THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY
2011, 64 (4), 792–806

Psychology Press
Taylor & Francis Group

Neural temporal dynamics of contingency judgement

Jennifer J. Heisz, Samuel Hannah, Judith M. Shedden and Lorraine G. Allan
Department of Psychology, Neuroscience & Behaviour, McMaster University, Hamilton, Ontario, Canada

The present study captures the dynamics of neural processing across positively contingent, negatively contingent, and noncontingent relations. In the setting of a hypothetical chat room conversation, participants rated the contingency of emotional response between two individuals. Event-related potentials (ERPs) were time-locked to the onset of each emotional event. Although each event alone was ambiguous regarding contingency, its neural response was characteristic of the overall contingent relation and the subsequent contingency rating. Very early displays of contingency modified the ERP anterior N1 (AN1) component amplitude. In contrast, the ERP selection negativity (SN) component amplitude seemed to be more sensitive to display properties than contingency. Our results point to the recruitment of early attentional processes for contingency judgement and highlight the efficiency of statistical information processing.

Keywords: Contingency judgement; Event-related potential; anterior N1; Selection negativity; Attention.

Recognizing relations of contingency among events in the environment is a component task of many decision-making, categorization, and reasoning processes. A rich literature of more than four decades has detailed the behavioural responses to varying contingent information (see De Houwer & Becker, 2002; Shanks, 2007); however, little is known about the underlying neural processes.

The contingency judgement task typically involves assessing the relation between two binary events—a cue and an outcome—presented across many discrete trials. On each trial, a cue is either presented or is not presented, and then an outcome either occurs or does not occur. Different cues and outcomes have been used to represent various real-world situations. The cue may represent that an individual has eaten strawberries or not, and the outcome may represent that the same individual has suffered an allergic reaction or not (Wasserman, 1990); the cue may represent that a plant has been fertilized or not, and the outcome may represent plant growth or not (Spellman, Price, & Logan, 2001); the cue

---

Correspondence should be addressed to Jennifer J. Heisz, Rotman Research Institute at Baycrest, 3560 Bathurst Street, Toronto, Ontario, M6A 2E1, Canada. E-mail: jheisz@rotman-baycrest.on.ca

This research was supported by Natural Sciences and Engineering Research Council of Canada (NSERC) grant to L.G.A., NSERC grant to J.M.S., and NSERC Canadian Graduate Scholarship to J.J.H.

We would like to thank Shepard Siegel and Matthew Crump for their helpful suggestions and comments throughout all phases of this research. We would also like to thank Dan Bosnyak for his useful suggestions concerning data analysis.

Jennifer J. Heisz is now at the Rotman Research Institute at Baycrest, Toronto, Canada. Samuel Hannah is now at the University of Queensland, St. Lucia, Australia.

DOI:10.1080/17470218.2010.517322

may represent that an individual has smiled or not, and the outcome may represent that another individual has smiled back or not (Allan, Hannah, Crump, & Siegel, 2008).

Regardless of the particular cue–outcome set there are four possible pairings—the cue is either presented (C) or not (~C), and then the outcome either occurs (O) or not (~O). Each cue–outcome pair is conventionally labelled by the letters *a*, *b*, *c*, and *d* as summarized by a 2 × 2 contingency matrix (Table 1). Across a series of trials, the relative frequency of each cue–outcome pair establishes the objective relation between the cue and the outcome. For example, a greater number of *a* and *d* events provide support for a positive contingent relation, whereas a greater number of *b* and *c* events provide support for a negative contingent relation. The contingency between the cue and the outcome is commonly defined by the difference between two conditional probabilities, summarized in a statistic called ΔP (Allan, 1980), which can range from +1.0 (perfect positive contingency) to −1.0 (perfect negative contingency):

$$\begin{aligned}\Delta P &= P(\mathrm{O}|\mathrm{C}) - P(\mathrm{O}|\sim\mathrm{C}) \\ &= \frac{a}{(a+b)} - \frac{c}{(c+d)}\end{aligned} \qquad 1$$

Usually participants are instructed to passively view presentations of the cue and the outcome. Following all cue–outcome presentations (i.e., at the end of a trial series), participants are asked about the relationship between the cue and the outcome. For example, they may be required to rate the strength of the cue–outcome relationship on a scale ± 100, where a rating of +100 represents a perfect positive relation, −100 represents a perfect negative relation, and 0 represents no relation.

Table 1. *2 × 2 matrix of the cue–outcome pairings in a contingency assessment task*

	O	*~O*
C	*a*	*b*
~C	*c*	*d*

Note: The letters indicate the four cue–outcome combinations: The cue is either presented (C) or not (~C), and the outcome either occurs (O) or not (~O).

Although participants' ratings of contingency tend to correlate with programmed contingency (see Shanks, 2007), ratings are usually made at the end of a trial series and provide no details regarding how a contingency judgement is formed as information is presented. Neuroimaging techniques, such as event-related potentials (ERPs), could allow us to measure this. However, in the traditional contingency judgement task, the presentation of contingency information is slow, such that a series of trials is presented over several minutes. To achieve a reliable ERP signal, one would need a minimum of 50 responses per condition per point on the learning curve, rendering the traditional way of presenting information in a contingency task impractical.

Crump, Hannah, Allan, and Hord (2007) modified the traditional contingency judgement task, making it more amenable to neuroimaging methods. Their streamed-trial procedure maintains the traditional trial structure but with rapid trial presentations. With the streamed-trial format, a contingency relation can be established in mere seconds, whereas the same relation may take many minutes to establish with the traditional format. Despite these modifications, performance with the streamed-trial procedure replicates central findings in the contingency literature (Crump et al., 2007; Hannah, Crump, Allan, & Siegel, 2009). Since the streamed-trial procedure allows many trials to be presented in a single session, it may be a promising new method for neuroimaging investigations.

The most common analysis of ERPs relies on waveform components, providing information about the timing and stage of processing. Different ERP components are thought to be indicative of specific psychological processes and are named for their time and sign of deflection (e.g., the first negative deflection is the N1 component). With millisecond temporal resolution, ERPs can capture the precise timing of neural processes involved in contingency judgement.

