

An ERP Comparison of Derived Relations in Stimulus Equivalence Classes

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AQ: au **Angel Tabullo, Alberto Yorio, Silvano Zanutto, and Alejandro Wainseboim**

AQ: 2 Instituto de Medicina y Biología Experimental, Conicet, Buenos Aires, Argentina

We conducted an ERP study of derived relations within stimulus equivalence classes. After successful training of baseline relations, subjects performed a priming task and their ERP responses to the following prime-target pairs were registered: (a) stimuli related through symmetry, (b) stimuli nonrelated through symmetry, (c) stimuli related through symmetry-transitivity combined (equivalence), and (d) stimuli nonrelated through equivalence. A P300-like component was observed in related targets, which was earlier for symmetry and later for symmetry-transitivity, whereas an N400-like effect was found in nonequivalent stimuli. The P300 delay after equivalent stimuli was interpreted as evidence that relational strength within equivalence classes is inversely related to the **number** of logical operations required to link the stimuli. The N400 effect for nonequivalent stimuli was congruent with previous literature, and suggests a potential overlap between the neural correlates of priming in language and stimulus equivalence.

Keywords: derived stimulus relations, equivalence classes, N400, P300, priming

Since its original formulation by Sidman, (Sidman & Tailby, 1982) the Stimulus Equivalence (SE) paradigm has been widely applied to the study of category learning in human and nonhuman species. Stimulus equivalence has been the basis of a broader research program, the Relational Frame Theory (Hayes, Barnes-Holmes, & Roche, 2001), which proposes that language can be described in terms of derived stimulus relations (of which equivalence would be the simplest case, other examples being same/opposite or serial order, for instance) and relational networks.

An equivalence relation is established when, after learning a series of arbitrary stimulus-stimulus relations among a set of stimuli, subjects are able to derive new untrained relations among them. These derived stimulus relations verify the properties of mathematical and logical equivalence: reflexivity, symmetry, and transitivity. In a typical stimulus equivalence experiment, the baseline stimulus-stimulus relations are trained by some form of conditional discrimination (reinforcement of a behavior as a response to a stimulus depends upon the presence of another stimulus, which serves as a discriminative context), usually through a matching-to-sample (MTS) procedure. During MTS training, a sample stimulus (for instance A1) and several comparison stimuli (two in the simplest case, B1 and B2) are presented, and only the selection of one comparison (in this case, B1) is reinforced. In the simplest SE experiment, four stimulus-stimulus relations need to be trained: A1-B1, A2-B2, B1-C1, and B2-C2 (see Figure 1). Subjects move on to a test stage then, where they must respond to new MTS tasks without further reinforcement in order to probe for emergent new relations, symmetry (reversals of the trained sample-comparison pairings, such as B1-A1 and C1-B1), transitivity (A1-C1, A2-C2), and the combina-

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Angel Tabullo, Alberto Yorio, Silvano Zanutto, and Alejandro Wainseboim, Instituto de Medicina y Biología Experimental, Conicet, Buenos Aires, Argentina.

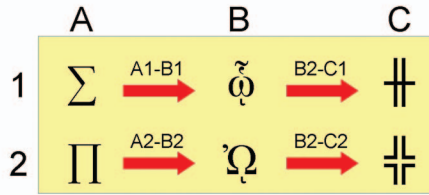
Alejandro Wainseboim are now at the Instituto de Ciencias Humanas, Sociales y Ambientales (INCIHUSA), Mendoza, Argentina.

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Correspondence concerning this article should be addressed to Angel Tabullo, who is now at INCIHUSA - CCT Mendoza; Av. Ruiz Leal s/n (5500), Ciudad de Mendoza, Mendoza, Argentina. E-mail: angeltabullo@ibyme.conicet.gov.ar

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Baseline Trained Relations



Derived Relations

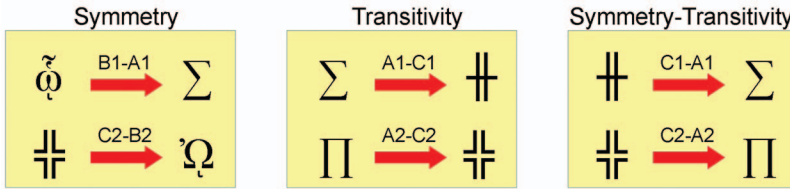


Figure 1. Example of baseline and derived relations in the formation of two three-stimuli equivalence classes using arbitrarily related symbols. After establishing AB and BC relations through Matching-to-Sample procedures (upper half), the derived relations of symmetry, transitivity, and combined symmetry-transitivity (lower half) should be verified. See the online article for the color version of this figure.

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tion of symmetry and transitivity (C1–A1, C2–A2), sometimes labeled as “equivalence” (see Figure 1). Symmetric and transitive relations between A, B, and C stimuli map on to the mathematical relation on set theory of an equivalence set (Sidman & Tailby, 1982). Because the combination of symmetry and transitivity (C1–A1, C2–A2) logically implies both properties it is often used as an abbreviated test for equivalence. The remaining property of reflexivity (identity matching A1–A1, B2–B2, etc.) is also implied, but seldom tested. It should be noted that the derived relations of symmetry, transitivity and their combination (the abbreviated test for equivalence) are defined as a function of the baseline trained relations. In the previous example, where A–B and B–C relations are trained, the comparison stimuli (B) from one set of baseline relations (A–B) serves as sample stimuli for the other set (B–C). This training structure is known as “linear series protocol” (Saunders & Green, 1999). In this case, symmetry relations are defined as B–A and C–B, transitivity as A–C and the combination of symmetry and transitivity as C–A. However, it is also possible to train all baseline relations using the same sample stimuli for each set (for in-

stance: A–B; A–C). This structure is known as “sample-as-node” or “one-to-many” protocol (Saunders & Green, 1999). In this case, symmetry would be defined as B–A and C–A, and the combination of symmetry and transitivity as: B–C and C–B, while the relation of transitivity could not be analyzed independently (B–C implies both symmetry relation B–A and trained relation A–C, C–B implies both symmetry relation C–A and trained relation A–B).

If subjects verify these derived relations in additional nonreinforced MTS tests, it is considered that two classes of three equivalent stimuli (A1, B1, C1; A2, B2, C2) have been formed. Equivalence relations are relevant for the study of categorization because they do not rely on physical or perceptual similarities, and cannot be readily explained by traditional discrimination and generalization principles (Keller & Schoenfeld, 1950; Hall, 1996). Moreover, additional learning involving one stimulus of an equivalence relation is transferred to the rest of the equivalence class without further training (Barnes et al., 1996; Roche & Barnes, 1997), providing a basis for generalization that is not constrained by stimulus perceptual similarities.

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Once an equivalence class has been formed, all its members become functionally substitutable (Sidman, 1994). This effect can be observed both in the context of MTS tests and transfer of function, which occurs always within-class and never between classes (Barnes, Browne, Smeets, & Roche, 1995; Barnes & Keenan, 1993; Fields, Adams, Verhave, & Newman, 1993; Rehfeldt & Hayes, 1998; Saunders, Wachter, & Spradlin, 1988). Although these results support the claim that all stimuli within an equivalence class are equally related (Sidman, 1994, 2000; McIlvane & Dube, 2003), there is also evidence that suggests otherwise. Fields and Verhave (1987) have identified four factors that determine the relational structure of an equivalence class, and may influence the level of relatedness between the stimuli within: class size (total number of stimuli), nodal distance (the number of intervening stimuli required to link two stimuli within the class, for instance, if A–B and B–C have been trained, the A–C relation involves one nodal stimulus: “B”), nodal density (the number of stimulus related to a particular node) and directionality of training. Most of the available evidence seems to indicate that the relatedness of stimuli in an equivalence class is inversely related to their nodal distance, as is the case in delayed emergence of relations with higher nodal distance (Bentall, Jones, & Dickins, 1999; Fields, Adams, Verhave, & Newman, 1990; Kennedy, 1991; Kennedy, Itkonen, & Lindquist, 1994; Sidman, Kirk, & Willson-Morris, 1985; Spencer & Chase, 1996), faster responses (Bentall et al., 1999; Kennedy, 1991; Spencer & Chase, 1996; Tomanari, Sidman, Rubio, & Dube, 2006; Wulfert & Hayes, 1988), better performance in transfer of function tests (Fields et al., 1993), and preference of lower nodal distance relations in within-class preference tests (Alligood & Chase, 2007; Fields et al., 1993; Moss-Lourenco & Fields, 2011). Doran and Fields (2012) have extended these findings, showing that directionality of training (which is inverted in symmetry and combined symmetry-transitivity) has an additional effect over stimulus relatedness, and concluded that those relations which require fewer logical operations to link the stimuli are stronger.

