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ELECTROPHYSIOLOGICAL CORRELATES OF STIMULUS EQUIVALENCE PROCESSES

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Research reported here concerns neural processes relating to stimulus equivalence class formation. In Experiment 1, two types of word pairs were presented successively to normally capable adults. In one type, the words had related usage in English (e.g., uncle, aunt). In the other, the two words were not typically related in their usage (e.g., wrist, corn). For pairs of both types, event-related cortical potentials were recorded during and immediately after the presentation of the second word. The obtained waveforms differentiated these two types of pairs. For the unrelated pairs, the waveforms were significantly more negative about 400 ms after the second word was presented, thus replicating the ''N400'' phenomenon of the cognitive neuroscience literature. In addition, there was a strong positive-tending wave form difference post-stimulus presentation (peaked at about 500 ms) that also differentiated the unrelated from related stimulus pairs. In Experiment 2, the procedures were extended to study arbitrary stimulus–stimulus relations established via matching-to-sample training. Participants were experimentally naïve adults. Sample stimuli (Set A) were trigrams, and comparison stimuli (Sets B, C, D, E, and F) were nonrepresentative forms. Behavioral tests evaluated potentially emergent equivalence relations (i.e., BD, DF, CE, etc.). All participants exhibited classes consistent with the arbitrary matching training. They were also exposed also to an event-related potential procedure like that used in Experiment 1. Some received the ERP procedure before equivalence tests and some after. Only those participants who received ERP procedures after equivalence tests exhibited robust N400 differentiation initially. The positivity observed in Experiment 1 was absent for all participants. These results support speculations that equivalence tests may provide contextual support for the formation of equivalence classes including those that emerge gradually during testing.

Key words: equivalence, arbitrary matching, N400, mouse click, normally capable adults

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In his article in *The American Psychologist,* Skinner (1989) presented perhaps his most clearly articulated position on the relationship between behavior analysis and the neurosciences. He wrote ''There are two unavoidable gaps in any behavioral account: one between the stimulating action of the environment and the response of the organism and one between consequences and the resulting change in behavior. Only brain science can fill those gaps. In doing so, it completes the account; it does not give a different account of the same thing'' (p. 18). Research reported here addresses the first of the two unavoidable gaps identified by Skinner—processes intervening between the stimulating action of the environment and the behavioral response. Our interest is not in intervening psychological variables but rather actual physical processes operating in the nervous system. Those processes are measured directly via electrophysiology rather than by inference from behavioral data as in cognitive psychology. Hence, we avoid the problem of attributing behav-

Electrophysiological data from Experiment 2 were originally presented in a different form at the 2000 Reunião da Sociadade Brasileira de Psicologia and the 2003 meeting of the Association for Behavior Analysis. We gratefully acknowledge financial support from the National Institute of Child Health and Human Development (Grant Nos. HD25995, HD04147). We also acknowledge gratefully the help Laura Becker and Kim Mazzitelli in conducting the behavioral work and the technical assistance of Amanda DiFiore in collecting some of the electrophysiological data. We also thank William Dube, who gave helpful feedback on earlier versions of this manuscript. Finally, we thank Karl Pribram for stimulating the interest of our laboratory in application of electrophysiological methods to the more general problem of stimulus equivalence in visual perception.

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ioral outcomes such as stimulus equivalence to unobservable behavioral processes or other private events (cf. McIlvane & Dube, 1996).

Our specific interest is whether electrophysiological methods can be used to measure neural activity correlated with equivalence classes as defined by Sidman (1994). To provide context for our work, we return to a controversy that appeared in the equivalence literature many years ago. In an early paper, Sidman, Kirk, and Willson-Morris (1985) suggested that the prerequisites for a positive equivalence-test outcome might include not only the critical baseline training (e.g., AB and AC) but also exposure to the test trials themselves (e.g., BC and CB) (see p. 39). Speaking loosely, the classes might not exist prior to the tests. Sidman's suggestion had the understandable consequence of initiating searches for behavioral evidence of class formation prior to testing. McIlvane and Dube (1990) argued subsequently, however, that such searches had a logical inconsistency: any other behavioral tests that might be given to detect equivalence might themselves provide behavioral prerequisites similar to the equivalence tests. In sum, they argued that ''Do classes exist before the tests?'' was not a good way to formulate the relevant question at the behavioral level.

By contrast, electrophysiological measures provide one possible route to answering a related question: Can one detect neural activity correlates of equivalence class formation prior to the typical tests for symmetry and transitivity? To address this question, we adapted a well-researched technique from the cognitive neuroscience literature—termed the N400 technique (cf. Kutas & Hillyard, 1980; 1984). In their original study, college students were exposed to two types of sentences: (1) ''I take my coffee with cream and *sugar*.'' (2) ''I take my coffee with cream and *dog*.'' Event-related potentials were obtained by analyzing segments of the electroencephalogram (EEG). The electrophysiological response was measured coincident with the presentation of the last word of each sentence. Electrophysiological responses to the two types of sentences differed in the region of about 400 ms; there was marked negative voltage drop to the latter but not the former sentences (hence, the N400 nomenclature).