Although ERP recordings have been used in a wide variety of learning tasks (e.g., Holroyd & Coles, 2002; Miltner, Braun, Arnold, Witte, & Taub, 1999), there are few reports of such recordings in tasks involving judgements about the relationship between binary events. In a recent paper by Wills, Lavric, Croft, and Hodgson (2007), ERP data were recorded in a prediction-learning task using a conventional two-phase blocking design. In prediction learning, a cue is presented or not presented. The participant then predicts whether the outcome will occur or will not occur. Finally, the participant is told whether the outcome did or did not occur. In two-phase blocking, multiple cues are paired with a common outcome. Wills et al. (2007) observed more negative anterior N1 (AN1) and right posterior selection negativity (SN) responses to cues from which the outcome was initially more difficult to predict. The AN1 (e.g., Clark & Hillyard, 1996; Lang et al., 2006; Töllner, Gramann, Müller, & Eimer, 2008) and SN (e.g., Anllo-Vento & Hillyard, 1996; Harter, Aine, & Schroeder, 1982) components are thought to reflect selective attentional processes, suggesting that cues associated with greater prediction error may attract more attention. The conventionally slow presentation format of the learning phase in Wills et al. (2007) produced too few trials for ERP analysis during learning; ERP analysis was limited to trials presented after learning and was thus blind to processing during learning. Also, Wills et al. used a deterministic design (see Hannah et al., 2009) and thus did not manipulate the contingency between the cue and the outcome.

The present study used ERPs to provide a detailed, online analysis of processing during a contingency assessment task. Specifically, we time-locked to the onset of each cue–outcome pair to capture the temporal dynamics of contingency assessment as the contingency unfolded. We used the streamed-trial procedure (Crump et al., 2007) to achieve sufficient trial numbers to separately analyse contingency processing at different points in the participant's knowledge of the actual contingent relation. Such analysis may provide important information regarding the time course by which statistical relations are extracted.

We opted for the simplest version of the contingency task consisting of only one cue and one outcome (see Figure 1). We used the chat room version of the streamed-trial task reported by Allan et al. (2008). The experiment was presented as a hypothetical chat room conversation, initiated by Person 1 (cue) and accepted by Person 2 (outcome). Both individuals were represented as emoticons. Person 1 was presented just left of centre and was represented by a yellow emoticon with light brown eyes, mouth, and contour. Person 2 was presented just right of centre and was represented by a yellow emoticon with orange eyes, mouth, and contour. Person 1 either smiled (C) or not (∼C), and Person 2 either smiled (O) or not (∼O). A streamed trial consisted of a series of 60 frames, each frame displaying one of the four possible cue–outcome combinations; each frame was presented for 100 ms, with a 250-ms interframe interval. The four possible cue–outcome pairs are depicted in Figure 1A, and a schematic streamed trial is depicted in Figure 1B.

The relative frequency with which the two individuals displayed the same emotion (i.e., cells *a* and *d* of the contingency matrix in Table 1) versus different emotions (i.e., cells *b* and *c* of the

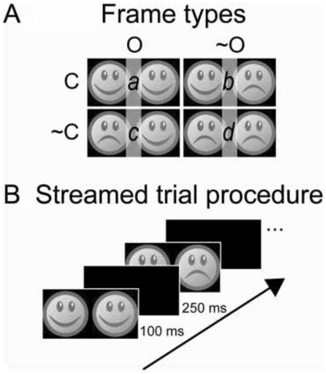

Figure 1. *(A) The four possible stimulus displays (frames) of a streamed trial. (B) An example of frame presentation sequence in the streamed-trial procedure. Each streamed trial consisted of 60 frames. The particular frequencies of each frame within a streamed trial are provided in Table 2.*

Table 2. *2 × 2 matrices of the cue–outcome pairings for positively contingent, negatively contingent, and noncontingent streams*

	Positive contingent $\Delta P = .467$		*Noncontingent* $\Delta P = 0$		*Negative contingent* $\Delta P = -.467$	
	O	*∼O*	*O*	*∼O*	*O*	*∼O*
C	22	8	15	15	8	22
∼C	8	22	15	15	22	8

Note: The values in the cells indicate the frequency of occurrence of each of the four cue–outcome combinations in each of the stream types. C = cue; O = outcome.

contingency matrix in Table 1) established the objective contingency between cue and outcome. Frames in which the two individuals displayed the same emotion provided support for a positive contingent relationship, whereas frames in which the two individuals displayed different emotions provided support for a negative contingent relationship. In each stream, the relationship between the cue and outcome was positively contingent, negatively contingent, or noncontingent. At the end of each stream, participants rated the strength of the relationship on a scale ±100, where a rating of +100 represents a perfect positive relation, −100 represents a perfect negative relation, and 0 represents no relation.

We divided the 60-frame stream into four quarters to capture contingency learning effects; the first quarter consisted of Frames 2 to 15,[1] the second quarter consisted of Frames 16 to 30, the third quarter consisted of Frames 31 to 45, and the fourth quarter consisted of Frames 46 to 60. Consequently, the four quarters represented a gradual increase in the participant's knowledge of the actual contingent relation. Overall, the experiment was a 3 × 4 design with treatment conditions of stream contingency (positive, noncontingent, negative) and stream quarter (first, second, third, fourth).

Our application of ERP methodology to contingency processing focused on addressing two questions: (a) which ERP components are sensitive to contingency task manipulations, and (b) how soon within a streamed trial is contingency extracted (i.e., time course effects)? Based on the findings of Wills et al. (2007), we were particularly interested in the effect of contingency on the AN1 and SN ERP components. Although Wills et al. examined prediction error rather than contingency judgement, both tasks represent aspects of statistical learning and therefore may share similar mechanisms. Furthermore, the novelty of our paradigm and the lack of previous ERP research on contingency judgements allow for the possibility that other component processes (in addition to those reflected by the AN1 and SN) may be important. To assess the entire ERP signal for contingency effects across stream quarter without any a priori assumptions, we used the multivariate technique partial least squares analysis (PLS; Lobaugh, West, & McIntosh, 2001; McIntosh & Lobaugh, 2004). This approach reveals critical time windows of particular electrode sites that showed the strongest contingency effects.

Method

Eighteen right-handed McMaster University students (14 female; mean age of 18 years ± 1 year *SD*) participated for course credit in undergraduate psychology courses. All reported normal or corrected-to-normal vision. One participant (female) was unable to detect the contingency manipulation and therefore was excluded from further analysis.

---

[1] The first frame of each stream was excluded from analysis because it was the only frame that was not immediately preceded by another frame, and we saw this as a potential artefact.

Apparatus and stimuli

Stimulus presentation and response measurement were controlled by Presentation experimental software (Version 11), running on a Pentium 4 computer under Windows XP operating system. Participants were seated 80 cm from the display, and the experiment was run in a dimly lit room.