If Doran and Fields (2012) hypothesis is correct, it should be expected that differences in derived relations processing are associated with

different patterns of brain activity. One early fMRI study reported similar left-lateralized activity in dorsolateral and inferior parietal regions for directly trained and derived (symmetry, transitivity and equivalence) relations (Dickins et al., 2001). On the other hand, Schlund, Hoehn-Saric and Cataldo (2007) found that BOLD responses during tests of transitivity and equivalence reflected activation of bilateral dorsolateral and ventrolateral frontal and inferior parietal regions, while no ventrolateral and parietal activity was observed in symmetry tests. At a subcortical level, additional differences were observed in the activity of thalamic nuclei for the three relations (responding to symmetry was correlated with activation in the right ventral anterior nucleus and pulvinar, while transitive relations were associated with the left lateral posterior nucleus, and equivalence relations with the ventral lateral nucleus). In a subsequent study, Schlund, Cataldo, and Hoehn-Saric (2008) compared brain responses to pairs of stimuli that were related or nonrelated (belonged to different classes) through equivalence, and found that transitive and equivalence relations elicited bilateral hippocampal activation, while symmetry was associated to parahippocampal activity. Whereas fMRI provides a detailed description of changes in metabolic activity throughout the brain, EEG offers an online measure of changes in cortical electric activity. Therefore, it constitutes a complementary method for the study of brain activity, with significantly lower spatial but much higher temporal resolution. In particular, Event-Related Potentials (ERPs; Vaughan, 1969) allow to describe changes in brain activity that display stable time relationships to sensory, motor, or cognitive reference events. Previous ERP studies of stimulus equivalence found an N400—a negative component typically found in the context of semantic processing—(Kutas & Hillyard, 1980; see Kutas & Federmeier, 2011 for a review) when comparing pairs of stimuli that belonged to the same equivalence class with stimuli from different classes (Haimson, Wilkinson, Rosenquist, Ouiet, & McIlvane, 2009). Furthermore, an increasing N400 effect was observed when comparing stimulus pairs that were either directly related (by training), related by equivalence (symmetry, transitivity, or both combined) or nonrelated (belonging to different classes or one

of them was a new stimulus; Barnes-Holmes et al., 2005). However, none of these studies discriminated between ERP responses to stimuli related by symmetry, transitivity and combined symmetry-transitivity. A recent study (Wang & Dymond, 2013) did compare ERPs generated by stimuli related through training, symmetry and combined symmetry-transitivity, finding a late P3-like component that was largest for symmetry, smaller for symmetry-transitivity combined and smallest for the directly trained relation. The P300 potential is elicited by task-relevant stimuli in a wide range of stimulus discrimination and categorization tasks (Duncan-Johnson, & Donchin, 1982; see Picton, 1992; Polich, 1998, 2007; Verleger, 1997, for reviews), and has been previously observed in stimulus equivalence contexts (Yorio, Tabullo, Wainseboim, Barttfeld, & Segura, 2008). Unlike Barnes-Holmes et al. (2005) and Haimson et al., (2009), no clear evidence of N400 was found in this work. While this study included stimulus pairs that were related or non-related (belonging to different classes), it did not analyze the interaction between class membership (same equivalence class, different classes) and relation type (trained, symmetry, equivalence) of the stimuli. As a result, potential differences between the processing of related and nonrelated stimuli in the context of symmetry (e.g., B1–A1 vs. B2–A1) and symmetry-transitivity (e.g., C1–A1 vs. C2–A1) could not be analyzed. Moreover, common averaging of within-class (e.g., B1–A1) and between-class (e.g., B1–A4) trials in the ERP analysis of directly trained, symmetry and symmetry-transitivity stimulus pairs may have obscured differences between related and nonrelated stimuli, leading to results that were not congruent with previous studies (Barnes-Holmes et al. found that equivalence-related stimulus pairs elicited more negative potentials than directly trained pairs, whereas Wang & Dymond reported more negative potentials for directly trained pairs than symmetry and equivalence-related pairs). Consequently, a comparison of ERP correlates of derived relations in stimulus classes that distinguishes between related and nonrelated stimuli in each case is currently lacking.

The main objective of the present work was to further investigate ERP correlates of derived relations in equivalence classes, comparing

brain potentials elicited by pairs of stimuli related and nonrelated (belonging to different equivalence classes) through symmetry and equivalence (combined symmetry-transitivity). We decided to compare symmetry and equivalence to keep directionality of training constant (because both relations require the inversion of directly trained relations), leaving nodal distance as the only factor that could affect stimulus relatedness (symmetry-transitivity requires one intervening node, whereas symmetry requires none). If the number of logical operations required to link the stimuli determines their relational strength, as Doran and Fields (2012) suggested, we should expect differences in performance and ERP responses to both derived relations. In addition, and considering previous reports of N400 effects when comparing equivalence related and nonrelated stimuli (Barnes-Holmes et al., 2005; Haimson et al., 2009), we would expect differences in ERP responses to related and nonrelated stimuli in the context of symmetry and combined symmetry-transitivity derived relations.

Method

Participants

Eighteen healthy right-handed students (9 women), ranging in age from 19 to 34 years (Mean: 27.2 ± 5.1 years old) took part in the study. Subjects spoke Spanish as first language, had normal or corrected-to-normal vision, and had no history of psychiatric or neurological disorders, neither were they under any medication at the time of the experiment.

Procedure

Stage I: Baseline relations training. In this stage, four stimulus–stimulus relations were trained by MTS procedures. Participants were instructed to decide which of the two comparison stimuli presented at the bottom of the computer screen corresponded to the sample stimuli presented at the top, informing their choice by pressing the right or left Ctrl key. They were also instructed to respond as fast and accurately as possible. They were told that they would receive corrective feedback (which consisted in the words “Correct” or “Error”) after they made their choice. They were also informed that the

stimuli would be meaningless artificial words and that their relation would be arbitrary. The following artificial words were used in the study: A1: *pemo*, A2: *laco*; B1: *bune*, B2: *kime*; C1: *nufa*; C2: *rona*.

We chose a “Sample as Node” (also known as “One to many”) training protocol because it has been shown to give better outcomes in stimulus equivalence tests (Arntzen, Grondahl, & Eilifsen, 2010; Arntzen & Holth, 1997, 2000). It requires training a series of conditional discriminations using the same stimuli as sample in all trials (Figure 2a). Therefore, this stage consisted of three training blocks: AB, AC (presented in a counterbalanced order to all subjects), and a final mixed AB–AC baseline relations block. The first AB and AC training blocks had a duration of 16 trials, and the relations, A1-B1, A2-B2; A1-C1, A2-C2 were trained on each one, respectively. The final mixed block had a duration of 64 trials, and all previously trained relations were presented again, in a pseudorandomized order. Each training block was preceded by a computer screen summarizing the instructions. Each trial (Figure 2b) was initiated by the presentation of the sample stimuli at the center of the upper half of the screen, followed after 300 ms by the simultaneous presentation of both comparison stimuli at the left and right halves of the lower portion of the screen. The position of the comparison stimuli was randomized across trials, such that the correct comparison stimuli would appear with equal probability at each side of the screen. Subjects could make their choice by pressing left or right Ctrl keys at any time after the presentation of the comparison stimuli, and it was immediately followed by the words “Correct” or “Error” as feedback. The intertrial interval was 1500 ms. After completion of the three training stages, participants moved on to the test stage.

