA) using the SPSS version 10 software package. The purpose of the PCA was to reduce data from 225 individual time samples (corresponding to the 225 \times 4 msec = 900 msec) per brain wave to a smaller number of uncorrelated components (i.e., segments of the brain wave) reflecting high and systematic variability across all 2,320 ERPs and accounting for the maximum amount of variance. For electrophysiological data, such components generally correspond to ERP peaks or slopes. The Scree test (Cattell, 1966) was used to select the number of factors for subsequent analyses. Next, the factors were rotated using the Varimax method to obtain maximum separation, or independence for the extracted factors (Gorsuch, 1983; Harman, 1976). This analysis approach has been extensively used by Molfese since 1976 (Molfese, Nunez, Seibert, & Ramanaiah, 1976) and its findings have been replicated in programmatic research across numerous laboratories (Brown, Marsh, & Smith, 1979; Chapman, McCrary, Chapman, & Bragdon, 1978; Donchin, Tueting, Ritter, Kutas, & Heffley, 1975; Ruchkin, Sutton, Munson, Silver, & Macar, 1981; Segalowitz & Cohen, 1989). Although questions regarding the possibility of misallocation of variance in a PCA across immediately adjacent components have been raised in the past (e.g., Wood & McCarthy, 1984), even Wood and McCarthy (1984) noted that traditional amplitude and latency approaches are "no less subject to the problem of component overlap" (pg. 258; see also Beauducel & Debener, 2003; Chapman & McCrary, 1995, for more recent treatments of this discussion).

The rotated factor scores were used as dependent variables in a repeated measures ANOVA used to determine whether the observed variability occurred systematically in relation to the variables under investigation. Data from the pretest and posttest sessions were combined to represent different levels of the stimulus type variable and included in the same design: stimulus type (4: to-be-learned, learned, novel, rule transfer) \times match condition (2: match, mismatch) \times electrode region (5: frontal, central, parietal, temporal, occipital) \times hemisphere (2: left, right).

The PCA of the pretest and posttest data identified four factors that accounted for 86.42% of the total variance (see Figure 4 for the factor structure and corresponding variances). Factor 1 accounted for 32.17% of the total variance and corresponded to the slow positive portion of the ERP that occurred 476 to 900 msec after stimulus onset. The maximum region of variability was reached at 804 msec. Factor 2 accounted for 20.55% of the total variance and characterized the variability in the interval from 160 msec through 508 msec (with its maximum peak at 316

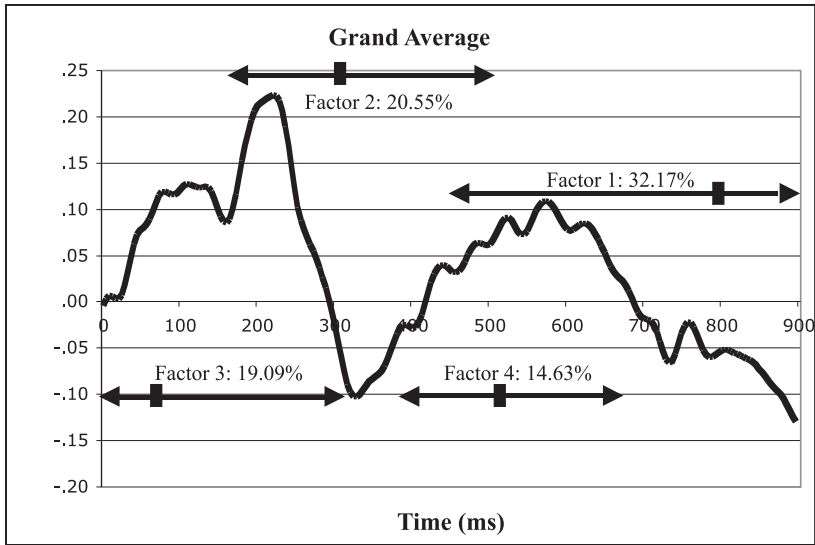


FIGURE 4 Centroid, or grand averaged ERP. Horizontal lines mark the time intervals for four factors derived by the PCA. Black squares on the lines correspond to the maximum of each factor. Percentage of variance accounted for by each factor is indicated next to the line markers.