Figure 1A depicts the experimental stimuli. Person 1 was represented by a yellow emoticon with light brown eyes, mouth, and contour. Person 2 was represented by a yellow emoticon with orange eyes, mouth, and contour. Person 1 was always presented to the left of Person 2. Both emoticons were approximately 2.6 degrees of visual angle wide and approximately 2.6 degrees of visual angle high. The two emoticons were separated by approximately 0.2 degrees of visual angle, and the pair was centred with respect to the display.

Procedure

The experimental session consisted of 105 streamed trials. Each streamed trial lasted 21 seconds and consisted of 60 frames presented in a rapid serial visual presentation. As depicted by Figure 1B, each frame was presented for 100 ms followed by an interframe interval of 250 ms. On a given frame, Person 1 (cue) either smiled (C) or did not smile (~C), and Person 2 (outcome) either smiled (O) or did not smile (~O). Table 2 depicts the frequency of each of the resulting four pairs of events for a positively contingent stream ($\Delta P = .467$), a noncontingent stream ($\Delta P = 0$), and a negatively contingent stream ($\Delta P = -.467$). Different contingencies were presented in a randomized order within a session. Immediately after each stream, participants rated how well Person 1's happiness predicted Person 2's happiness by keying in a number between ± 100, where $+100$ represented a perfect positive contingency, -100 represented a perfect negative contingency, and 0 represented no contingency.

Electrophysiology

The ActiveTwo Biosemi electrode system was used to record continuous electroencephalographic (EEG) activity from 128 silver/silver chloride (Ag/AgCl) scalp electrodes plus four additional ocular (electrooculographic, EOG) electrodes placed at the outer canthi and just below each eye. Two additional electrodes—common mode sense (CMS) active electrode and driven right leg (DRL) passive electrode—were also used. These electrodes replace the "ground" electrodes used in conventional systems. The continuous signal was acquired with an open pass-band from DC to 150 Hz and was digitized at 512 Hz. The signal was bandpass filtered offline at 0.1 to 30 Hz and re-referenced to a common average reference. EEG acquisition methods were consistent with previous reports (e.g., Heisz & Shedden, 2009).

ERP averaging and analysis were performed using EEProbe software (ANT). EEG and EOG artefacts were removed using a ± 35-μV deviation over 200 ms intervals on all electrodes. A 450 ms recorded EEG epoch, including a 100 ms prestimulus baseline and a 350 ms interval following stimulus onset, was chosen for ERP averaging. ERP waveforms were then averaged separately for each electrode for each experimental condition.

AN1. The AN1 ERP component was assessed using a similar electrode set and time window as reported in Wills et al. (2007). We assessed a set of 12 electrodes: 6 electrodes from each of left and right hemispheres. Electrode position corresponded to locations defined by the 10–20 system: F1/F2, F3/F4, CF1/CF2, CF3/CF4, C1/C2, and C3/C4 (F = frontal; CF = frontocentral; C = central). The peak amplitude of the AN1 component was isolated using a time window ranging from 88 to 160 ms, obtained via inspection of the grand average waveforms.

SN. The SN ERP component was assessed using a similar electrode set and time window as reported in Wills et al. (2007). We assessed a set of six electrodes: three electrodes from each of left and right hemispheres. Electrode position corresponded to locations defined by the 10–20 system: O1/O2, PO3/PO4, PO7/PO8 (O = occipital; OP = occipital parietal). The mean amplitude of the SN component was isolated using a time window ranging from 145 to 260 ms, obtained via inspection of the grand average waveforms.

PLS. Partial least squares (PLS; Lobaugh et al., 2001; McIntosh & Lobaugh, 2004) multivariate technique was used to assess the effects of contingency conditions on the ERP signal without biasing the analysis to particular ERP components assumed to be most relevant. We used task PLS to assess changes in mean brain activity as a function of stream contingency.

The input matrix for task PLS consists of rows with participants within conditions and columns with electrode by time information. Singular value decomposition is applied to the input matrix, which produces a set of orthogonal latent variables (LVs). Each LV consists of two parts: a "brain LV" (the brain portion of the LV) and a "design LV" (design portion of the LV). The brain LV represents the weighted linear combination of electrode sites and time points that covary with the design LV pattern. Projecting the brain LV onto each participant's ERP data by condition yields *scalp scores*, which can be positive or negative, depending on the relation between electrode/time and design LV. Associated with each LV is a singular value. From this value we can derive the percentage of covariance accounted for by the LV. Thus, an LV provides information regarding the relationship between the experimental conditions that accounts for some amount of covariance across the set of electrodes and time points.

Assessing the significance of an LV is done with a permutation test (1,000 iterations), which shuffles conditions within participants. The cumulative 95th percentile of the distribution of shuffled singular values is taken as the significance threshold. The reliability of the corresponding scalp topography (the distribution of electrode sites across time) is assessed by a bootstrap estimation of standard errors for the salience (500 iterations) by resampling participants. Using this standard error to divide the singular value weights of electrode site/time point composing the topography gives us a bootstrap ratio, which is similar to a z score when the singular values weights are normally distributed.

Results

Behavioural ratings

Contingency ratings of positively contingent, noncontingent, and negatively contingent streams were subjected to a one-way repeated-measures analysis of variance (ANOVA). Contingency ratings (on a scale ± 100) correlated with programmed contingencies, $F(2, 32) = 111.582$, $p < .001$, $\eta_p^2 = .88$, with positive ratings for positively contingent streams (50 ± 4 *SEM*), near-zero ratings for noncontingent streams (2 ± 1 *SEM*), and negative ratings for negatively contingent streams (−42 ± 4 *SEM*).

ERP component effects

AN1. The morphology of the AN1 component is illustrated in the grand averaged waveform of Figure 2A. Figure 2B depicts the mean AN1 peak amplitudes over right and left hemispheres for the three contingency values. AN1 peak amplitude was more negative for positively contingent streams than for negatively contingent streams, and this effect of contingency was more pronounced over the right hemisphere. These observations were supported by a two-way repeated measures ANOVA conducted on the peak amplitude of the AN1 with factors of hemisphere (right, left) and stream contingency (positive, non, negative). The main effect of stream contingency was significant, $F(2, 32) = 10.375$, $p < .001$, $\eta_p^2 = .39$, as was the two-way interaction of stream contingency with hemisphere, $F(2, 32) = 7.164$, $p < .01$, $\eta_p^2 = .31$.