Stage II (test): Relatedness judgment task.

The relatedness judgment task was adapted from previous stimulus equivalence studies (Barnes-Holmes et al., 2005; Haimson et al., 2009; Wang & Dymond, 2013), and derived from the semantic priming paradigm used in language studies (Meyer & Schvaneveldt, 1971; Neely, 1977). In this stage, participants were informed that they would see a pair of successive stimuli appear at the center of the screen, and would have to decide whether they were related or not. They were told that they would

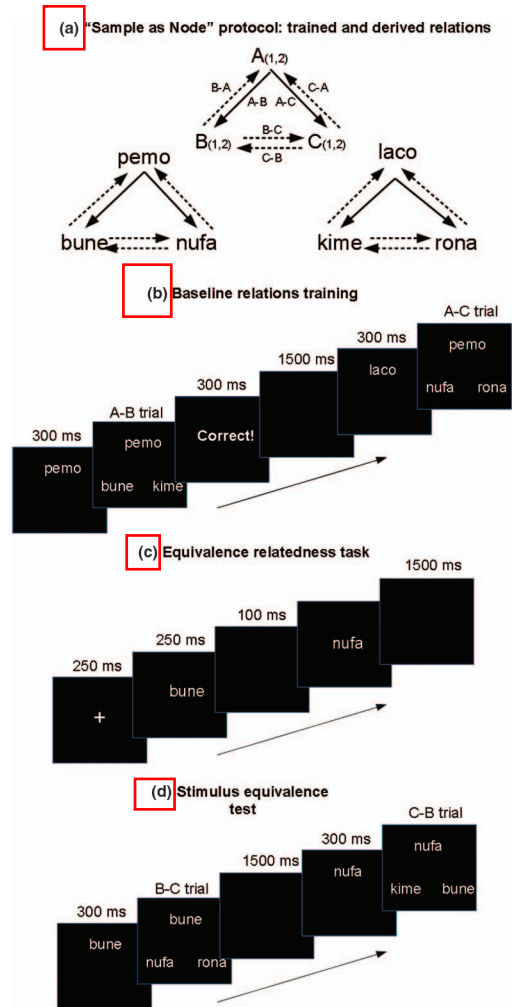


Figure 2. (a) Description of trained and derived relations applying the “Sample as Node” protocol to our set of stimulus (A1: *pemo*, A2: *laco*; B1: *bune*, B2: *kime*; C1: *nufa*; C2: *rona*). Baseline trained relations are indicated by solid lines: A–B (A1–B1, A2–B2); A–C (A1–C1, A2–C2). Derived relations are represented by dotted lines: symmetry (B1–A1, B2–A2, C1–A1, C2–A2); combined symmetry-transitivity: (B1–C1, B2–C2, C1–B1, C2–B2). (b) Time course of AB and AC trials during Matching-to-Sample training. (c) Time course of a symmetry-transitivity combined (B1–C1) related trial of the Relatedness Task. (d) Time course of BC and CB trials of the Stimulus Equivalence Matching-to-Sample test. See the online article for the color version of this figure.

not receive feedback this time but it was still possible to get every answer right based on what was previously learned. Finally, they were told to make their responses after the presentation of

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the second stimulus in the pair, using the right and left Ctrl keys.

A total of 160 trials were presented, divided in two 80-trial blocks with a short break between them. The same number of trials (40) from the following experimental conditions were shown: (a) prime-target pairs related through symmetry (henceforth: “symmetry-related” or “symmetrical”; B1–A1, B2–A2, C1–A1, C2–A2); (b) prime-target pairs nonrelated through symmetry (henceforth “symmetry-non-related” or “non-symmetrical”; B1–A2, B2–A1, C1–A2, C2–A1); (c) prime-target pairs related through combined symmetry-transitivity (henceforth: “equivalence-related” or “equivalent”; B1–C1, B2–C2, C1–B1, C2–B2); (d) prime-target pairs nonrelated through combined symmetry-transitivity (henceforth: “equivalence-non-related” or “non-equivalent”; B1–C2, B2–C1, C1–B2, C2–B1). The trials were presented in a pseudorandomized order. Each trial (Figure 2c) was initiated by the presentation of a fixation cross at the center of the screen, for 250 ms. It was followed by the first stimuli of the pair (prime), which disappeared after 250 ms and was followed by a 100 ms blank screen. After that, the target stimuli appeared, and subjects were able to make their response. In this way, Stimulus Onset asynchrony (SOA) was 350 ms, the same that was used in [Kreher, Holcomb, and Kuperberg \(2006\)](#) semantic priming study. The intertrial interval was 1500 ms. During this stage, EEG activity was recorded and synchronized to the onset of target stimuli.

Stage III (test): Stimulus equivalence test. Stimulus equivalence class formation was evaluated in this stage by means of MTS tests of combined symmetry-transitivity (B–C and C–B) relations without feedback. Procedure was similar to stage 1 in terms of stimulus presentation and instructions, although subjects were told that no feedback would be provided at this stage. A total of 32 trials of BC and CB relations (16 of each type) were presented in a single block with a pseudorandomized order. Each trial (Figure 2d) was initiated by the presentation of the sample stimuli at the center of the upper half of the screen, followed after 300 ms by the simultaneous presentation of both comparison stimuli at the left and right halves of the lower portion of the screen. Subjects could make their choice by pressing left or right Ctrl

keys at any time after the presentation of the comparison stimuli.

Behavioral Data Analysis

Two behavioral variables were considered to analyze participants performance: accuracy (defined as the percentage of correct responses within a stage of the experiment) and response times. Mean response times of correct responses were analyzed during the equivalence relatedness test. Individual response times were measured from the onset of the target stimuli to the moment of the subject’s response. Response latencies longer or shorter than two standard deviations were excluded from the analysis following literature recommendations ([Ratcliff, 1993](#)), as were those faster than 200 ms. This resulted in a trial loss no greater than 5% for each subject. The remaining values were log-transformed for subsequent statistical analysis.

EEG Recording and Analysis

EEG activity was recorded from 19 cap-mounted tin electrodes (extended international 10/20 system, Electro-Cap International Inc.) with a binauricular reference using an AKONIC BIOPC system. Electrode impedances were kept under 10 k Ω . EEG signal was sampled at 256 Hz and filtered offline at 0.5–30 Hz. EEG preprocessing and ERP analysis were analyzed using EEGLAB software v11.0.3.1. ERPs epoch length was 1000 ms, and a 200-ms pre-stimulus baseline correction was applied. Ocular artifacts were removed from the data by means of the ADJUST ICA-based correction algorithm ([Mognon et al., 2011](#)). Epochs containing other kinds of artifacts were detected by visual inspection and excluded from the analysis (resulting in a trial loss less than 6%).