An important follow up study was conducted by Holcomb and Neville (1990), who contrasted ''related'' (i.e., contextually equivalent) word pairs (e.g., ''table'' & ''chair,'' ''car'' & ''truck,'' etc.) vs. ''unrelated'' pairs (i.e., ''hammer'' & ''lake,'' ''dog'' & ''knife,'' etc.). They also obtained a reliable N400 to the unrelated pairs, showing that the words need not appear in sentences to obtain the effect. Notably, studies of the N400 thus far have used pairs of words drawn from natural language. In other words, their contextual relations were defined extraexperimentally. Was the extraexperimental history critical?

The first study reported here was a systematic replication of studies with extraexperimentally-defined stimulus–stimulus relations. Our primary purposes in reporting it are to (1) provide data to contrast with those collected with intraexperimentally defined stimulus–stimulus relations and (2) assess comparability of results from our laboratory with those reported in prior studies of the N400 effect. The second study initiated N400 research using arbitrary visual stimuli and intraexperimentally-defined stimulus–stimulus relations of a type typical of current stimulus equivalence research. The critical baseline relations were established via a conventional arbitrary matching-to-sample training procedure. In subsequent electrophysiological testing, pairs of matching and nonmatching stimuli were presented, and the electrophysiological response to each was recorded. Would we obtain conventional N400 differentiation? In addition, some participants received electrophysiological tests prior to behavioral equivalence tests and others were tested only after those tests. Would both groups display N400 differentiation or only the latter (i.e., would prior exposure to outcome tests prove to be critical to obtain the electrophyiological signature of stimulus equivalence)?

EXPERIMENT 1

METHOD

Participants

Seventeen participants were recruited from the student population at the University of Massachusetts–Dartmouth. All participants had normal or corrected-to-normal vision. Data from 12 participants were included in all analyses. Data from the remaining 5 were excluded because of instrumentation problems or excessive ocular artifacts. Each participant was tested in a single session lasting about 2 hr.

Stimuli

Stimuli consisted of two sets of 50 pairs of words each. The ''related'' set featured word pairs judged to be members of extraexperimentally defined stimulus classes in English. By contrast, the ''unrelated'' pair set featured word pairs that were not judged to be members of such classes. The status of pair membership was not experimentally assessed by the method of Sidman and Tailby (1982). Rather, the pairs were drawn from an earlier pilot study to identify word pairs that would be judged reliably as ''related'' or ''nonrelated'' by normally capable adults or taken from lists of related/unrelated words that had achieved this aim in earlier studies (Chiarello, Burgess, Richards, & Pollock, 1990; Holcomb & Anderson, 1993).

Electrophysiological Recording[1]

A desktop computer with a Pentium processor under the control of the Neuroscan Stim software package was used for presenting visual stimuli and recording latencies to a two-button response pad. All electrophysiological activity was collected on a Grass Model 12 Neurodata Acquisition System (low frequency cutoff at 0.1 Hz; high frequency cutoff at 100 Hz) with the Neuroscan Scan System. EEG recordings were obtained from 19 standardized locations (P3, C3, F3, F7, T3, T5, O1, Fp1, Pz, Cz, Fz, Fp2, F8, F4, T4, T6, C4, P4, O2 according to the 10–20 system) with an Electro-Cap electrode system. All leads were referenced to linked mastoids. In addition, vertical eye movements were monitored via electrooculogram (EOG), which records differences in standing voltage between the front and back of the eye. The continuous analog activity from all channels was transmitted online to a second computer along with a synchronization signal associated with the presentation of the visual stimuli. The electrophysiological data were digitized at a rate of 512 Hz and stored for subsequent processing.

Procedure

Prior to testing, participants were given 20 practice trials (10 with related and 10 with unrelated word pairs) to familiarize them with the task. On each of 100 trials, each word of a pair was presented successively. The presenting monitor was located about 85 cm from the participant's head. The first word of each pair (termed ''the prime'') was presented for 300 ms. After 1.9 s, the second word (''the target'') was presented, also for 300 ms.

During practice, participants were instructed verbally to observe the stimulus presentations and to identify the pairs as related or unrelated. Their choice was made by pressing either of two buttons to indicate the relational status of each pair. The maximum permissible response latency (limited hold) was 1.6 s. No differential consequences followed responses. Interpair intervals were 2.9 s, defined from the termination of the second stimulus of the pair. Participants were allowed a rest period of approximately 2 min after the first 50 pairs.

Results and Discussion

Button-Pressing Data

All participants responded virtually without error to the ''related'' vs. ''unrelated'' discrimination task—consistent with the histories of these extraexperimentally-defined stimulus–stimulus relations.

Electrophysiological Data

Continuous electrophysiological activity was divided into epochs relating to the target stimulus on each trial. Each trial epoch was obtained from points 200 ms prior to the presentation of the target to 1200 ms following it. Next, epoch data were subjected to several processing procedures to adjust the baseline and to filter extraneous noise. In addition, ocular artifacts were controlled by excluding all epochs with amplitudes in excess of ±75 µv. Following these corrections, averaged waveforms at each electrode site were obtained for both the related and unrelated conditions.