To explore the relationship between the AN1 component and subjective contingency ratings, we examined the correlation between the mean AN1 peak amplitude across the 60-frame stream and behavioural rating at the end of the stream. When individual differences are evaluated, the magnitude of an individual's contingency rating

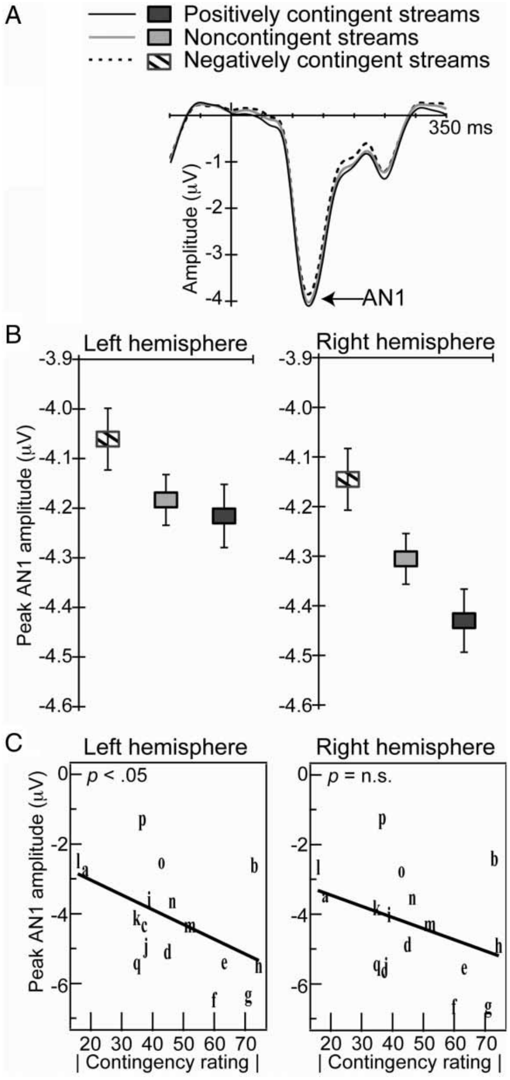

Figure 2. *(A) Grand averaged waveform depicts the AN1 ERP (anterior N1 event-related potential) response for positively contingent, negatively contingent, and noncontingent streams. (B) AN1 averaged peak amplitude over right and left hemispheres. Error bars are corrected (for repeated measures) standard errors. (C) Scatter plots depict correlations of the absolute behavioural ratings of contingent streams with AN1 peak amplitude over right and left hemispheres. Each letter of the scatter plot represents a participant.*

may be more important than the sign of the contingency being rated, and so we averaged across the absolute values of contingency ratings for positive and negative contingency streams. Using absolute ratings also provides a way of separating the effect of frame type from contingency. Contingency is confounded with frequency of co-occurrences; positive contingencies have a greater number of same emotion frames—cells *a* and *d* of the contingency matrix, Table 1A—than do negative contingencies, with null contingencies intermediate. Thus, the AN1 peak amplitude may not be a response to contingency, but to perceptual or semantic congruency. By taking the absolute value of the contingency rating and collapsing over the sign of the contingency, we are examining the response to contingency regardless of whether it is defined by more congruent frames (positively contingent streams) or more incongruent frames (negatively contingent streams). If frame type is driving our AN1 effects then the absolute value of contingency rating should not correlate with AN1 amplitude.

Figure 2C depicts the correlations between absolute contingency rating and AN1 peak amplitude for each hemisphere. Participants who made more extreme contingency ratings tended to have more negative AN1 amplitudes. The correlation was observed bilaterally, but was only significant at electrodes over the left hemisphere, as revealed by separate Pearson's correlation tests conducted on AN1 peak amplitude and absolute contingency ratings at electrode positions over the right hemisphere, $r(15) = -.37$, $p = .14$, and the left hemisphere, $r(15) = -.50$, $p < .05$.

SN. The morphology of the SN component is illustrated in the grand averaged waveform of Figure 3A. Figure 3B depicts SN mean amplitude over right and left hemispheres for the three contingency values. SN mean amplitude was affected by contingency value, being more negative for frames in negatively contingent streams than for those in positively contingent streams. This observation was supported by a two-way repeated measures ANOVA conducted on the mean amplitude of the SN component with factors of hemisphere (right, left) and stream contingency (positive, non, negative). The main effect of stream contingency was significant, $F(2, 32) = 4.444$, $p < .05$,

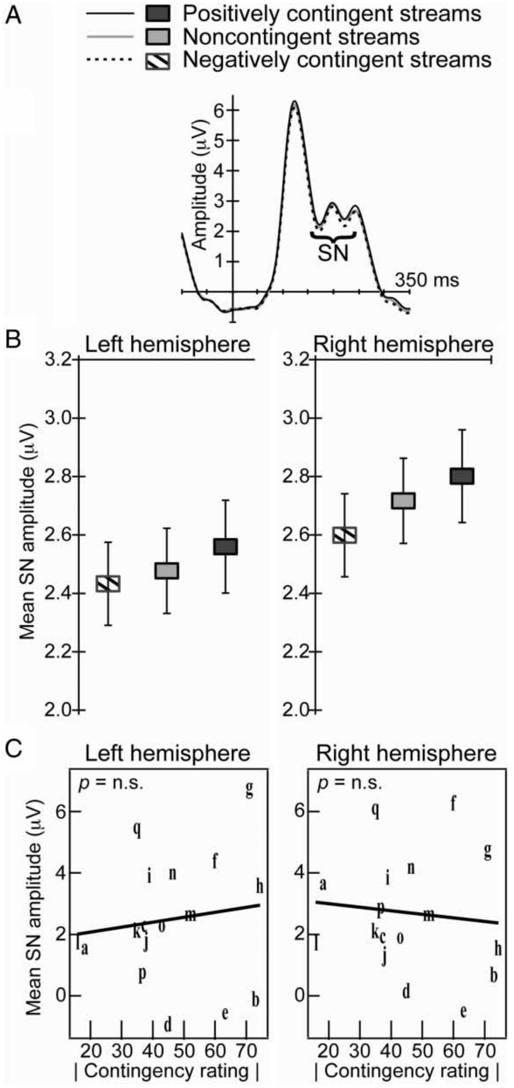

Figure 3. *(A) Grand averaged waveform depicts the SN ERP (selection negativity event-related potential) response for positively contingent, negatively contingent, and noncontingent streams. (B) SN averaged mean amplitude over right and left hemispheres. Error bars are corrected (for repeated measures) standard errors. (C) Scatter plots depict correlations of the absolute behavioural ratings of contingent streams with SN mean amplitude over right and left hemispheres. Each letter of the scatter plot represents a participant.*

$\eta_p^2 = .22$. No other main effects or interactions were significant.