Time-windows of interest (400–500 ms and 520–620 ms) were determined by visual inspection of grand-average waveforms of experimental conditions and compatible with previous literature, following standard procedure in ERP studies, such as language priming studies ([Batterink et al., 2010](#); [Justus et al., 2009](#); [Radeau et al., 1998](#); [Kreher, Holcomb, & Kuperberg, 2006](#); [Misra & Holcomb, 2003](#); [Ortu, Allan & Donaldson, 2013](#)) and previous stimulus equivalence studies ([Barnes-Holmes et al., 2005](#); [Yorio et al., 2008](#)). ERPs mean voltage was calculated within time-windows of interest

and analyzed by means of a $3 \times 5 \times 2 \times 2$ repeated-measures ANOVA (Tabullo et al., 2011, 2013) with the following within-subject factors: Region (Anterior: comprising electrode sites F7, F3, Fz, F4, F8, Central: comprising electrode sites T3, C3, Cz, C4 and T4, and “Posterior” comprising electrode sites T5, P3, Pz, P4 and T6.), Lateral Electrode Site (1 to 5 from left to right, for instance: position 1 refers to F7, T3 and T5, whereas position 5 includes F8, T4 and T6), Relation (Symmetry, Equivalence) and Stimulus Type (Related, Nonrelated). Effect sizes were estimated by the partial eta-squared coefficient η_p^2 (Cohen, 1973; Haase, 1983). Greenhouse-Geisser correction was applied in cases of sphericity violations, and Bonferroni adjustment was used for post hoc pairwise comparisons. ERP latencies were estimated using the fractional area latency measure (Hansen & Hillyard, 1980; Kiesel, Miller, Jolicoeur, & Brisson, 2008; Luck, 2005). Fractional area latency was defined as the point within the time-window of interest that divided the area under the ERP waveform in half, for each experimental condition, in each participant; and calculated using the ERPLAB Toolbox (Lopez-Calderon & Luck, 2014). ERP latencies were analyzed in the same way as mean voltages.

Results

Behavioral Data

From 18 participants, 15 achieved high levels of performance during the baseline relations training ($91.46 \pm 7.11\%$). The remaining three subjects performed worse than chance (50%) and were therefore excluded from the study.

Percentage of correct responses during the equivalence relatedness test was analyzed by means of a 2×2 repeated measures ANOVA with Relation (symmetry, equivalence) and Stimulus Type (related, nonrelated) as within-subject factors. A main effect of Relation was found, $F(1, 14) = 23.413$, $p < .001$, $\eta_p^2 = 0.626$. Performance was higher in symmetry than in equivalence trials, but did not differ between related and nonrelated stimuli. Subjects Mean percentage of correct responses (and standard deviations) by trial type in this stage were as following: *Symmetry-related*: 86 ± 14.7 ; *Symmetry-non-related*: 88.66 ± 8.17 ;

Equivalence-related: 71.55 ± 19.17 ; *Equivalence-nonrelated*: 77.39 ± 17.21 . Accuracy of responses during the stimulus equivalence test stage was also high ($83.32 \pm 6.8\%$), verifying the formation of two three-stimuli equivalence classes.

A 2×2 repeated measures ANOVA conducted on mean response times of the equivalence relatedness task revealed a Stimulus Type main effect, $F(1, 14) = 10.095$, $p = .007$, $\eta_p^2 = 0.419$, and a significant Relation \times Type interaction, $F(1, 14) = 12.188$, $p = .004$, $\eta_p^2 = 0.465$. Responses were faster in symmetry-related (1275.77 ± 273.76 ms) than in equivalence-related trials (1499 ± 517.49 ms; $p = .012$), but did not differ between nonrelated symmetry and equivalence trials. Furthermore, shorter response times were observed in symmetry-related compared to nonrelated trials ($p < .001$), but no significant differences were found between equivalence related and nonrelated trials.

ERP Analysis

Visual inspection of grand-average ERPs indicated differences between experimental conditions within the 400–620 ms range. Related stimuli in symmetry and equivalence trials elicited two successive broadly distributed positivities. Between 400 and 500 ms, ERPs for symmetry-related targets were slightly more positive than those for nonrelated stimuli in symmetry trials, which in turn were more positive than equivalence-related and equivalence-nonrelated stimuli (see Figure 3). In the following time-window (500–620 ms), the positivity was larger for equivalence-related targets and intermediate for symmetry-related and nonrelated stimuli. ERPs elicited by nonequivalent stimuli remained more negative through this whole time window (see Figure 3). Figures 4 and 5 show ERP grand averages by relation type (collapsing related and nonrelated trials) and stimulus type only (collapsing symmetry and equivalence trials), respectively. Figure 6 displays the ERP grand averages from nine representative sites. Time course of the ERPs was within the range of P300 (see Polich, 2007 for a review) and N400 (see Kutas & Federmeier, 2011, for a review) components, and previous stimulus equivalence studies have also reported ERP effects within this time frame (Barnes-

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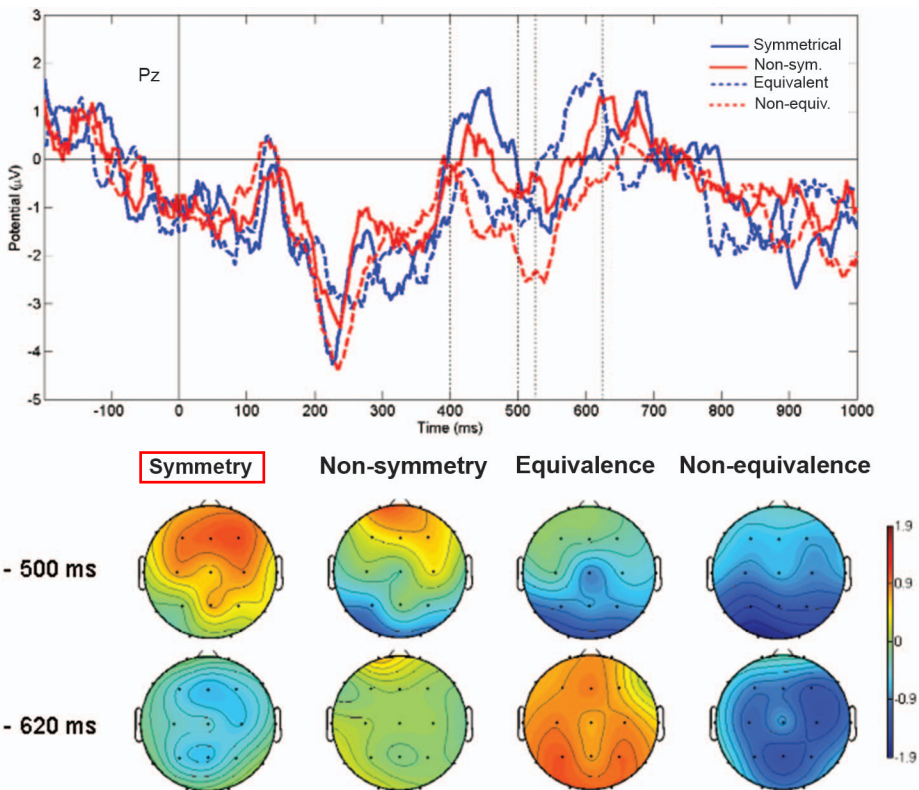


Figure 3. Grand-average waveforms (up) of the ERPs in the Relatedness Task, by experimental condition: symmetrical stimuli (solid blue line), nonsymmetrical stimuli (solid red line), equivalent stimuli (dotted blue line), nonequivalent stimuli (dotted red line), in a representative channel (Pz). Vertical dotted lines represent time-windows of interest. Scalp topographies (down) of mean voltages within both time-windows of interest: 400–500 ms and 520–620 ms. See the online article for the color version of this figure.

Holmes et al., 2005; Yorio et al., 2008; Haimson et al., 2009; Wang & Dymond, 2013). Therefore, the definition of time-windows of interest was compatible with previous literature. Statistical analysis of both time-windows is described below:

400–500 ms. A significant relation main effect was found, $F(1, 14) = 15.228$, $p = .002$, $\eta_p^2 = 0.521$. ERPs of equivalence trials were more negative than those of symmetry trials, but no significant differences between related and nonrelated stimuli were found.

520–620 ms. A significant Relation \times Type interaction was observed, $F(1, 14) = 11.406$, $p = .005$, $\eta_p^2 = 0.449$. Nonrelated targets elicited more negative ERPs in equivalence trials ($p = .005$), whereas no differences were found between related and nonrelated stimuli in

symmetry trials ($p = .207$). Furthermore, ERPs for symmetry-related stimuli were more negative than those generated by equivalence-related targets ($p = .009$).