Figure 1 shows grand average waveforms at selected electrode sites, which were representative of the individual data for both condi-

[1] For readers who are unfamiliar with basic recording techniques, accessible primers (e.g., Nelson & Luciana, 2008) are now available to supplement the information available in earlier *JEAB* papers that have described them. A recent paper by Barnes-Holmes et al. (2005) is particularly relevant to the present experiments.

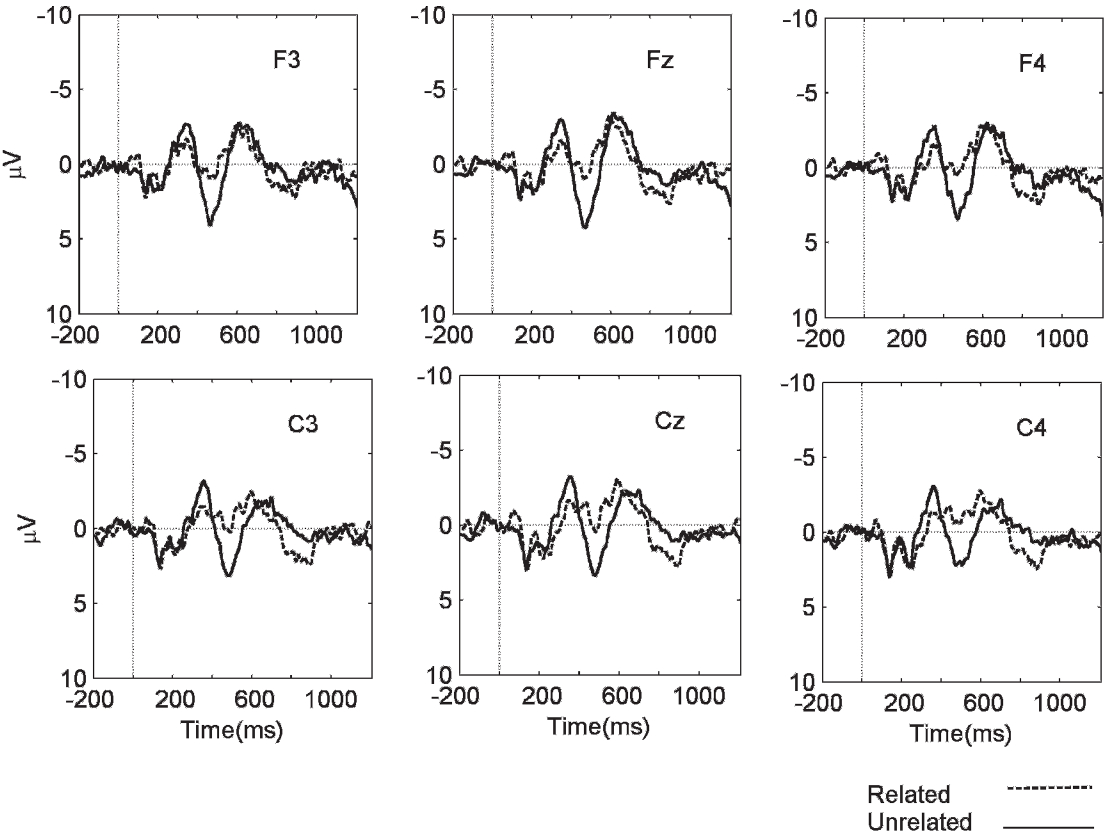

Fig. 1. Waveforms obtained for related (broken lines) and unrelated (solid lines) word pairs presented during Experiment 1. The notations (F3, Fz, F4, C3, Cz, C4) refer to locations for electrode placements according to the International 10–20 system. A ''z'' (zero) refers to an electrode placed on the midline. F and C refer to ''frontal'' and ''central,'' respectively. Even numbers refer to electrode positions on the right hemisphere; odd numbers refer to those on the left hemisphere.

tions. The waveforms indicate greater negativity for the unrelated condition in the 320-ms to 450-ms time window[2].

To further analyze these data, point-by-point voltage differences were calculated by subtracting waveforms from the related pair from those from the unrelated pairs. These difference waves are shown in Figure 2. Next, a peak detection program was used to obtain the peak negative voltage within the 320- to 450-ms time window. The peak amplitudes differed significantly ($p < .001$) from zero at all electrode sites. These results confirm the greater negativity for the unrelated pairs in that time window as compared to the related pairs, thus systematically replicating prior results from N400 studies. Not anticipated by us but clearly present were two other differences—a large positivity from approximately 450 ms to 600 ms and a smaller subsequent negativity. We will comment further on the relationship between the negativity-to-positivity-to-negativity transition in our waveforms after the results of our second experiment are presented.

EXPERIMENT 2

In this experiment, the procedures were extended to study ''related'' vs. ''unrelated'' stimulus–stimulus relations that were established via typical arbitrary matching training. An earlier program of pilot research had

[2] Following a conventional practice in electrophysiological research, the ordinate places the negative values above the abscissa and the positive values below it.