To explore the relationship between the SN component and contingency ratings, we examined the correlation between SN mean amplitudes and behavioural ratings of the streams. As before, when evaluating individual differences, we averaged across absolute contingency ratings of positive and negative contingency streams. This also allowed us to separately assess the effect of contingency regardless of whether the contingent relationship is defined by more congruent frames (positively contingent streams) or more incongruent frames (negatively contingent streams). If frame type is driving our SN contingency effects then the absolute value of contingency rating should not correlate with SN amplitude. Absolute contingency ratings did not correlate with SN amplitude at electrodes over the right or left hemispheres (Figure 3C). These observations were supported by separate Pearson's correlation tests conducted on SN mean amplitude and absolute contingency ratings at electrode positions over the right hemisphere, $r(15) = -.10$, $p = .7$, and the left hemisphere, $r(15) = .14$, $p = .6$.

In summary, AN1 and SN responses were sensitive to stream contingency. The greatest AN1 peak amplitude was observed for positively contingent streams. In contrast, the greatest SN response was observed for negatively contingent streams. Furthermore, the AN1 response correlated with absolute contingency ratings, whereas the SN response did not. It is possible that the SN component may reflect the processing of frame properties rather than stream contingency. We evaluated this hypothesis, and, indeed, frame type modulated SN mean amplitude (Table 3). This observation was supported by a two-way repeated measures ANOVA conducted on the mean amplitude of the SN with factors of hemisphere (right, left) and frame type (*a*, *b*, *c*, and *d*). The main effect of frame type was significant, $F(2, 32) = 5.563$, $p < .01$, $\eta_p^2 = .23$. All pairwise comparisons were made but only the paired *t* test comparing frame type *a* against frame type *b* was significant after applying a Bonferroni correction for repeated comparisons (corrected $p < .008$). A similar ANOVA was done assessing the effect of frame type on AN1 peak amplitude. However, in this case, there were no significant effects involving frame type.

Table 3. *AN1 and SN grand mean amplitude responses for frames a, b, c, and d, collapsed across contingency*

	a	*b*	*c*	*d*
AN1	−4.20 (0.03)	−4.23 (0.03)	−4.24 (0.03)	−4.23 (0.03)
SN	2.52 (0.04)	2.78 (0.03)	2.68 (0.03)	2.71 (0.04)

Note: Grand mean amplitude in μV. Corrected (for repeated measures) standard errors in parentheses. AN1 = anterior N1. SN = selection negativity.

Time course effects

Task PLS was used to explore differences in mean ERP activity across stream contingency for each stream quarter. Figure 4 bar graphs depict the scalp scores reflecting the projection of the pattern of brain activity as a whole onto each treatment condition. Treatment conditions with statistically different scalp scores are indicated by nonoverlapping 95% confidence intervals (CIs). The significance of the contrast at particular electrodes (y axis, Figure 4, image plots) and time-points (x axis, Figure 4, image plots) is provided by bootstrap ratios (approximately equivalent to a z score). The most significant electrodes and time-points are represented by black (−) and white (+) bootstrap ratios, equal to or greater than ± 3 ($p \leq .001$). The sign of the bootstrap ratio indicates the direction of the mapping between scalp score and ERP amplitude differences. A positive bootstrap ratio indicates that the scalp score and the ERP amplitude difference are in the same direction (e.g., a more negative scalp score represents more negative amplitudes for one condition than for the other conditions). A negative bootstrap ratio indicates that the scalp score and the ERP amplitude difference are in opposite directions (e.g., a more negative scalp score represents more positive amplitudes for one condition than for the other conditions). Notably, PLS (Figure 4) revealed an effect of stream contingency within the first stream quarter, with the corresponding spatiotemporal topography (Figure 4, image plot) consistent with that of the AN1 component (Figure 2). To directly compare the PLS results with those of the AN1, we conducted separate two-way repeated-measures ANOVAs for each stream quarter on the peak amplitude of the AN1 with factors of hemisphere (right, left) and stream contingency (positive, non, negative). Table 4 presents AN1 mean amplitudes for each contingency during each stream quarter.

Figure 4A depicts the PLS results for the first quarter. Amplitude differences represented by scalp scores differentiated negatively contingent streams from positive and noncontingent streams (bar graph), accounting for 65.7% of the cross-block covariance ($p < .05$). This contrast was most stable between 100 ms and 150 ms postframe onset at frontal and central electrode position over the right hemisphere (image plots). The negative bootstrap ratio (black) of frontal and central sites indicates that amplitudes were more positive for the negatively contingent streams than for the positive and noncontingent streams. The focused analysis conducted on the AN1 component (Table 4) revealed the same pattern, with a two-way interaction between hemisphere and stream contingency, $F(2,\ 32) = 9.383$, $p < .01$, $\eta_p^2 = .37$, and a linear trend of stream contingency in the right hemisphere, $F(1, 16) = 9.311$, $p < .01$, $\eta_p^2 = .36$.

Figure 4 also depicts the PLS results for the second (B), third (C), and fourth (D) quarters. Across the remaining stream quarters, we observed a similar pattern of amplitude differences among the three streams (bar graphs), accounting for a significant portion of the cross-block covariance ($p < .01$). The spatiotemporal distribution of the contingency effect remained fairly consistent but with some slight variation across quarters (images plots). Notably, the timing of the contingency effect during the fourth quarter was significant at a slightly later time window (160 ms and 225 ms). The focused analysis conducted on the AN1 component (Table 4) revealed significant

