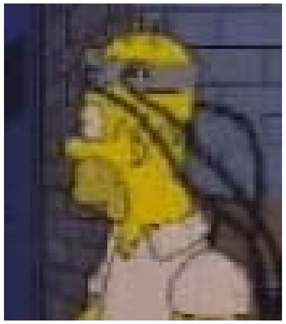
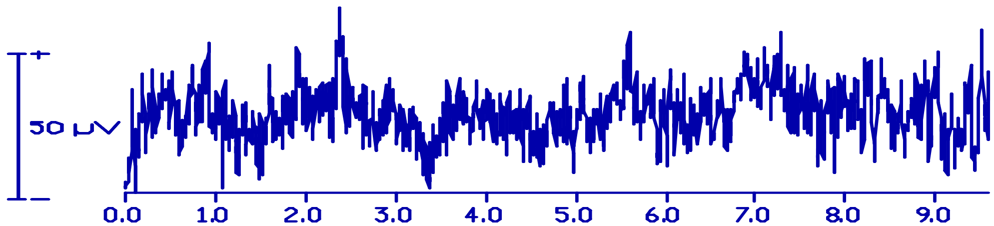
The Event-Related Potential (*aka* the ERP)

A continuation…

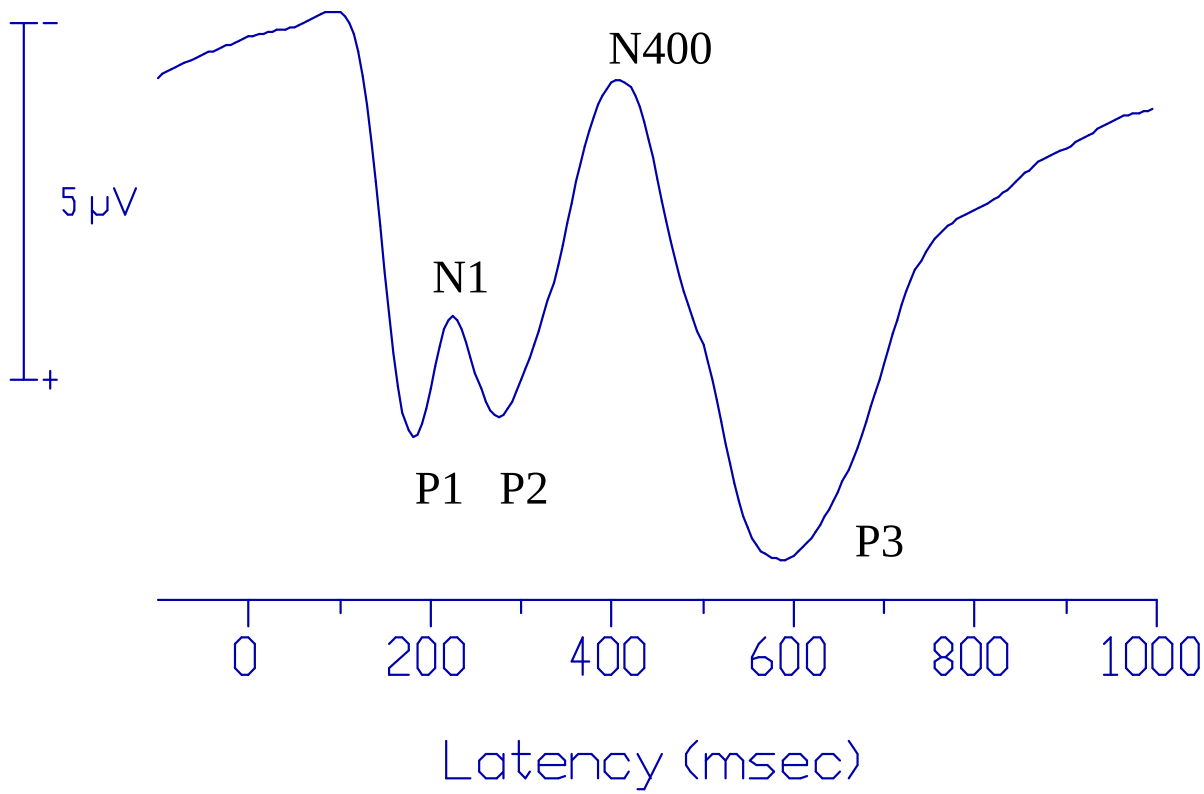


Ongoing EEG



Stimuli

Visual Event-related Potential (ERP)