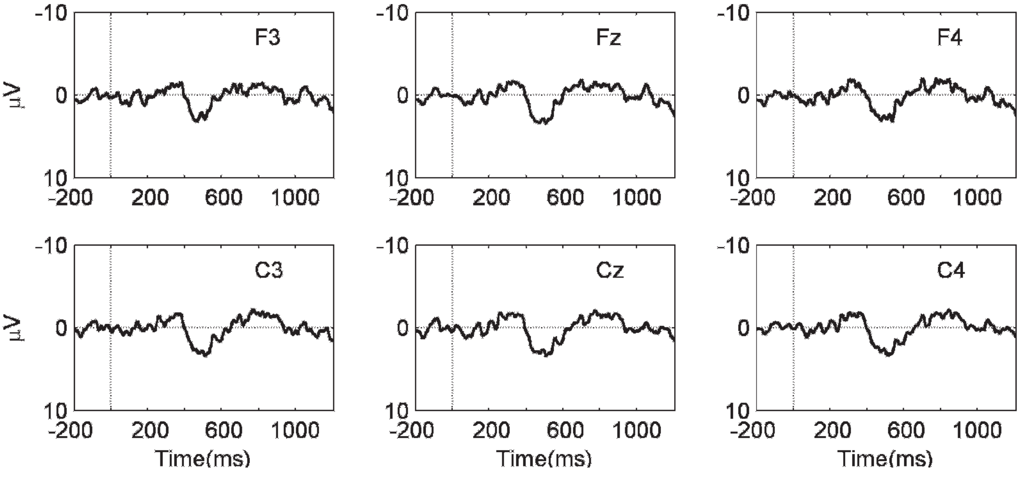

Fig. 2. Difference waves by arithmetic subtraction of waveforms shown in Figure 1. The notations (F3, Fz, F4, C3, Cz, C4) refer to locations for electrode placements according to the International 10–20 system. A ''z'' (zero) refers to an electrode placed on the midline. F and C refer to ''frontal'' and ''central,'' respectively. Even numbers refer to electrode positions on the right hemisphere; odd numbers refer to those on the left hemisphere.

suggested that this type of procedure could in fact produce N400 differentiation (see DiFiore et al., 2000 for a description of the project's early stages). One of our pilot studies presented English–Latin word pairs with participants who had no experience with the latter language. The present study used stimuli and procedures more similar to those commonly used in current stimulus equivalence research. In addition to systematic replication our earlier work, the study sought to determine whether the order of behavioral equivalence and electrophysiological testing would affect the presence and/or quality of the N400. Half of the participants were exposed to the equivalence tests first and the electrophysiology tests second, and the remainder experienced these procedures in reverse order.

Method

Participants

Twelve normally capable, experimentally naïve adults participated. All participants were right-handed and had normal or corrected-to-normal vision. The data from 4 participants were excluded because of excessive ocular artifact, which would have compromised the integrity of the event-related potentials correlated with the stimulus–stimulus relations that were the focus of the experiment.

Stimuli

Three potential equivalence classes were defined, each consisting of six visual stimuli. The stimuli and experimentally defined stimulus–stimulus relations are illustrated in Figure 3.

Arbitrary Matching-to-Sample

All training was conducted on a desktop computer using software designed for this purpose (Dube, 1991). The software controlled all stimulus presentations and response recording. Stimuli were presented on the computer screen, and participants responded by placing the mouse cursor directly over a stimulus and depressing its button (i.e., ''clicking').

Establishing arbitrary stimulus–stimulus relations. Relations between Set A stimuli and Set B stimuli were taught in the first experimental session. Set A stimuli (the trigrams SIG, BEH, POR) always served as samples. The comparisons always consisted of Set B stimuli, and Set A samples were presented in an unsystematic order. There were two phases of training. In the first phase, all trials began with the presentation of a trigram in the center of the computer screen. After a mouse click to the sample stimulus, a single ''comparison'' stimulus (i.e., only the positive comparison) was

Fig. 3. Stimuli presented during matching-to-sample procedures and electrophysiological testing in Experiment 2. The trigrams constituted Set A and the forms ordered left-to-right constituted Sets B, C, D, E, and F.

displayed in one of the four corners of the screen, and the sample remained. If the sample was A1, for example, only B1 appeared in a corner of the screen. All mouse clicks to positive stimuli were followed by a computer-generated ''beep'' and the word ''CORRECT'' displayed for about 1 s, consequences that proved sufficient to sustain high performance levels. Each of the three samples from Set A was presented twice in this format (six trials total).

During the second training phase, three comparison stimuli (one positive and two negative) were displayed on every trial. If the sample was A1, for example, the comparison stimuli were B1, B2, and B3, and B1 was the positive comparison. As before, each of the samples from Set A was presented twice (six total trials). If the participant made three or more errors on the Phase-2 trial types, s/he would be returned to Phase 1 for six additional trials. Another Phase-2 trial block would follow. Training continued until the AB relation was mastered.