ERP latency analysis. Fractional area latencies were calculated within the 400–620 ms window. A significant Relation \times Type \times Lateral Electrode Position was found, $F(4, 56) = 4.250$, $p = .004$, $\eta_p^2 = 0.233$. Symmetry-related ERPs had shorter latencies than equivalence-related ERPs at left ($ps < .046$), central ($p = .029$), and right ($ps < .036$) sites, but no other significant differences were observed. At electrode Pz, mean fractional area latencies were as following: *Symmetry-related*: 472.58 ± 31.81 ; *Symmetry-non-related*: 503.38 ± 44.26 ; *Equivalence-related*: 502.18 ± 43.37 ; *Equivalence-nonrelated*: 487.64 ± 32.55 . Pooling data from

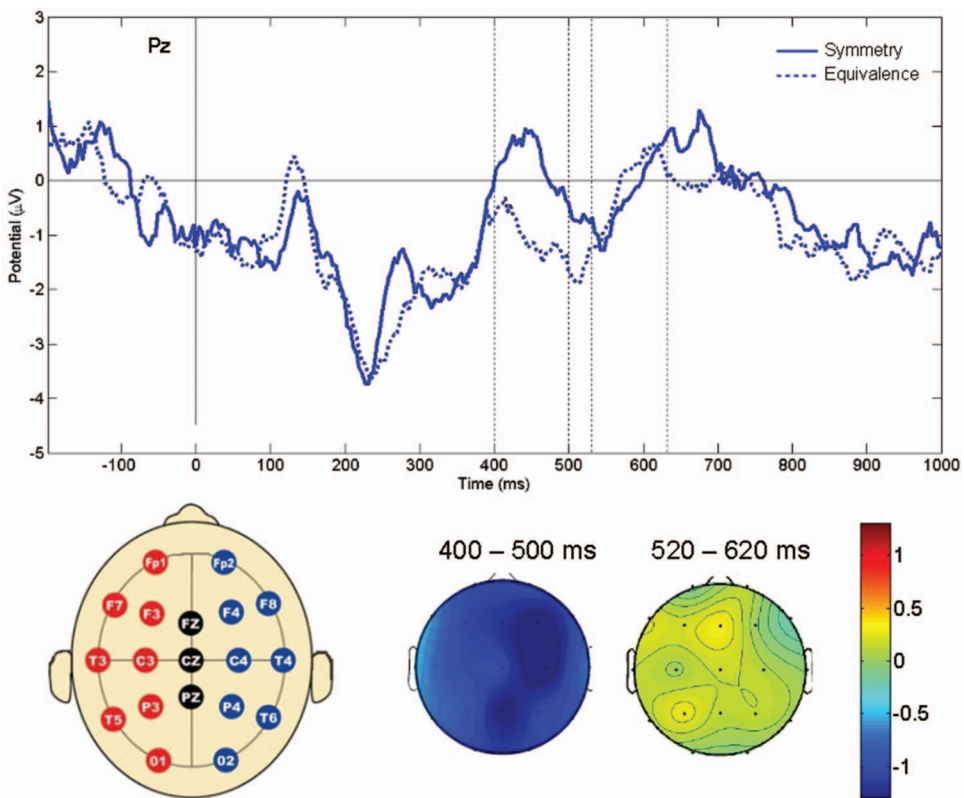


Figure 4. Grand-average waveforms (up) of the ERPs in the Relatedness Task, by relation type: symmetry (solid blue line) and equivalence (dotted blue line) in a representative channel (Pz). Vertical dotted lines represent time-windows of interest. Scalp topographies (down, right) of equivalence minus symmetry difference wave mean voltages within both time-windows of interest: 400–500 ms and 520–620 ms. Electrode sites layout (down, left). See the online article for the color version of this figure.

all channels, mean fractional area latencies were as following: *Symmetry-related*: 476.45 ± 33.38 ; *Symmetry-non-related*: 489.33 ± 37.18 ; *Equivalence-related*: 498.72 ± 37.83 ; *Equivalence-nonrelated*: 489.92 ± 29.44 .

Discussion

After successful completion of MTS training, participants were able to discriminate between pairs of stimuli that belonged to the same equivalence class (being related through symmetry or combined symmetry-transitivity) and stimuli that were not related through symmetry or equivalence, thus showing class-consistent responding. This was confirmed by MTS symmetry-transitivity tests, which verified equivalence

class formation. Accuracy data analysis indicated that equivalence trials in the relatedness task were more difficult than symmetry trials, regardless of stimulus type, whereas response time analysis showed faster responses to symmetry-related compared to equivalence-related trials. ERP amplitude analysis showed that symmetry-related stimuli elicited an earlier positivity compared to equivalence-related pairs, a fact that was confirmed by latency analysis. Furthermore, stimuli nonrelated through equivalence elicited a widely distributed negativity, which topography and time-course were similar to the N400. On the other hand, nonsymmetrical stimuli ERPs did not show the same pattern as those of nonequivalent targets, and the difference between symmetrical and nonsymmetrical condi-

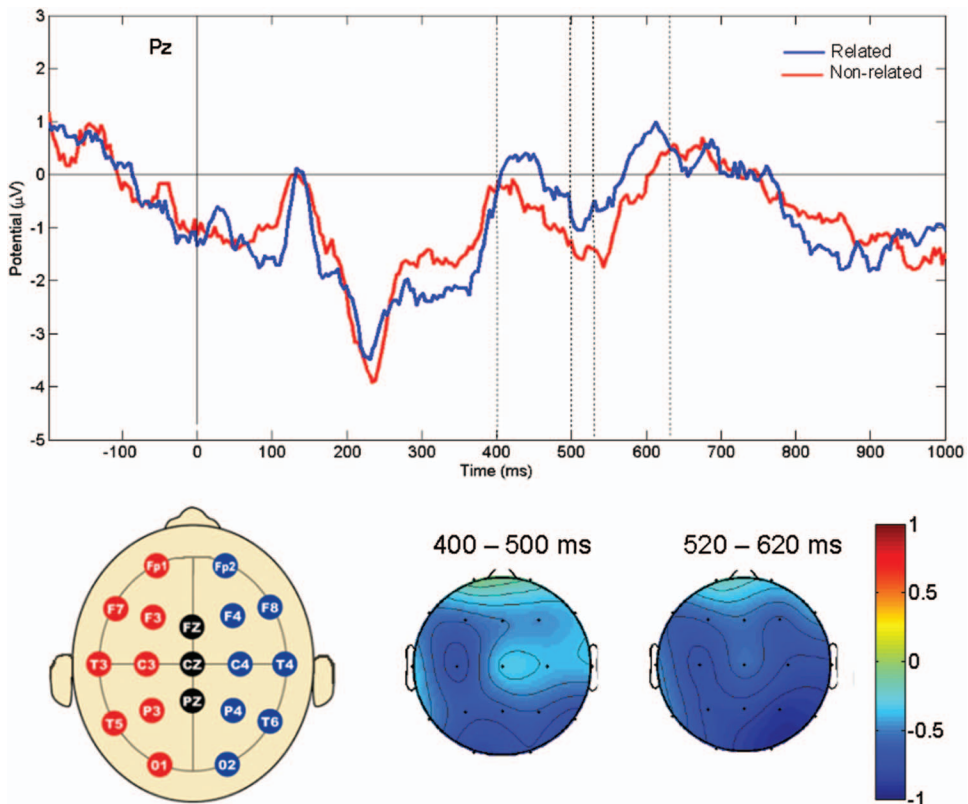


Figure 5. Grand-average waveforms (up) of the ERPs in the Relatedness Task, by stimulus type: related (solid blue line) and nonrelated (solid red line) in a representative channel (Pz). Vertical dotted lines represent time-windows of interest. Scalp topographies (down, right) of nonrelated minus related difference wave mean voltages within both time-windows of interest: 400–500 ms and 520–620 ms. Electrode sites layout (down, left). See the online article for the color version of this figure.

tions did not reach statistical significance. These findings are discussed below.