Construct Validity of P300 (P3, P3b)

- First observed by Sutton, Braren, Zubin, & John (1965)
- P300 Amplitude; Johnson's model is

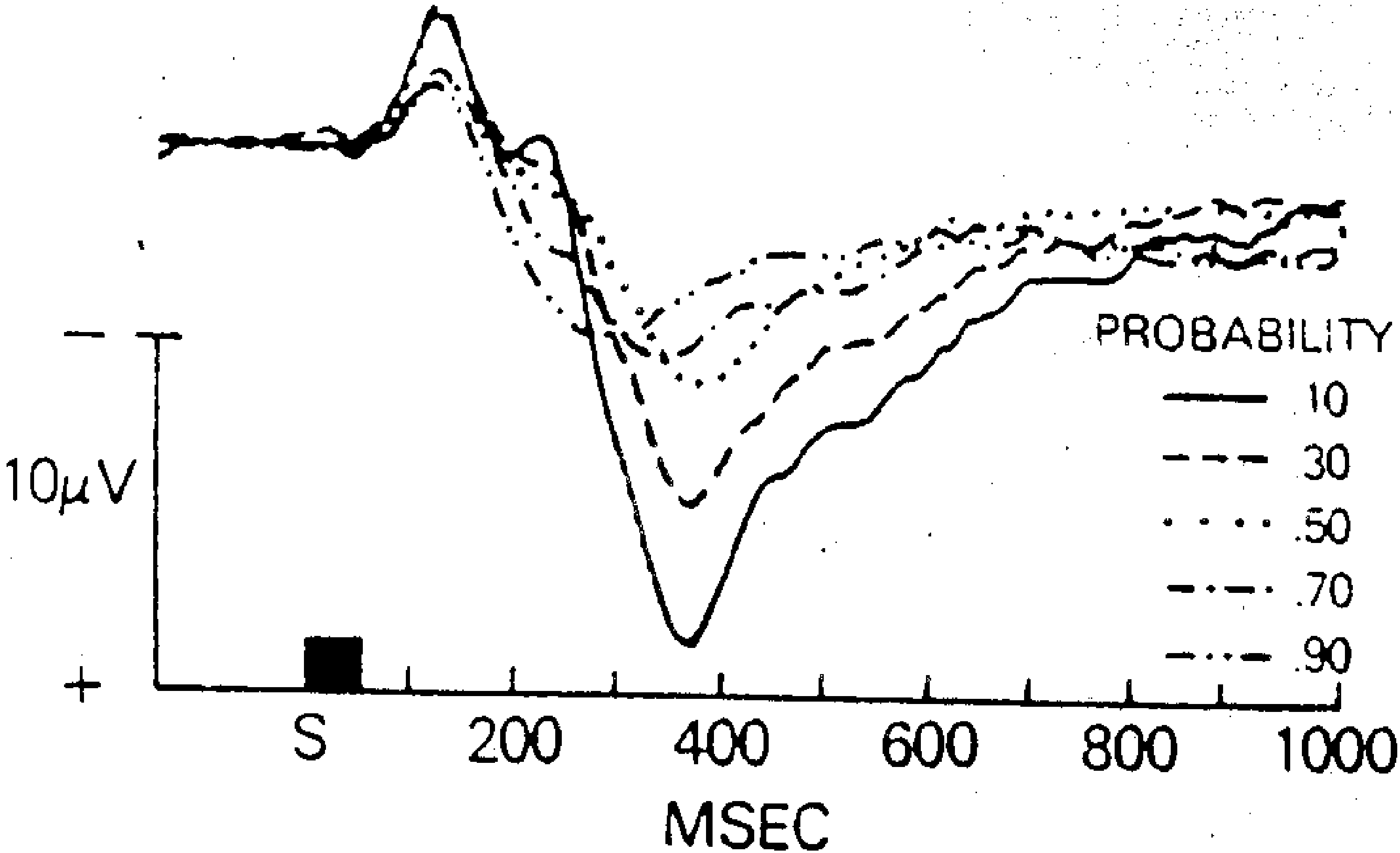
$$\text{P300 Amplitude} = f[T \times (1/P + M)]$$

where

- P = probability of occurrence,
- M = Stimulus meaning, &
- T = amount of information transmitted