In the next session, relations between Set A and Set C stimuli were taught. Comparisons always consisted of the three Set C stimuli, and the samples alternated unsystematically among the Set A stimuli. The same procedures were followed to establish sample–comparison relations involving the remaining stimulus sets (AD, AE, AF). After training with each, additional blocks were presented that reviewed the previously mastered relations (one trial each). Typically, multiple sessions were conducted per day with a brief break in between each session.

When all of the relations had been mastered, further procedures were implemented to prepare the participants for equivalence testing. The first preparation session consisted of 30 intermixed trials that reviewed all of the previously mastered trial types. Reinforcing consequences followed all correct selections. Criterion to progress to the next session was ≥97% (no more than one error). Thereafter, the participant moved on to a 42-trial session that included (1) reduced probability of reinforcement to 50% and (2) additional trials to approximately equalize the number of trials with each of the relations. The latter ''even up'' procedure was implemented because the relations trained earlier (i.e., AB, AC) had appeared on more trials than those trained later (i.e., AE, AF). The proportion of trials in this final review session was adjusted to correct for such differences. Criterion for moving on to the equivalence testing was ≥95% (i.e., no more than two errors in the final training session).

Testing for Emergent Stimulus–Stimulus Relations

Symmetry and transitivity probe trials were interspersed within baseline trials and typically conducted over two sessions—prior to electrophysiological testing for some participants and following it for the remaining participants. Each symmetry/transitivity probe session contained 30 baseline trials and 18 probe trials. Baseline reinforcement was scheduled at 50% and no programmed consequences followed responses on probe trials. The procedure used to evaluate these relational properties was similar to the ''unique probe'' method developed by Dube et al. (1989). Each sample–comparison relation was tested only once, and no differential consequences followed any probe selection. Not all of the possible symmetrical and transitive relations were tested. Of the numerous probe-trial types possible, only a well-distributed subset (i.e., 18 symmetry and 18 transitivity) was included on the behavioral tests. The remaining trials were presented in electrophysiological testing.

The rationale for the divided testing procedure was four-fold: (1) From results of prior work, we anticipated that 36 well-selected trials would be an adequate probe for symmetric and transitive behavioral relations. (2) We thought it unwise to conduct electrophysiological tests with relations that had been subjected to extinction (a situation that applied to those participants who received the behavioral tests first); the as-yet-untested relations had no such history. (3) With respect to the requirements for electrophysiological testing, previous research (e.g., Young & Rugg, 1992) suggested that the amplitude of the N400 may decrease with stimulus-pair repetition. (4) From a more general data interpretation standpoint, we judged it advantageous to conduct electrophysiological testing with relations not directly evaluated on behavioral tests. Any N400 differentiation could be attributed to emergent stimulus–stimulus relations rather than a specific behavioral history with the tested stimulus pairs.

Electrophysiological Testing

Stimulus presentations. Potentially related and unrelated stimulus pairs were presented on a desktop computer system with ''Stim'' (NeuroScan, Inc.) software. Trigrams were not used in this portion of the study. Potentially related pairs had been positive comparison stimuli selected in relation to the same trigram during the training. The unrelated pairs had been selected in relation to different trigrams. For those participants who had symmetry and transitivity probes prior to the electrophysiological testing, 60 stimulus pairs were presented (30 related and 30 unrelated).

For those participants who were exposed to the symmetry and transitivity probes after electrophysiological testing, testing consisted of 120 stimulus pairs (60 related and 60 unrelated). The first 30 pairs of each type were those presented to the other participants, and the remainder presented stimulus combinations not previously presented successively during the electrophysiological testing.

Participants viewed all stimuli from a distance of 85 cm. The horizontal and vertical visual angles of each stimulus ranged from 2^0 and 4^0. The first stimulus of each pair was presented at the center of a computer screen for 400 ms. After a 750-ms delay, the second stimulus appeared for 400 ms. Each pair was separated by 3.1 s.

Before testing began, the experimenter instructed the participant to judge (silently) whether or not the two stimuli of a given pair were related. No overt response was required. In addition, the participant was asked to refrain from blinking when the second stimulus of the pair was presented. Subsequent to the electrophysiological procedure, all participants were fully debriefed and encouraged to ask questions or express concerns (if any).

Electrophysiological recording. Procedures were similar to those of Experiment 1. An eNet (Physiometrix, Inc.) was used to obtain recordings from 19 scalp locations, and all leads were referenced to linked mastoids. In addition, electrooculogram activity was monitored by electrodes placed above and below the right eye. Impedance was less than 5 kΩ for the scalp electrodes and less than 10 kΩ for the EOG electrodes. All recordings were processed by Grass model P511K AC amplifiers with a low frequency cutoff at .01 Hz, a high frequency cutoff at 100 Hz, a 60 Hz notch filter, and a gain set at 20,000. The analog EEG and EOG activity was digitized on-line at a rate of 512 Hz using ''Scan'' software (NeuroScan, Inc.).