Behavioral Data

The high performance of the subjects in the relatedness task constitutes evidence of class-consistent responding, and shows that they acquired significant knowledge about the stimulus derived relations. It has been previously noted that the relatedness task may function as a type of test for the formation of equivalence classes (Barnes-Holmes et al., 2005), and it has been suggested that it may provide a more accurate behavioral model of untrained indirect relations than matching-to-sample testing (Wang & Dymond, 2013). Class-consistent responding

was confirmed in the stimulus equivalence test, which verified the formation of two equivalence classes. Subject responses in the relatedness task were more accurate for symmetry than for combined symmetry-transitivity (equivalence) trials. In addition, responses to symmetry-related trials were faster than those to equivalence-related and symmetry nonrelated ones. This response pattern has been observed in a wide range of studies: accurate responding to symmetry-related stimuli emerges sooner than responding to transitivity and equivalence trials (Bush, Sidman, & de Rose, 1989; Bentall, Jones, & Dickins, 1999; Fields et al., 1990), and responses are typically faster in baseline relations and symmetry than in transitivity and equivalence trials (Bentall, Dickins, & Fox,

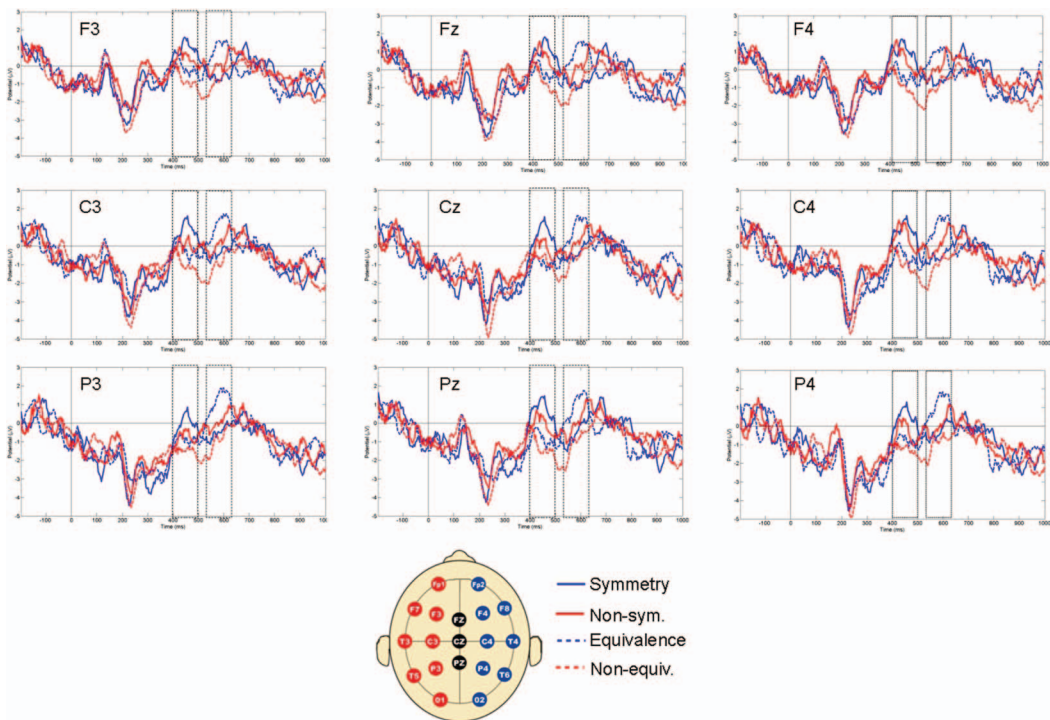


Figure 6. Grand-average waveforms of the ERPs in the Relatedness Task, by experimental condition: symmetrical stimuli (solid blue line), nonsymmetrical stimuli (solid red line), equivalent stimuli (dotted blue line), nonequivalent stimuli (dotted red line), in nine representative channels (F3, Fz, F4, C3, Cz, C4, P3, Pz, P4). Vertical dotted lines represent time-windows of interest. See the online article for the color version of this figure.

1993; Spencer & Chase, 1996; Wulfert & Hayes, 1988). Furthermore, the same effect is observed when emergent relations involve an increasing number of nodes, both in accuracy (Fields et al., 1990) and response latencies (Bentall, Jones, & Dickins, 1999; Spencer & Chase, 1996; Tomanari et al., 2006). These results have been interpreted as evidence against the claim that all members of an equivalence class are equally related (Sidman, 1994, 2000; McIlvane & Dube, 2003) and in favor of the hypothesis that the relational strength of stimuli within equivalence classes is determined by their nodal distance (Fields et al., 1990). A recent study (Doran & Fields, 2012) that compared relational preference of transitivity over equivalence and baseline relations over symmetry has extended this interpretation, concluding that the strength of a relation is greater when fewer logical operations are required to link the stimuli.

The aforementioned evidence from MTS tests is congruent with results of relatedness judgment tasks such as the one we employed in our experiment. Wang and Dymond (2013) observed faster and more accurate responses in symmetry than in equivalence trials. Using an adapted version of the lexical-decision task to study priming effects within equivalence classes, Barnes-Holmes et al. (2005) observed faster responses when comparing directly trained versus combined symmetry-transitivity related stimulus pairs, but found no significant differences between symmetry, transitivity and combined symmetry-transitivity related pairs. Furthermore, responses to each related trial type (directly trained, symmetry, transitivity, and equivalence) were faster than those to non-related trials. The authors interpreted these results as evidence of mediated facilitation priming effects in the response times to stimulus pairs that belonged to the same equivalence class,

since both directly related (by trained and symmetry relations) and indirectly related (by transitivity or combined symmetry-transitivity) stimulus pairs elicited faster responses than nonrelated stimuli. We replicated this finding when comparing response times to symmetry related and nonrelated stimuli, but not in the case of equivalence-related versus nonrelated trials. However, one important methodological difference precludes a direct comparison of both studies: Barnes-Holmes et al. (2005) did not discriminate between symmetry nonrelated and nonequivalent stimuli, but pooled together the data from all nonrelated trials instead. In addition, their task did not require an explicit response about the relationship between prime and target stimuli, because the participants only had to decide whether the target was part of the training stimulus set.

In conclusion, accuracy and response time data were consistent with previous literature in showing that more directly related stimuli within equivalence classes are processed faster and more easily than indirectly related ones. This pattern of results is congruent with Doran and Fields (2012), who claim that relational strength is inversely related to the number of logical operations involved in the stimulus relation.