Aspects of the Model

- Rarity
  - The P300 is observed in variants of the "oddball paradigm"
  - The rare stimulus almost invariantly elicits a P300: largest at parietal, then central, and then frontal sites
  - **Subjective probability**
- Stimulus meaning
  - Actually composed of three dimensions
    - task complexity
    - stimulus complexity
    - stimulus value
- Information Transmission (proportion 0 to 1; more shortly)



PROBABILITY
.10
.30
.50
.70
.90
10μV
−
+
S
200
400
600
800
1000
MSEC

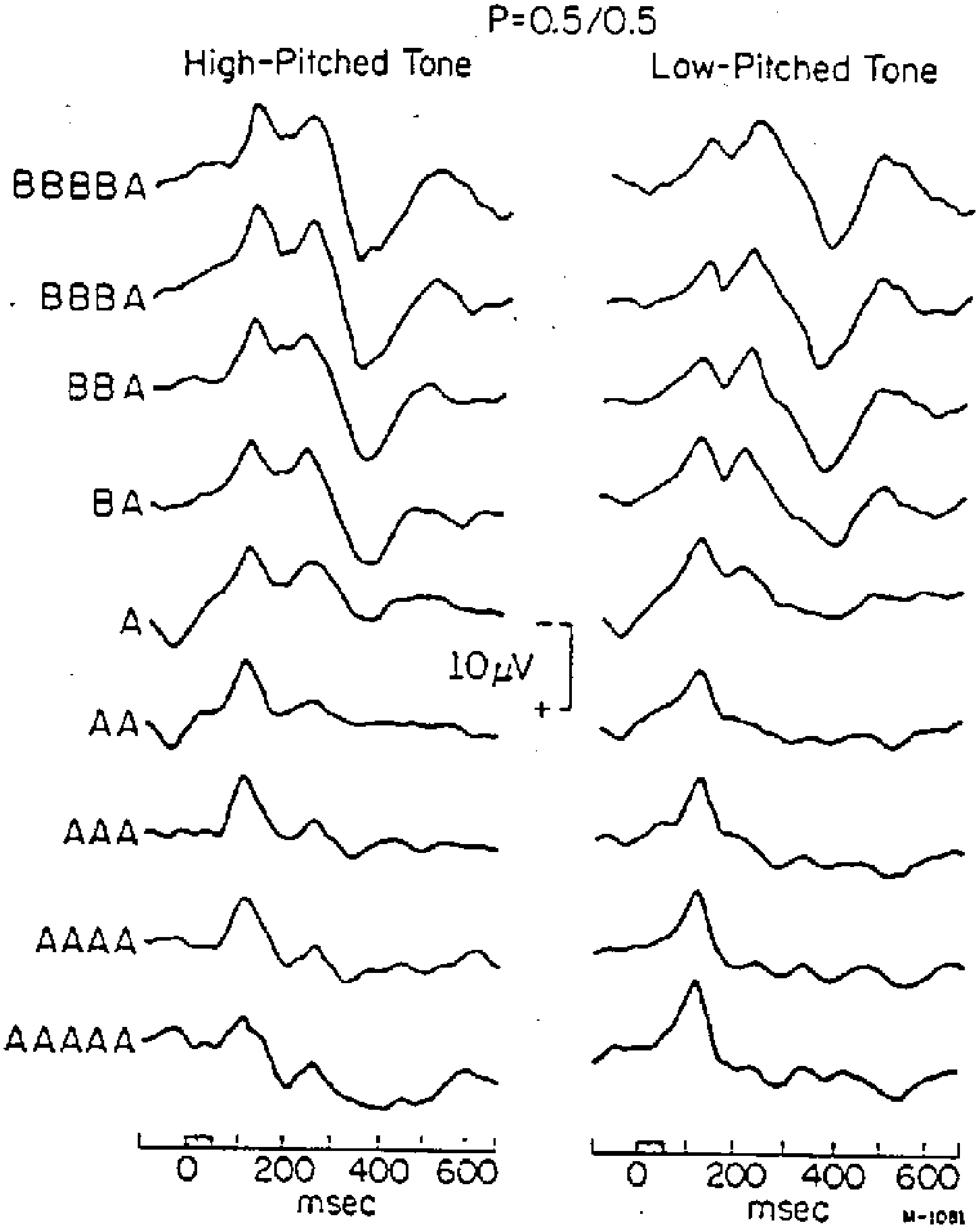


Figure 12-1. The ERPs in each column were elicited by the same physical tone; high-pitched tones were used for the left column and low-pitched tones for the right column. Both were presented in a Bernoulli series in which the probability of the two stimuli were equal. In the middle of each column (labeled "A") is the ERP elicited by all the presentations of the stimulus. The curve labeled "AA" was obtained by averaging together all the tones of one frequency that were preceded on the previous trial by tones of the same frequency. On the other hand, the curves labeled "BA" were elicited by stimuli preceded on the previous trial by the tones of different frequency. Similar sorting operations were applied to all other curves in this figure. It can be seen that the same physical tone elicited quite different ERPs, depending on the events that occurred on the preceding trials. Whenever a tone terminated a series of tones from the other category, a large P300 was elicited, and its magnitude was a function of the length of the stimulus series. (From "Effect of Stimulus Sequence on the Waveform of the Cortical Event-Related Potential," by K. C. Squires, C. D. Wickens, N. K. Squires, and E. Donchin. *Science*, 1976, 193, 1142–1146. Copyright 1976 by the AAAS.