Following the electrophysiological recording session, event-related potential epochs were extracted for the time interval from 200 ms before through 1500 ms after the appearance of the second stimulus in each pair. Next, a baseline correction procedure was applied to all epochs by subtracting the electrical activity for the 100-ms period prior to the appearance of the second stimulus from the entire waveform. In addition, all epochs were processed with a band pass filter set between .01 Hz (24 db) and 50 Hz (24 db). Finally, epochs with ocular artifacts were excluded if the amplitude at Fp1, Fp2, or the EOG channel exceeded ±50 μv for the time period between 50 ms and 1200 ms after the second stimulus.

Average waveforms to the second stimulus for the potentially related and unrelated pairs were obtained for both groups of participants. For those who received the symmetry and transitivity probes first, average waveforms were determined for the 30 related and 30 unrelated pairs. For those who received electrophysiological testing first, data were subdivided into early trials (pairs 1–60) and late trials (61–120).

Results and Discussion

Behavioral Data

Participants had little trouble learning the relations during training. No participant required repetition of the initial single-choice comparison block in teaching in any session. The lowest mean accuracy during training was 98% correct. All participants scored at 100% accuracy on both the mixed baseline review of baseline relations and the ''even-up'' procedure in which reinforcement was reduced to 50%. All participants but one exhibited selections consistent with the expected equivalence relations on all of the 36 symmetry and transitivity probes—whether the probes were conducted before or after electrophysiology testing. The remaining participant—who received the tests before electrophysiological testing—showed a ''gradual emergence'' pattern on the probes. That is, during his first session in which probes were included, his behavior was consistent with the expected equivalence relations on only 12 of 18 trials. In two subsequent testing sessions, however, all 18 probe trials were consistent with equivalence relations.

Electrophysiological Data

Figure 4 shows average difference waves for the participants who were given the equivalence tests prior to their electrophysiological testing. There was clear, very robust differentiation between waves obtained for pairs that were and were not members of verified equivalence classes. The differences were observed in the N400 region, and each of the participants showed this differentiation. Thus, these results replicated systematically findings from the N400 literature with arbitrary stimuli and intraexperimentally-defined stimulus–stimulus relations.

Figure 5 shows initial (first 60 test trials) results obtained from participants who were given the equivalence tests after the electrophysiological recording. The results differed initially from those shown in Figure 4. Specifically, we saw little evidence of characteristic N400 differentiation. As the electrophysiological tests continued (last 60 test trials), however, Figure 6 shows that such differentiation began to emerge. This ''gradual emergence,'' present in both the group and the individual data, thus parallels the analogous and frequent observation in behavioral research on stimulus equivalence of gradual emergence of equivalence relations during behavioral testing, even if the tests are conducted without differential consequences (Sidman, 1994). In the present case, however, these participants had not yet experienced symmetry or transitivity probes (at least as they are typically structured when gradual emergence has been observed). Here, the participants experienced merely successive presentations of stimulus pairs with no discrimination requirement whatsoever (i.e., no positive comparison–negative comparison stimuli displays that required a choice of one comparison stimulus in relation to a sample). Moreover, when standard symmetry and transitivity probes were conducted after the electrophysiological testing, all participants immediately exhibited stimulus equivalence as it is typically defined in behavioral research.

GENERAL DISCUSSION

Interpreting differences between Experiment 1 and Experiment 2. Although the difference waves obtained in both studies showed significantly

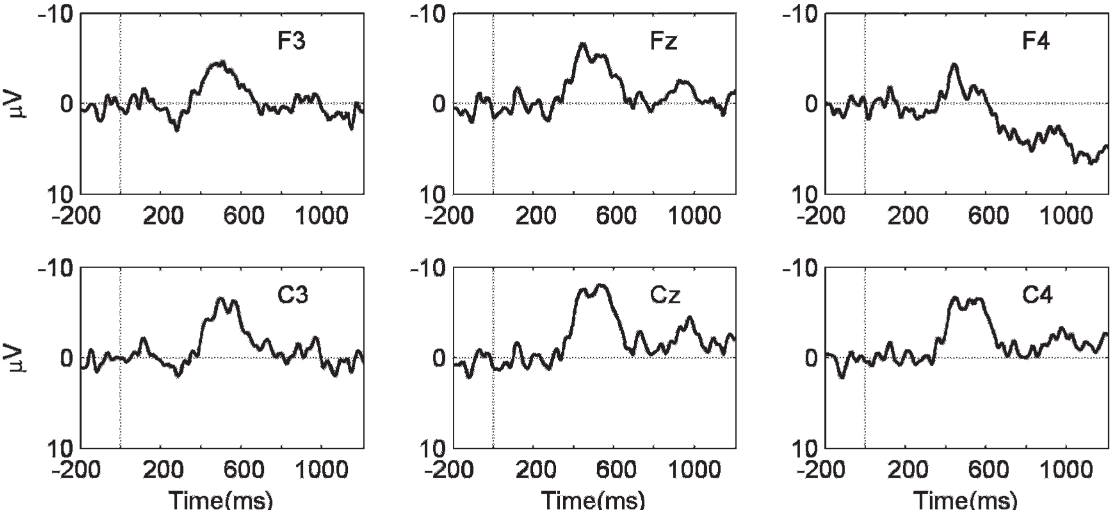

Fig. 4. Difference waves obtained from participants who were exposed to behavioral equivalence tests prior to electrophysiological testing. The notations (F3, Fz, F4, C3, Cz, C4) refer to locations for electrode placements according to the International 10–20 system. A ''z'' (zero) refers to an electrode placed on the midline. F and C refer to ''frontal'' and ''central,'' respectively. Even numbers refer to electrode positions on the right hemisphere; odd numbers refer to those on the left hemisphere.