msec, approximating the N2 peak). Factor 3 accounted for 19.09% of the variance and corresponded to the poststimulus interval of 0 to 272 msec (maximum peak at 84 msec, approximately P1-N1 complex). Factor 4 accounted for 14.63% of the total variance and also characterized the variability for the interval from 380 to 668 msec, corresponding to the P3 range (maximum variability at 508 msec).¹

Stimulus effects. As expected, ERPs to the to-be-learned, novel, and rule transfer stimulus combinations differed across hemispheres and electrode regions and changed from pretest to posttest trials.

In the 160- to 508-msec poststimulus interval (Factor 2), the ANOVA identified a two-way interaction of Stimulus \times Electrode, $F(12, 336) = 2.771$, $p < .03$, and a higher order interaction of Stimulus \times Electrode \times Hemisphere, $F(12, 336) = 1.901$, $p < .033$. Post-hocs indicated that stimulus differences were noted over frontal regions in the left hemisphere and over frontal, central, and parietal areas in the right hemisphere. Specifically, over frontal left sites, learned pairs were characterized by larger amplitudes than to-be-learned items, $t(29) = -2.12$, $p = .043$, and

¹Although the time interval for this factor overlaps Factor 1, the maximum points for each factor are well separated and the statistical effects characterizing each segment are very different, suggesting that the factors represent distinct components. The observed overlap could be attributed to the slow-changing nature of the late ERP component resulting in a larger number of correlated time samples.

rule transfer stimuli elicited greater amplitudes than to-be-learned, $t(29) = -2.219$, $p = .034$, or novel stimuli, $t(29) = -2.374$, $p = .024$. A similar pattern was noted for the frontal right region: learned versus to-be-learned, $t(29) = -2.281$, $p = .03$; and rule transfer versus to-be-learned, $t(29) = -2.194$, $p = .036$, except for the latter comparison, which was not significant. A different discrimination effect was observed over the right central area where novel items elicited larger ERPs than the learned, $t(29) = -2.587$, $p = .015$, or the rule transfer stimuli, $t(29) = 2.413$, $p = .022$. Over the right parietal area, to-be-learned stimuli were characterized by larger ERPs than the learned pairs, $t(29) = 2.09$, $p = .046$.

Furthermore, the left hemisphere was associated with larger brain waves relative to the right hemisphere for to-be-learned, learned, and rule transfer stimuli. However, the distribution of the observed effects varied across the stimuli. For to-be-learned items, these differences were present over frontal, $t(29) = 2.871$, $p = .008$; central, $t(29) = 2.426$, $p = .022$; and temporal areas, $t(29) = 2.79$, $p = .009$. Left hemisphere dominance for learned items was noted over central, $t(29) = 2.317$, $p = .028$, and temporal regions, $t(29) = 2.121$, $p = .043$. Rule transfer pairs were associated with hemisphere differences over temporal, $t(29) = 2.617$, $p = .014$, and occipital sites, $t(29) = 2.133$, $p = .042$. No hemisphere effects were present for the novel stimuli.

The later 380- to 668-msec range (Factor 4) was characterized by a main effect of stimulus, $F(3, 84) = 3.002$, $p < .035$, and a Stimulus \times Hemisphere interaction, $F(3, 84) = 3.29$, $p < .026$. Over the left hemisphere, ERPs for to-be-learned items were consistently smaller than for the learned, $t(29) = -2.049$, $p = .05$; rule transfer, $t(29) = -2.056$, $p = .049$; and novel stimuli, $t(29) = -2.776$, $p = .01$. Over the right hemisphere, to-be-learned stimuli were associated with larger amplitudes than learned, $t(29) = 2.321$, $p = .028$, and rule transfer pairs, $t(29) = 2.086$, $p = .046$. These effects are illustrated in Figure 5, which depicts ERPs recorded from over the left and right frontal electrode sites for the to-be-learned and learned conditions.