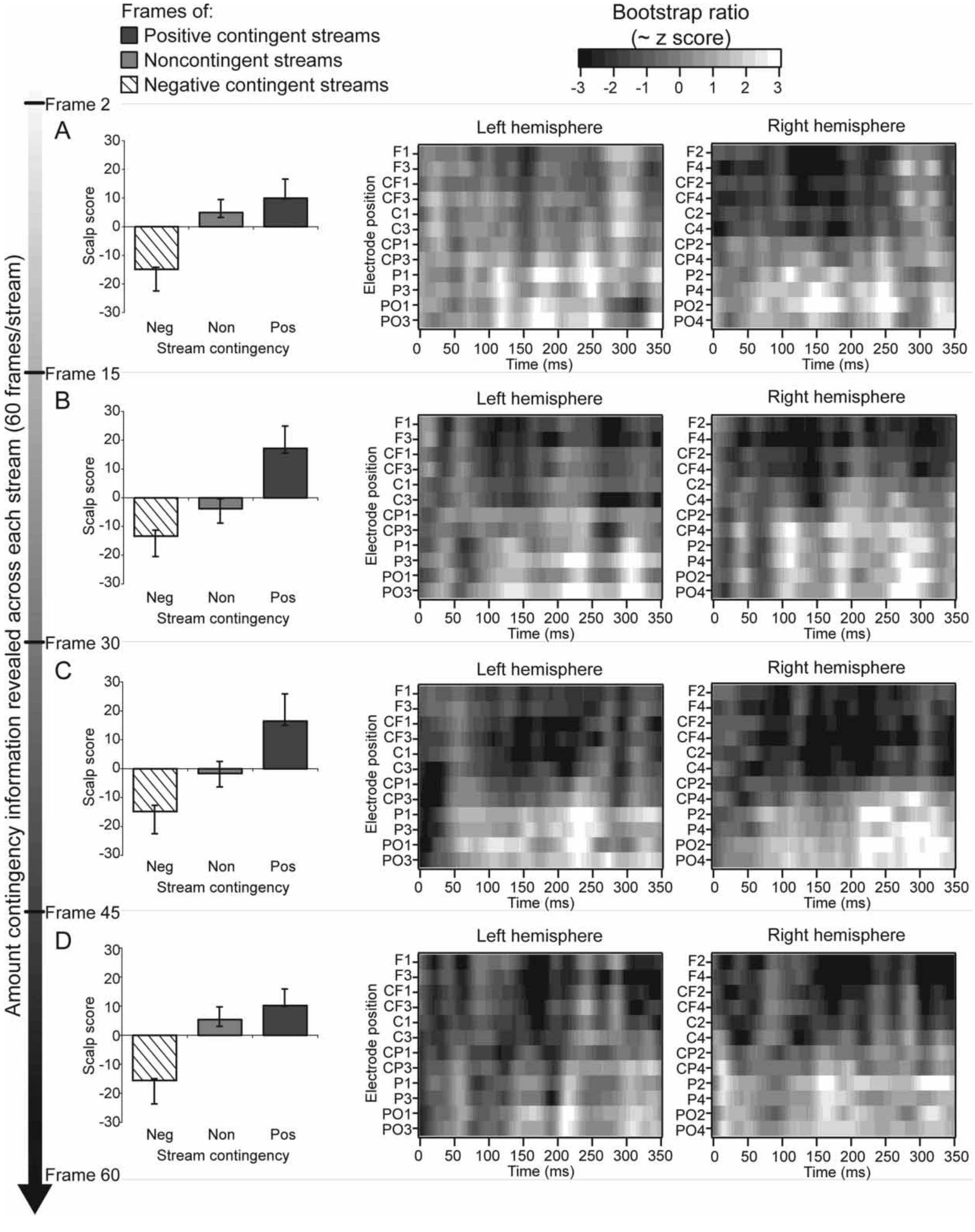

Figure 4. *PLS (partial least squares analysis) results for positively contingent, negatively contingent, and noncontingent streams during the first (A), second (B), third (C), and fourth quarters (D) of a streamed-trial. The bar graphs depict scalp scores; error bars are 95% confidence intervals (CIs). The image plots depict bootstrap ratios (approximately equivalent to a z score). Electrode positions correspond to locations defined by the 10–20 system: F = frontal; CF = frontocentral; C = central; CP = centroparietal; P = parietal; PO = parieto-occipital.*

Table 4. *AN1 grand mean amplitude responses for positively contingent, noncontingent, and negatively contingent streams during each of the stream's quarters*

	Stream quarter							
	Left hemisphere				*Right hemisphere*			
	1	*2*	*3*	*4*	*1*	*2*	*3*	*4*
Positive	−4.61 (0.09)	−4.39 (0.09)	−4.04 (0.10)	−3.81 (0.09)	−4.87 (0.11)	−4.53 (0.10)	−4.28 (0.07)	−4.04 (0.09)
Non	−4.61 (0.08)	−4.32 (0.07)	−3.97 (0.07)	−3.84 (0.07)	−4.67 (0.08)	−4.37 (0.06)	−4.09 (0.08)	−4.08 (0.09)
Negative	−4.62 (0.10)	−4.15 (0.09)	−3.78 (0.07)	−3.70 (0.09)	−4.53 (0.11)	−4.17 (0.08)	−3.99 (0.09)	−3.89 (0.08)

Note: Grand mean amplitude in μV. Corrected (for repeated measures) standard errors in parentheses. AN1 = anterior N1.

linear trends of stream contingency for both the second, $F(1, 16) = 7.567$, $p < .05$, $\eta_p^2 = .32$, and third, $F(1, 16) = 6.370$, $p < .05$, $\eta_p^2 = .32$, quarters. However, during the fourth quarter, the AN1 response was larger at electrodes over the right hemisphere, $F(1, 16) = 4.674$, $p < .05$, $\eta_p^2 = .23$, and displayed no effect of stream contingency. This fits with the PLS analysis, which showed slightly later timing of the contingency effect during the fourth quarter. Recall that the AN1 component was isolated using a time window ranging from 88 ms to 160 ms. Instead, it is likely that the PLS analysis is capturing the activity of the positive deflection following the AN1 component (Figure 2, waveform).

In summary, the ERP signal differentiated stream contingency within the first quarter, and the corresponding spatiotemporal topography was consistent with that of the AN1 component. Such early emergence of contingency-related processing highlights the efficiency of statistical information processing.

Discussion

We are the first to capture the fine-grained temporal dynamics of processing during a contingency assessment task. Our data reveal information about the neural mechanisms that underlie contingency assessment regarding two questions: which ERP components are sensitive to our contingency task manipulations, and how soon within a streamed trial is contingency extracted (i.e., time course effects)? With respect to the ERP component, AN1 and SN components were sensitive to our streamed-trial contingency task. The AN1 ERP component varied with the objective contingency and correlated with participants' contingency ratings. In contrast, the SN ERP component varied with the type of display and did not correlate with participants' contingency ratings. With respect to the time course of such recruitment, we demonstrate that contingency-sensitive responses can be extracted from very little information presented over a brief 5-second interval. Within the first 5 seconds of display, neural activity correlated with objective stream contingency. This is especially remarkable given that each frame was only presented for 100 ms.