greater negativity in the N400 region, the substantial later positivity was shown only in the first experiment. We believe this is likely due to differences in the histories of the stimuli in relation to the verbal instructions. In Experiment 1, the stimulus–stimulus relations examined were both extraexperimentally defined and not immediately maintained within the context of the experimental procedures. In Experiment 2, by contrast, the stimulus–stimulus relations were defined and reviewed within the experimental context. We think it possible that the positivity may be accounted for by contextual effects of mixing

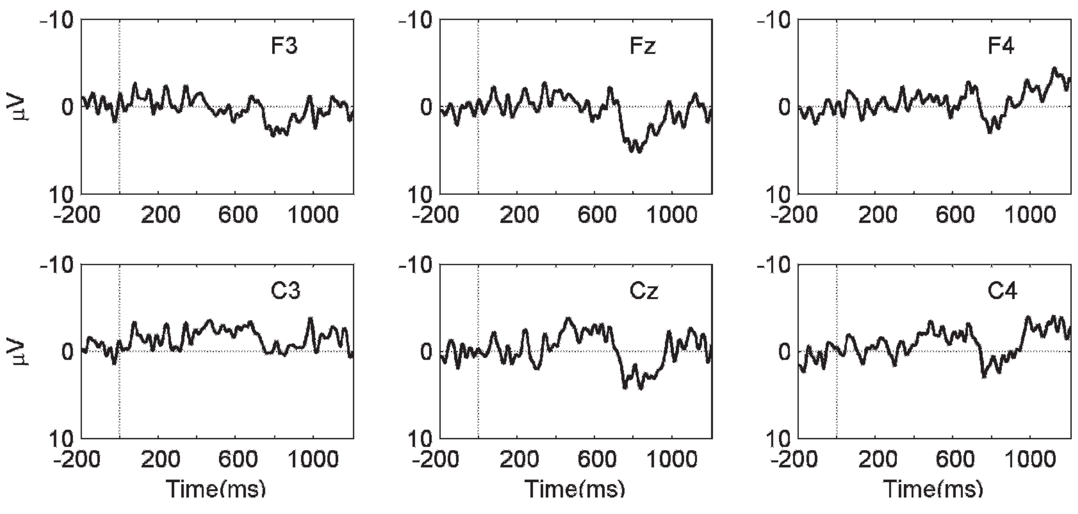

Fig. 5. Difference waves obtained from the first 60 trials of electrophysiological testing obtained with participants who were exposed to behavioral equivalence tests after that testing. The notations (F3, Fz, F4, C3, Cz, C4) refer to locations for electrode placements according to the International 10–20 system. A ''z'' (zero) refers to an electrode placed on the midline. F and C refer to ''frontal'' and ''central,'' respectively. Even numbers refer to electrode positions on the right hemisphere; odd numbers refer to those on the left hemisphere.

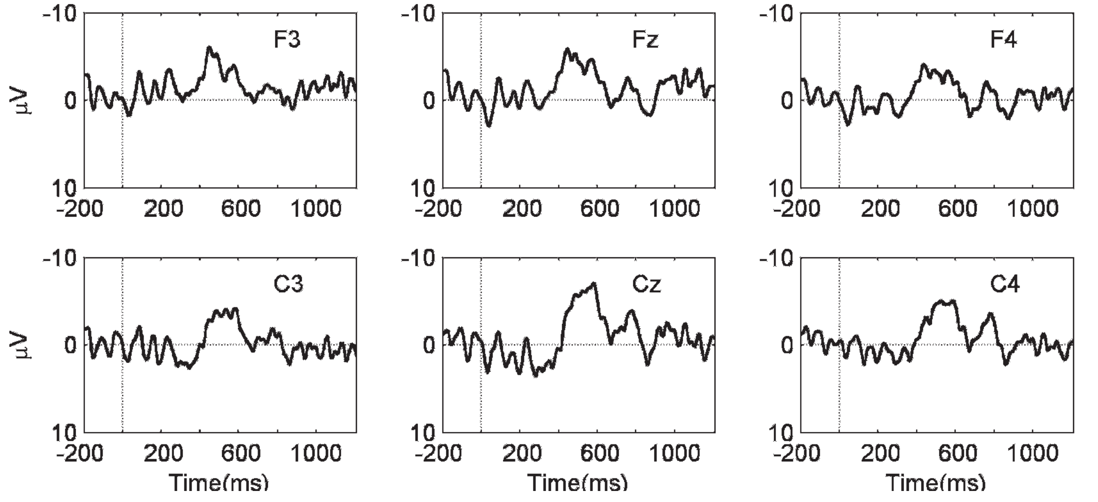

Fig. 6. Difference waves obtained from the second 60 trials of electrophysiological testing obtained with participants who were exposed to behavioral equivalence tests after that testing. The notations (F3, Fz, F4, C3, Cz, C4) refer to locations for electrode placements according to the International 10–20 system. A ''z'' (zero) refers to an electrode placed on the midline. F and C refer to ''frontal'' and ''central,'' respectively. Even numbers refer to electrode positions on the right hemisphere; odd numbers refer to those on the left hemisphere.