Match–mismatch effects. Additional effects associated with the match condition were also present. ERP differences in the early portion of the wave (0–272 msec, Factor 3) were attributed to a main effect of match, $F(1, 28) = 8.068$, $p < .035$ and a Match \times Electrode Region interaction, $F(4, 112) = 3.018$, $p < .021$. In the middle section (380–668 msec, Factor 4), ERP differences were described by a Match \times Hemisphere interaction, $F(1, 28) = 4.378$, $p < .046$. The second half of the brain wave (476–900 msec, Factor 1) reflected differences associated with a main effect of match, $F(1, 28) = 10.838$, $p < .003$.

In general, within 0 to 272 msec after stimulus onset, compared to the mismatching pairs, matching stimuli elicited larger amplitudes over central regions, $t(29) = 2.099$, $p = .045$, and smaller ERPs over temporal areas, $t(29) = -4.303$, $p < .001$. In the 380- to 668-msec interval (Factor 4), mismatched stimuli were associated with more positive amplitudes than matched pairs over the left hemisphere,

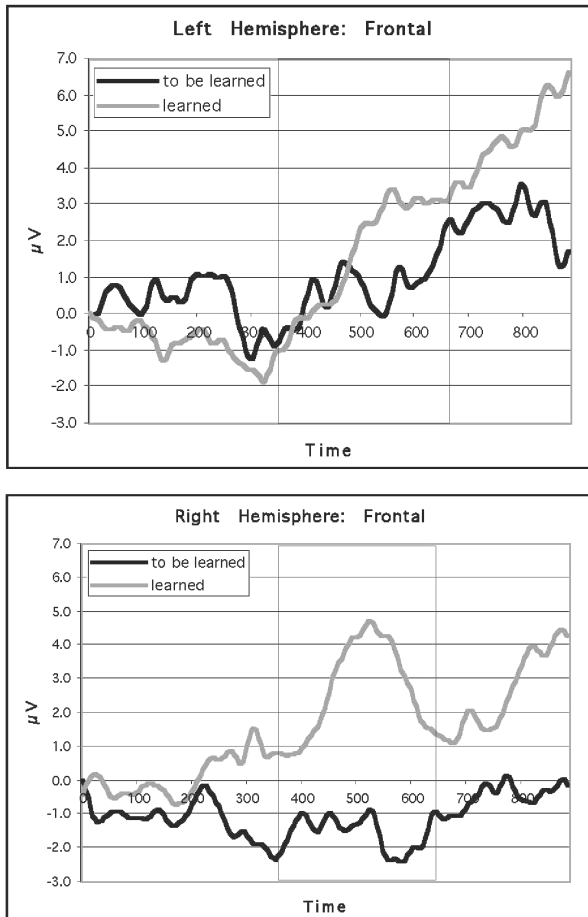


FIGURE 5 ERPs recorded from over the left and right frontal regions for ERPs collected in response to the stimuli prior to training (to be learned) and following training (learned). Positivity is up. ERP duration is 900 msec. Note the large positivity for the learned stimuli occurring between 400 and 600 msec.

$t(29) = -2.164, p = .039$, whereas the reverse was true for the right hemisphere, $t(29) = 2.985, p = .006$. ERPs for mismatched items were larger than for the matched stimuli in the later portion of the wave (476–900 ms, Factor 1).

Hemisphere differences. A main effect of hemisphere was noted within the 160- to 508-msec interval (Factor 2), $F(1, 28) = 10.298, p < .003$, where brain waves were more positive over the left hemisphere.

DISCUSSION

This study investigated the psychophysiological correlates of learning defined as the process of memorizing a set of stimuli, acquiring a rule for combining stimulus components, and the application of the rule to previously unknown combinations. Young adults were presented with complex visual stimuli with each composed of two distinct elements. Next, participants learned the labels for a small set of the elements (low memory load) and the rule for creating the complex visual character. The success of learning was measured in terms of the correct identification of learned and novel items (similar to the measures used in the recognition and recall paradigms) and by the respondent's ability to apply the rule correctly to previously unseen combinations of learned components.