ERP component effects

ERPs were time-locked to the onset of each frame to capture neural responses during a contingency judgement task. We focused on the AN1 and SN components. Both are thought to reflect selective attentional processes (e.g., Anllo-Vento & Hillyard, 1996; Clark & Hillyard, 1996) and have been implicated in attentional processes of learning by prediction error (Wills et al., 2007). We were particularly interested in whether these ERP components were also sensitive to contingency task manipulations. We minimized explicit prediction by using the streamed-trial procedure: participants were not required to make predictions after each frame, and rapid simultaneous presentation of the cue–outcome pair reduced any potential volitional predictions. Even with these constraints, we observed effects of our contingency manipulation on the AN1 and SN components.

Furthermore, the observed AN1 and SN amplitude patterns differed from those expected on the basis of a prediction-error hypothesis. According to a prediction-error hypothesis, noncontingent streams should elicit the largest amplitude response because the cues of these frames are associated with greatest prediction error—any successful prediction of an upcoming event in a noncontingent stream would be by chance. However, positively contingent streams elicited the largest response by both AN1 and SN components.

AN1. Considering the pattern of the AN1 response in our task and across previous tasks (Lang et al., 2006; Töllner et al., 2008; Wills et al., 2007), we suggest that the AN1 may reflect a general attentional mechanism of statistical information processing required for different types of learning task. The magnitude of AN1 may index the amount of attention directed to the display in the service of detecting relational information. For example, Lang et al. (2006) assessed the AN1 response while participants performed a number reduction task (NRT). In the NRT, each trial consists of five serially presented numbers. Participants respond after each number; however, the ultimate goal of each trial is to determine the correct response following the fifth (final) number; participants indicate their final response by pressing "enter", and they can do this at any point in the sequence. In the Lang et al. study, the final response was always the same as the second response. Critically, participants who explicitly learned this perfect contingent relationship showed enhanced AN1 amplitude for the second and fifth numbers in the sequence. Moreover, these AN1 effects emerged within the first block (54 trials) even though there was no change in their behavioural performance.

Our results may reflect the same process whereby attention is directed to the display when the participant is entertaining a particular hypothesis about the stream's contingency. Based on previous empirical studies, positive contingencies may be easier to track than negative ones (Maldonado, Jiménez, Herrera, Perales, & Catena, 2006; Mutter & Williams, 2004), and this is probably rooted in a more liberal response criterion for positive contingencies (Allan et al., 2008). If participants are more likely to generate a hypothesis when considering a positive contingency than when considering a negative contingency, they may direct more attention to frames of a positively contingent stream than those of a negatively contingent stream. Although such hypothesis-directed attention is a speculative proposition, it would account for the pattern of the AN1 activity across contingency conditions, the consistency of the AN1 response across frame type and the observed effects of contingency-sensitive AN1 activity during the first three quarters. This would also account for the lack of contingency-sensitive AN1 activity during the last quarter. By the end of the streamed trial, participants' subjective ratings distinguished among all contingencies; by the fourth quarter, participants may have come to a conclusion about the stream contingency and may no longer need to evaluate a hypothesis.

SN. Negatively contingent streams produced the largest SN response. In addition, the SN response did not correlate with contingency ratings. Instead, the SN response seemed to be linked to frame type: frame type *a* produced the largest SN response, and there was a trend for this to be more pronounced in negatively contingent streams. Interestingly, this pattern maps onto a prediction-error hypothesis, if we assume that frame type *a* is the strongest contributor to predictions of positive contingency. Moreover, given the common behavioural finding that positive events (*a* cells in Table 1) are weighted more heavily in contingency tasks than events represented by the other cells in Table 1 (e.g., Wasserman, Dorner, & Kao, 1990; White, 2003), SN processes may reflect feature-based selective attention, indexing sensitivity to the frame properties independent of contingency. Such interpretation is consistent with previous SN results, which generally find a more negative SN for attended versus unattended features (e.g., Anllo-Vento & Hillyard, 1996; Harter et al., 1982; O'Donnell, Swearer, Smith, Hokama, & McCarley, 1997). Although information about a particular frame could be used to derive stream contingency, the mapping between frame type and the stream contingency is complex, involving the cumulative frequency of four different stimuli over time.

Time course effects

With the streamed-trial procedure, we were able to track changes in the ERP response across learning, allowing for a more detailed analysis of the time course of contingency acquisition. We were particularly interested in the earliest point within a streamed trial at which contingency information could be extracted. The results suggest a remarkably efficient system for extracting statistical relations: in less than five seconds (with only 15 cue–outcome pairings), the ERP response distinguished contingency across rapidly presented information streams.

The neural response averaged across the first quarter of a streamed trial was very similar to that averaged across the last quarter of a streamed trial. Thus, processes reflected by this neural activity are engaged quite early in the series. Although this time-course assessment resulted from our unbiased whole brain analysis (i.e., PLS), the corresponding spatiotemporal pattern of the activity (Figure 4, image plot) was highly consistent with that of the AN1 component (Table 4). Taken together, these results suggest that the processing of statistical information may engage very early in contingency assessment.

Such early effects of contingency may surprise some researchers. However, others have demonstrated that participants can maintain the ability to rank order contingency judgements with little time and little information. Parr and Mercier (1998), for example, varied the number of cue–outcome pairings (8, 24, or 40 pairings) and the time between pairings (100 ms, 300 ms, and 1,000 ms). They tested three programmed contingencies, ranging from weak to strong, and participants rated their perceived contingency on a scale ranging from −100 to +100. Even with the least amount of time and information, subjective contingency ratings mapped onto the rank order of the programmed contingencies. Likewise, Clement, Mercier, and Pastò (2002) demonstrated that participants could accurately assess contingency from only a small sample of the relationship. They established four different contingencies over 40 pairings but presented participants with a random subset of those pairings. Even when presented with only 4 of the 40 pairings, participants could reliably distinguish among four different contingencies. Our data contribute to these results by revealing contingency processing in response to each frame (presented for a mere 100 ms) at different points on the learning curve.

Spatiotemporal changes in the contingency effect over time. Although the three contingency values elicited unique neural responses throughout the streamed trial, the distinction was initially more prominent at electrodes over the right hemisphere. Previous functional magnetic resonance imaging (fMRI) studies involving contingency assessment have reported a similar right hemisphere bias, with particular activation of the right dorsal lateral prefrontal cortex (Corlett et al., 2004; Fletcher et al., 2001; Turner et al., 2004). However, with the presentation of additional information, electrodes over the left hemisphere came to distinguish contingency. Also, recall from the correlational analysis that AN1 activity over the left hemisphere was predictive of subsequent contingency ratings. These results seem to emphasize the role of the left hemisphere in contingency assessment and may point to hemisphere specialization for different aspects of contingency learning. The right hemisphere may be more specialized in extracting statistical information whereas the left hemisphere may be more specialized in integrating statistical information for accurate contingency judgements. Neuroimaging techniques with greater spatial resolution should verify these hemisphere effects.