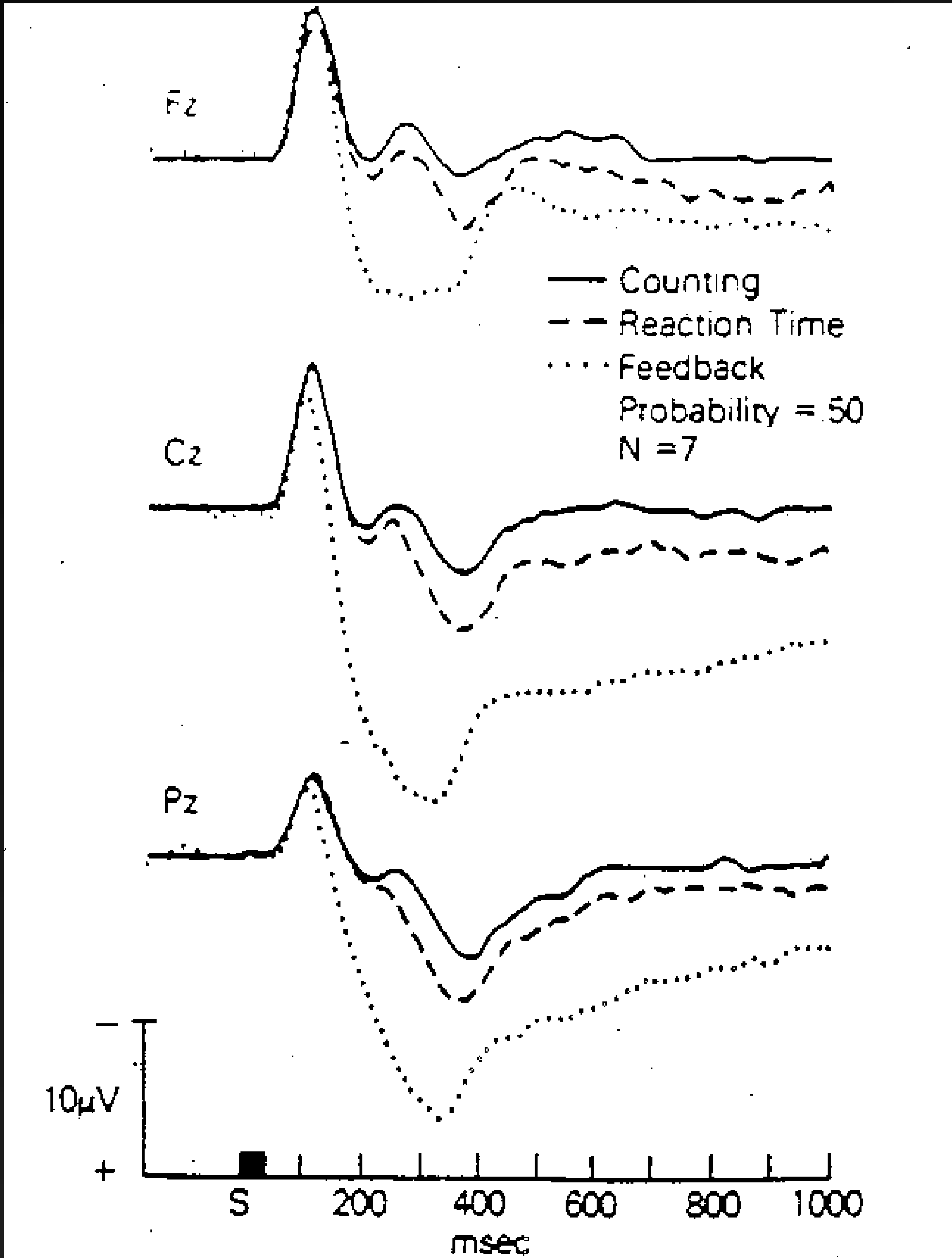