ERP Comparison of Symmetry and Equivalence Relations

Whereas Sidman's original proposal stated that all stimuli within an equivalence class are equally related, behavioral evidence from this and previous studies suggests that symmetry is processed faster than transitivity, and that the difficulty of derived relations increases with nodal distance. In particular, we observed faster responses to symmetry-related compared to equivalence-related targets. ERPs observed after symmetry and equivalence related targets were congruent with these results, as the onset of the positivity elicited by the simpler symmetry relation was earlier than the more complex symmetry-transitivity combined (not only did the effect occur in an earlier time-window, but the latency analysis indicated that the positivity developed faster in the case of symmetry). Previous stimulus equivalence studies (Yorio et al., 2008; Wang & Dymond, 2013) have also observed late positivities elicited by targets in

priming paradigms, and they have interpreted them as instances of the P300. The P300 component is a family of brain potentials found in a wide range of stimulus discrimination tasks (Duncan-Johnson, & Donchin, 1982; see Picton, 1992; Polich, 1998, 2007; Verleger, 1997, for reviews). Two subcomponents of P300 have been identified: P3a, an earlier and more anterior positivity related to attention orienting response and novelty processing, and P3b, a later and posteriorly distributed positivity elicited by task-relevant target stimuli (Comerchero & Polich, 1999). The P300 component has been observed after target stimuli in perceptual (Azizian, Freitas, Watson, & Squires, 2006) and semantic (Kutas, McCarthy, & Donchin, 1977; Dehaene et al., 1998) categorization tasks, including linguistic semantic priming (Hill, Ott, & Weisbrod, 2005; Hill, Strube, Roesch-Ely, & Weisbrod, 2002). Furthermore, P3b latency is proportional to stimulus evaluation timing and modulated by task processing demands (Dien, Spencer, & Donchin, 2004; Polich, 2007). The latency differences between the positivities found for symmetry and equivalence relations in our study are functionally similar to task demand effects over the P300. In this case, they might be reflecting the higher load of processing symmetry-transitivity combined relations. Although both relations share the same directionality (which is inverse to the trained relations), symmetry requires no intervening nodal stimuli, allowing faster categorization of the target. On the other hand, the combination of symmetry and transitivity involves one nodal stimuli and thus imposes higher processing demands, delaying the onset of the positivity. The fact that responses were faster and more accurate for symmetry than for equivalence trials is congruent with this interpretation, and both findings support Doran and Fields' (2012) claim that relational strength within equivalence classes is inversely related to the number of nodes and logical operations required to link the stimuli.

The observed ERP pattern for symmetry and equivalence-related stimuli is also congruent with the P300 semantic distance effects reported in lexical decision tasks with short SOAs for directly and indirectly semantically related words (Hill et al., 2002, 2005). In particular, Hill et al. (2005) found a larger and earlier P300 peak for directly related targets, and suggested that this might be reflecting the implicit detec-

tion of the semantic relationship, and the facilitation of target categorization by automatic activation spread processes. This hypothesis is also in line with interpretations of N400 effects elicited by nonrelated stimuli in language (Weisbrod et al., 1999; Hill et al., 2002, 2005; Kreher, Holcomb, & Kuperberg, 2006) and stimulus equivalence (Barnes-Holmes et al., 2005; Haimson et al., 2009) priming tasks, as we will discuss in the following section.

ERP Comparison of Related and Nonrelated Stimuli

The fact that nonequivalent stimuli elicited a more negative ERP through the whole time-window of analysis is consistent with previous reports of negativities in stimulus equivalence priming studies. An earlier study from our lab showed evidence of a negative component analogue to N400 after analyzing difference waves of equivalence-related minus nonequivalent stimuli (Yorio et al., 2008). In Barnes-Holmes et al.'s (2005) study, subjects were trained in a series of arbitrary relations between artificial nonwords that allegedly belonged to a foreign language. After successful completion of stimulus equivalence tests, they moved on to a priming lexical-decision task, where they were asked to discriminate the learned "foreign" words from untrained and new nonwords. Prime stimuli could be directly related (by previous training), belong to the same equivalence class (related by symmetry or equivalence), or be nonrelated through equivalence (being a stimuli from the opposite equivalence class, or a new nonword). An N400-like component was found, which was largest for nonequivalent stimulus pairs and intermediate for equivalent pairs when compared with directly trained stimuli. This pattern of results was similar to the N400 effects that are typically observed in language indirect semantic priming studies (Weisbrod et al., 1999; Hill et al., 2002, 2005; Kreher, Holcomb, & Kuperberg, 2006), where the amplitude of N400 increases with the prime-target semantic distance (being larger in "table" – "lion" than in "stripes" – "lion" word pairs, which are connected through the commonly related word "tiger"). This coincidence in N400 modulation in language and equivalence classes has been interpreted as evidence of the connection between them, because it suggests a functional overlap

between derived stimulus relations and semantic priming (Barnes-Holmes et al., 2005). Behavioral researchers have pointed out the formal similarities between the structure of semantic memory network models—where words and concepts are represented as interconnected nodes—(Anderson, 1983; Collins & Loftus, 1975) and nodal structure of stimulus equivalence classes (Fields et al., 1993; Fields & Verhave, 1987; Fields & Moss, 2007). Furthermore, the graded N400 effect observed in linguistic mediated semantic priming has been interpreted as evidence of automatic spread of activation within semantic memory (Kreher, Holcomb, & Kuperberg, 2006), an explanation that could be compatible with Barnes-Holmes et al.'s (2005) results. In the case of language, activation would spread from the prime to the commonly related word, and then to target, whereas in the equivalence class it would spread from the prime through the nodal stimuli that link it to the target. A later study (Haimson et al., 2009) also observed similar N400 effects when presenting nonequivalent stimulus pairs and nonrelated word pairs. This experiment employed a task more similar to ours, because participants were explicitly asked to decide whether the prime-target pairs were or not related.

Although we cannot claim that the N400 effect elicited by nonequivalent stimuli in our experiment constitutes evidence of an overlap between brain correlates of priming in language and stimulus equivalence, the result could be compatible with that hypothesis. A within-subject comparison between stimulus equivalence and language N400 effects would be required to determine the degree of overlap between both processes. So far, we can only conclude that the ERP response to stimulus pairs nonrelated through equivalence is similar to that observed after semantically nonrelated word pairs. In addition, we suggest that this effect might be reflecting automatic processes, like activation spread through the nodes of a network, instead of more controlled processes, like expectancy generation (Neely, 1977, 1991; Posner & Snyder, 1975). When the SOA is long enough (usually more than 400ms) participants are able to explicitly generate predictions about the upcoming words, and response facilitation occurs when the target fulfills these expectations. Since the SOA in our study was 350 ms,

it seems unlikely that our participants applied expectancy generation or other explicit strategies to solve the task (the same observation is made by Barnes-Holmes et al. [2005] in their study). Furthermore, a semantic priming study with the same SOA (Kreher, Holcomb, & Kuperberg, 2006) also concluded that the N400 was indexing automatic processes. As mentioned before, automatic spread of activation can also be invoked to explain P300 priming effects in the case of symmetry-related targets, in the same way Hill et al. (2002, 2005) have proposed for directly related words.

It is worth noting that N400-like ERPs associated to nonequivalent stimuli in our study and previous literature (Barnes-Holmes et al., 2005) were elicited by pseudowords devoid of any meaning, referent, or semantic content (Haimson et al., 2009 used abstract pictures, finding similar results), whereas this ERP is typically found in priming studies using actual words (Holcomb, 1988; Holcomb & Neville, 1990; Weisbrod et al., 1999) or meaningful nonverbal stimuli, such as pictures (Ganis et al., 1996), faces (Olivares et al., 1999) and environmental sounds (Van Petten & Riefelder, 1995). An intriguing possibility that has been addressed in recent studies is that the N400 effects observed in language priming tasks is not reflecting the activation of semantic relations between words, but is the result of associative relations occurring at lexical level instead (Ortu, Allan, & Donaldson, 2013; Rhodes & Donaldson, 2008). Associative relationships in language depend on the co-occurrence of two words in a specific order, regardless of their meaning or semantic properties (Anderson & Charles, 1977). Therefore, any two words can be associated as long as one tends to follow the other in common usage, even without sharing any physical or conceptual properties (for instance, the word pairs: “traffic-jam,” “nursery-rhyme,” or “atom-bomb”; Kiss, Armstrong, Milroy, & Piper, 1973). Semantic relations, on the other hand, rely on the overlapping features of the word referents (Kawamoto, 1993; Masson, 1995; Moss, Hare, Day, & Tyler, 1994) and can be defined independently of their contiguity in everyday language (for instance, the word pairs: “pig-chicken,” “violin-guitar,” or “cereal-bread”). Despite this distinction, there are many cases where featural overlap is the reason why the words tend to co-occur in language (as in the