In conclusion, we have characterized the timing of neural processing during contingency learning. Each frame elicited ERP activity that correlated with both objective contingencies and subjective contingency ratings. Furthermore, contingencies were distinguished by the ERP activity within five seconds of the trial start. Our results highlight the efficiency of human statistical information processing and establish the streamed-trial procedure as a useful method for investigating the event-related neuroimaging of contingency processes.

Original manuscript received 22 February 2010
Accepted revision received 17 June 2010
First published online 14 October 2010

REFERENCES

Allan, L. G. (1980). A note on measurement of contingency between two binary variables in judgement tasks. *Bulletin of the Psychonomic Society*, *15,* 147–149.

Allan, L. G., Hannah, S. D., Crump, M. J. C., & Siegel, S. (2008). The psychophysics of contingency assessment. *Journal of Experimental Psychology: General*, *137,* 226–243.

Anllo-Vento, L., & Hillyard, S. A. (1996). Selective attention to the color and direction of moving stimuli: Electrophysiological correlates of hierarchical feature selection. *Perception & Psychophysics*, *58,* 191–206.

Clark, V. P., & Hillyard, S. A. (1996). Spatial selective attention affects early extrastriate but not striate components of visual evoked potentials. *Journal of Cognitive Neuroscience*, *8,* 389–402.

Clement, M., Mercier, P., & Pastò, L. (2002). Sample size, confidence, and contingency judgements. *Canadian Journal of Experimental Psychology*, *56,* 128–137.

Corlett, P. R., Aitken, M. R. F., Dickinson, A., Shanks, D. R., Honey, G. D., Honey, R. A. E., et al. (2004). Prediction error during retrospective revaluation of causal associations in humans: fMRI evidence in favor of an associative model of learning. *Neuron*, *44,* 877–888.

Crump, M. J. C., Hannah, S. D., Allan, L. G., & Hord, L. K. (2007). Contingency judgements on the fly. *Quarterly Journal of Experimental Psychology*, *60,* 753–761.

De Houwer, J., & Becker, T. (2002). A review of recent developments in research and theories on human contingency learning. *The Quarterly Journal of Experimental Psychology*, *55B,* 289–310.

Fletcher, P. C., Anderson, J. M., Shanks, D. R., Honey, R., Carpenter, T. A., Papadakis, N., et al. (2001). Responses of human frontal cortex to surprising events are predicted by formal associative learning theory. *Nature Neuroscience*, *40,* 1043–1048.

Hannah, S. D., Crump, M. J., Allan, L. G., & Siegel, S. (2009). Cue-interaction effects in contingency judgement using streamed-trial procedure. *Canadian Journal of Experimental Psychology*, *63,* 103–112.

Harter, M. R., Aine, C., & Schroeder, C. (1982). Hemispheric differences in the neural processing of stimulus location and type: Effects of selective attention on visual evoked potentials. *Neuropsychologia*, *20,* 421–438.

Heisz, J. J., & Shedden, J. M. (2009). Semantic learning modifies perceptual face processing. *Journal of Cognitive Neuroscience*, *21,* 1127–1134.

Holroyd, C. B., & Coles, M. G. (2002). The neural basis of human error processing: Reinforcement learning, dopamine, and error-related negativity. *Psychological Review*, *109,* 679–709.

Lang, S., Kanngieser, N., Jaskowski, P., Haider, H., Rose, M., & Verleger, R. (2006). Precursors of insight in event-related brain potentials. *Journal of Cognitive Neuroscience*, *18,* 2152–2166.

Lobaugh, N. J., West, R., & McIntosh, A. R. (2001). Spatiotemporal analysis of experimental differences in event-related potential data with partial least squares. *Psychophysiology*, *38,* 517–530.

Maldonado, A., Jiménez, G., Herrera, A., Perales, J. C., & Catena, A. (2006). Inattentional blindness for negative relationships in human causal learning. *The Quarterly Journal of Experimental Psychology*, *59,* 457–470.

McIntosh, A. R., & Lobaugh, N. J. (2004). Partial least squares analysis of neuroimaging data: Applications and advances. *NeuroImage*, *23,* S250–S263.

Miltner, W. H. R., Braun, C., Arnold, M., Witte, H., & Taub, E. (1999). Coherence of gamma-band EEG activity as a basis for associative learning. *Nature*, *397,* 434–436.

Mutter, S. A., & Williams, T. W. (2004). Aging and the detection of contingency in causal learning. *Psychology and Aging*, *19,* 13–26.

O'Donnell, B. F., Swearer, J. M., Smith, L. T., Hokama, H., & McCarley, R. W. (1997). A topography study of ERPs elicited by visual feature discrimination. *Brain Topography*, *10,* 133–143.

Parr, W. V., & Mercier, P. (1998). Adult age difference in on-line contingency judgements. *Canadian Journal of Experimental Psychology*, *52,* 147–158.

Shanks, D. R. (2007). Associationism and cognition: Human contingency learning at 25. *Quarterly Journal of Experimental Psychology*, *60,* 291–309.

Spellman, B. A., Price, C. M., & Logan, J. M. (2001). How two causes are different from one: The use of (un) conditional information in Simpson's paradox. *Memory & Cognition*, *29,* 193–208.

Töllner, T., Gramann, K., Müller, H. J., & Eimer, M. (2008). The anterior N1 component as an index of modality shifting. *Journal of Cognitive Neuroscience*, *21,* 1653–1669.

Turner, D. C., Aitken, M. R. F., Shanks, D. R., Sahakian, B. J., Robbins, T. W., Schwarzbauer, C., et al. (2004). The role of the lateral frontal cortex in causal associative learning: Exploring preventative and super-learning. *Cerebral Cortex*, *14,* 872–880.

Wasserman, E. A. (1990). Attribution of causality to common and distinctive elements of compound stimuli. *Psychological Science*, *1,* 298–302.

Wasserman, E. A., Dorner, W. W., & Kao, S. F. (1990). Contributions of specific cell information to judgements of interevent contingency. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *16,* 509–521.

White, P. A. (2003). The effects of wording and stimulus format on the use of contingency information in causal judgement. *Memory and Cognition*, *31,* 231–242.

Wills, A. J., Lavric, A., Croft, G. S., & Hodgson, T. L. (2007). Predictive learning, prediction errors, and attention: Evidence from event-related potentials and eye tracking. *Journal of Cognitive Neuroscience*, *19,* 843–854.