related and unrelated word pairs drawn arbitrarily and without other review from the natural language. Perhaps the positivity reflected processes relating to efforts to detect extraexperimentally defined relationships between the unrelated pairs where none actually existed (cf. Ruchkin, Sutton, Kietzman, & Silver, 1980)—attending processes of the type inferred by Dinsmoor (1985) to account for certain differences in observing behavior.

Comparing the N400 waveforms in Experiments 1 and 2 (Figure 2 vs. Figure 4), we note that the former were substantially less robust than the latter. We think it likely that the relatively smaller N400 in Experiment 1 was due merely to arithmetic averaging of the later positivity with the earlier negativity, that is, electrical ''masking'' of the later phases of the N400. In Experiment 2, by contrast, the ''related'' vs. ''unrelated'' stimulus–stimulus relations were established intra-experimentally via programmed matching-to-sample training and equivalence testing trials. Given this context, the participants who received electrophysiological testing after the equivalence tests showed a very robust N400 with little or no competing positivity. This difference suggests that the N400 component may correlate especially well with behavioral processes that are the focus in typical stimulus equivalence work.

Contributions to development of a behavior analytic account of semantics. Sidman (1994) and many others have suggested that stimulus equivalence procedures may provide a useful laboratory model of semantic relations in naturally occurring language. There are two main sources of support for that suggestion. The first is intellectual argument. Natural semantic relations involve behavioral equivalence. For example, the printed word CAMEL may occasion certain behavior that is identical with or similar to that occasioned by the sight of a living camel, a picture of a camel, or even a package of cigarettes. Because Sidman's model entails behavior consistent with the logical definition of equivalence, it has face validity.

Data reported here and elsewhere (Barnes-Holmes et al., 2005) provide a new kind of support for Sidman's suggestion: N400 waveforms are associated both with experimentally established equivalence relations and naturally occurring semantic relations. As noted earlier, we believe that the substantial positivity that we observed in Experiment 1 but not Experiment 2 was an artifact of procedure (i.e., testing of word pairs/relations derived directly from the natural language without explicit intraexperimental verification on matching-to-sample trials); we did not observe any pre-N400 positivity in the English–Latin pilot study mentioned earlier. A reasonable question is whether the N400 effect is restricted to arbitrary equivalence relations? Would electrophysiological differentiation be obtained if the contrast was physically identical vs. nonidentical stimulus pairs? Thus far, the answer appears to be ''No.'' The N400 procedure appears to differentiate arbitrary matching relations (cf. Nigam, Hoffman, & Simons, 1992).

Effects of testing. Our data may bear also on the role equivalence-probe testing may have in promoting positive equivalence-test outcomes. As noted, there was a clear difference in the N400 response for participants who received the electrophysiological testing before and after equivalence testing: Only the latter exhibited a robust N400 effect initially—findings logically consistent with Sidman and colleagues' (1985) suggestion that testing could be necessary to establish the context for emergence of equivalence relations. In addition, the gradual emergence of the N400 in repeated testing suggests that other types of testing procedures might serve the same contextual function (as suggested by McIlvane & Dube, 1990). Notably, our participants received only repeated presentation of potentially related and unrelated stimulus pairs during the electrophysiological testing. The sample in this study was small, however, and it seems premature to draw conclusions in advance of more data. That said, these preliminary data encourage follow-up work with a larger sample.

Concluding comments. The electrophysiological methods used here recommend themselves to behavior analysts interested in interdisciplinary neuroscience research. Although new to the field of electrophysiology, we found it fairly easy to replicate the N400 effect (as have other behavior analysts, e.g., Barnes-Holmes et al., 2005). The N400 effect is very robust, and it was detectable at the individual participant level in both experiments. Our experience encourages further searches of the present type and extensions to other equivalence procedures. For example, will the N400 effect be obtainable only with fairly simple equivalence procedures or also in more complex procedures such as higher-order equivalence (e.g., Serna & Perez-Gonzales, 2003). Also of interest is to ask whether equivalence methods may be useful in studies that directly image the working brain via functional magnetic resonance imaging (fMRI) or magnetoencephalography (MEG) (e.g., Dickins, 2005; see Deutsch, Oross, DiFiore, & McIlvane, 2000, for a brief review of these methodologies and their potential relevance to the interests of behavior analysts).

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