case of the word pairs: “brother-sister,” “gold-silver,” or “lion-tiger”), and so they are related both semantically and associatively. Rhodes and Donaldson (2008) found N400 priming effects for prime-target word pairs that were either associatively or both semantically and associatively related, but not for words that were only semantically related only. Furthermore, a subsequent study showed that, holding semantic relatedness constant, highly associatively related pairs elicited larger N400 attenuation that moderately associated ones (Ortu et al., 2013). The authors concluded that the N400 “does not reflect the transient activation of semantic knowledge. Rather the N400 effect appears to reflect the acquisition of meaning via associations formed by the contiguity of distinct elements within one’s experience.” In addition, they pointed out that the presence of N400 priming effects in the context of intraexperimentally defined relations among arbitrary stimuli reflected the generality of the associative mechanism that may be underlying it. Since the stimuli used in our experiment were meaningless artificial nonwords with no referents or resemblance to any actual words, the N400 effect we observed for nonequivalent targets (and its absence for symmetry and equivalence related stimuli, in their respective time-windows) can be interpreted as evidence supporting this hypothesis. Nevertheless, a direct within subject comparison of priming effects in the context of semantic, associative, and equivalence relations would be required to draw further conclusions about the nature of the processes that the N400 is actually reflecting.

Although the negativity found after non-equivalent targets can be considered the result of the absence of priming between stimuli that are not directly nor indirectly related, we would have expected a similar ERP for nonsymmetrical targets too. However, no significant differences were observed when comparing ERPs for symmetrical and nonsymmetrical stimuli, in any of the time-windows. Moreover, ERPs for equivalent stimuli were actually more negative than both symmetrical and nonsymmetrical stimuli within the early time-window. One possible explanation for this pattern of results could be derived from the design of our training protocol. During baseline relations training (for instance, A-B trials), both the correct (B1) and the incorrect (B2) stimuli were presented to-

AQ: 7

AQ: 8

gether with the sample (A1). Systematic repetition of this co-occurrence may have developed an associative relation between the sample and the incorrect stimuli, in addition to the directly reinforced association with the correct comparison. Nevertheless, both relations would be qualitatively different, because the correct comparison stimulus controls a matching response, whereas the incorrect one generates a non-matching response. Therefore, they could be considered as functional analogues of the “same” and “opposite” relational operants (Dymond & Barnes, 1996; Steele & Hayes, 1991; Whelan & Barnes-Holmes, 2004a, 2004b). If this was the case, when presented with nonsymmetrical prime-target pairs (like B1–A2 or C2–A1), the existence of a direct “opposite” relation with the prime would attenuate the N400 component, as we observed in our experiment. Such priming effects are indeed found for opposites within the domain of language in the case of antonyms (such as “good–bad,” “hot–cold,” “black–white”; Kutas & Iragui, 1998; Roehm, Bornkessel-Schlewiesky, & Schlesewsky, 2007). On the other hand, no N400 attenuation should be found for nonequivalent stimulus pairs, because prime and target (B1–C2, C1–B2) never shared a common training context, and no direct association could have been formed between them. This interpretation would be congruent with the results of a study that showed direct and mediated priming in response times and performance for both “same” and “opposite” arbitrarily defined relations (Whelan, Cullinan, O’Donovan, & Rodríguez Valverde, 2005). This experiment found priming effects between stimuli related directly or indirectly (by transitivity) through arbitrarily defined “same” and “opposite” relations, when compared with completely nonrelated stimulus pairs. Although no differences were observed between directly and indirectly related stimuli in this experiment, it is possible that ERPs are more sensitive than response times to this kind of effects (if an “opposite” relation had been learned and transferred by symmetry-transitivity among the equivalent stimuli in our experiment, it should be expected that its priming effects over N400 are smaller than those observed in pairs of stimuli that became opposites during training).

One final note of caution is required regarding the presence of both P300 and N400 effects

in a priming task with short SOAs. As Hill et al. (2005) explained, P300 responses evoked by lexical decision tasks can overlay with N400 effects, potentially affecting interpretation of results. Although one way to avoid this overlap would be to delay the time of response within the trial (adding a cue after a posttarget interval to prompt the subject’s response, thus separating it from priming effects), a P300 potential modulated by semantic distance is still observed under these conditions (Hill et al., 2005). Therefore, the overlay between P300 and N400 at short SOAs cannot be prevented, even with a delayed response paradigm. In spite of this, Hill et al. (2005) were able to identify semantic distance effects for related words in the P300, as well as an N400 effect for semantically unrelated words. In the present study, we observed more positive ERPs for related stimuli (with an earlier onset for those more directly related), which are functionally analogue to P300, and a more negative ERP for nonequivalent stimuli, which is in line with previously reported N400 components. These results are congruent with the hypothesis that derived relations with the same directionality, but different nodal distance, would elicit a distinct pattern of ERPs. Therefore, we believe that the possible existence of an overlay between P300 and N400 at short SOAs does not (in the present work) preclude our interpretation of the data. Nevertheless, a future replication of the experiment with a delayed response paradigm could help minimize the P300–N400 overlap, and could provide a better discrimination of possible P300 and N400 components.

Comparison With Similar Studies

There is one previous study that analyzed ERPs to different derived relations in equivalence classes (Wang & Dymond, 2013). In a series of two experiments, four three-member equivalence classes were trained, and ERP responses were analyzed during a relatedness judgment task. In the first experiment, two groups of subjects were compared: one receiving equivalence class tests prior to the relatedness task and the other after it. This relatedness task was methodologically similar to ours, but employed different experimental conditions: directly trained related (e.g., A1–B1) and nonrelated (A1–B2), symmetry related (B1–A1) and

nonrelated (B1–A2), and equivalence related (B1–C1) and nonrelated (B1–C2). Two different ERP analyses were conducted: by trial type, collapsing all related and nonrelated stimuli together for each relation type, and within/between class, collapsing all trained and derived relations and comparing related (within) and nonrelated (between) stimuli. In the group that received the relatedness task prior to the equivalence test, a late parietal P300 component was observed, which was higher for symmetry trials, intermediate for directly trained and smaller for equivalent trials. In the second experiment, a single group of subjects participated, receiving the relatedness task before the equivalence test, and only those whose performance was above 80% in both tasks were included in the ERP analysis. A posterior P300 component was observed again, but this time it was higher for symmetry and equivalence than for directly trained trials. It should be noted that none of these experiments replicated the previous finding of an N400 effect for nonrelated stimuli. Thus, results in Wang and Dymond (2013) differ from ours in the following aspects: (a) they did not find evidence of successive P300 components for symmetry and equivalence-related stimuli, (b) they did not find evidence of N400 effects for nonrelated stimuli. On the other hand, there are crucial methodological differences in data analysis that preclude a direct comparison between both studies. In particular, there was no discrimination of related and nonrelated stimuli in the P300 analysis (thus obscuring potential differences attributable to category mismatch), neither did they discriminate between relation types in the within/between class analysis. The authors themselves reckon that “the absence of N400 may have resulted from the combinations of trial types presented, but also from the different experimental manipulations employed” (Wang & Dymond, 2013).

Conclusion

To sum up, we found differences in the ERPs elicited by symmetry and combined symmetry-transitivity relations within equivalence classes. The delay in the positivity for equivalence-related target as well as the accuracy and response time data, were interpreted as converging evidence that the combined symmetry-transitivity relation was more

difficult to process due to the intervening nodal stimuli. This result is compatible with the hypothesis that relational strength within equivalence classes is a function of the number of logical operations that derived relations involve (Doran & Fields, 2012). In addition we observed a more negative ERP for nonequivalent stimuli that is in line with previous stimulus equivalence studies, and might be interpreted as an N400 component. The presence of an N400 would indicate an at least partial overlap between stimulus equivalence and language priming processes. Future studies should address this possibility by directly comparing associative, semantic, and equivalence priming effects in language and equivalence classes.

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