As indicated by the behavioral results, in the pretest portion the participants responded at chance levels. However, after a brief training period, the number of correct responses for the learned material approached 90% whereas completely novel stimuli were still associated with chance levels of performance. Learning effects were present throughout the entire ERP segment, from the stimulus onset until the end of the segment, suggesting that training affected all stages of information processing, from the identification of the basic physical properties of each stimulus to making the decision about the response.

As predicted, learned items elicited more positive amplitudes, especially over the left hemisphere, compared to the to-be-learned and novel stimuli. A similar pattern was noted for ERPs elicited by the rule transfer combinations. There were no significant differences between the brain waves for the learned and rule transfer conditions. Also, in line with our expectations, there were no differences in ERPs associated with the stimuli presented in the pretest and the novel pairs from the posttest. This finding suggests that learning changes the state of the brain by increasing its preparedness for dealing with new combinations of the learned components.

An alternative explanation could suggest that the observed amplitude differences between the pre- and posttest sessions for all stimulus types could be solely due to increased familiarity rather than mastery and application of the rule. Indeed, our results provide some evidence of familiarization. Similar to the learned and rule transfer stimuli, increased late positivity over the left hemisphere was noted in response to the novel items in the posttest relative to the stimuli presented prior to training (which at that time would be similarly new). These results could indicate that during the course of the study the participants became more familiar with the general type of the stimuli (e.g., understood the system of naming a picture) and the procedure (e.g., got used to judging figure-label relations). Further, these findings are consistent with the results previously reported by Molfese and Molfese (1997), who reported that in adolescents, late positivity changed for both the trained and untrained stimuli from the pretest

to the posttest trials. The researchers suggested that the late-occurring ERP component reflected a familiarization effect.

However, in portions of the ERPs prior to the late positive components, learned and rule transfer items were clearly distinguished from the novel and to-be-learned stimuli. Further, rule transfer combinations were different in visual appearance and had new spoken labels, never seen or heard together prior to the posttest session. Therefore, one would not expect a strong familiarity response to such stimuli. Nevertheless, our data indicated no significant differences in ERPs to learned and rule transfer stimuli, suggesting that participants processed the information in greater detail than would be expected from the familiar–unfamiliar judgments alone.

Although supporting the idea that learning results in changes in brain waves, one could also argue that learned and rule transfer items elicited similar brain responses because, in fact, there was no rule extension. The participants might have learned not a general rule of matching labels to figures but a distinct set of components (e.g., first name–head and last name–body pairs) and in the posttest session merely recalled these exact facts rather than demonstrated generalization of the rule.² If this were the case, one would expect the rule transfer stimuli to elicit brain waves identical to those of the learned pairs. However, the results clearly indicate that ERPs associated with the rule transfer items, although sharing some commonalities with the data for learned stimuli, were characterized by a different pattern of topographic distribution, hemisphere differences, and a unique distinction from the other stimuli.

Another interesting question would be the longevity of the observed learning effects. One could argue that the changes in ERPs in response to learned and rule transfer items represented a temporary change rather than a more permanent shift in brain activity. However, even though data from this study were limited to one testing session immediately following the training, other studies indicate that reliable changes in ERPs can be detected for an extended period of time following training. Molfese, Morse, and Peters (1990) used ERPs to study the acquisition of names for different objects in 14-month-old infants. They noted that ERPs recorded after 5 days of training (20 min per day) discriminated between auditory stimuli correctly paired with the objects that they named versus objects that were trained to different names.

CONCLUSIONS

Learning effects can be assessed in different age populations using similar ERP procedures. This investigation with adults introduces the opportunity to view changes in ERPs not only in response to the learned stimuli following training but

²We would like to thank an anonymous reviewer for suggesting this possibility.

also to the generalization of learned information to new instances. This latter case may potentially offer a means to investigate changes in learning strategies and the brain's involvement in the learning process at different developmental stages. In this respect, we believe that the procedure offers some hope as a tool for identifying efficient and inefficient learning strategies, and thus can be of use in the study of learning disabilities.

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