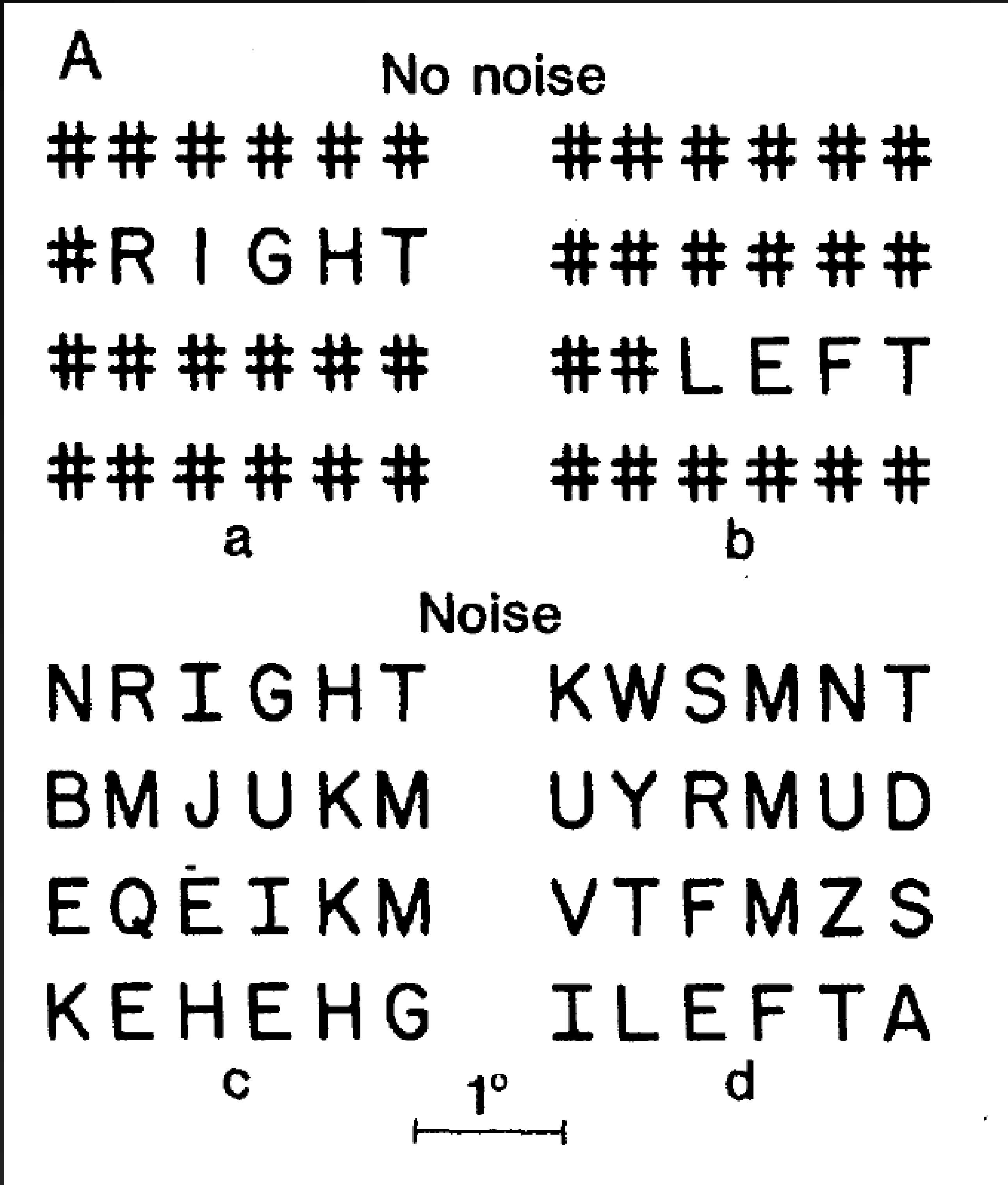


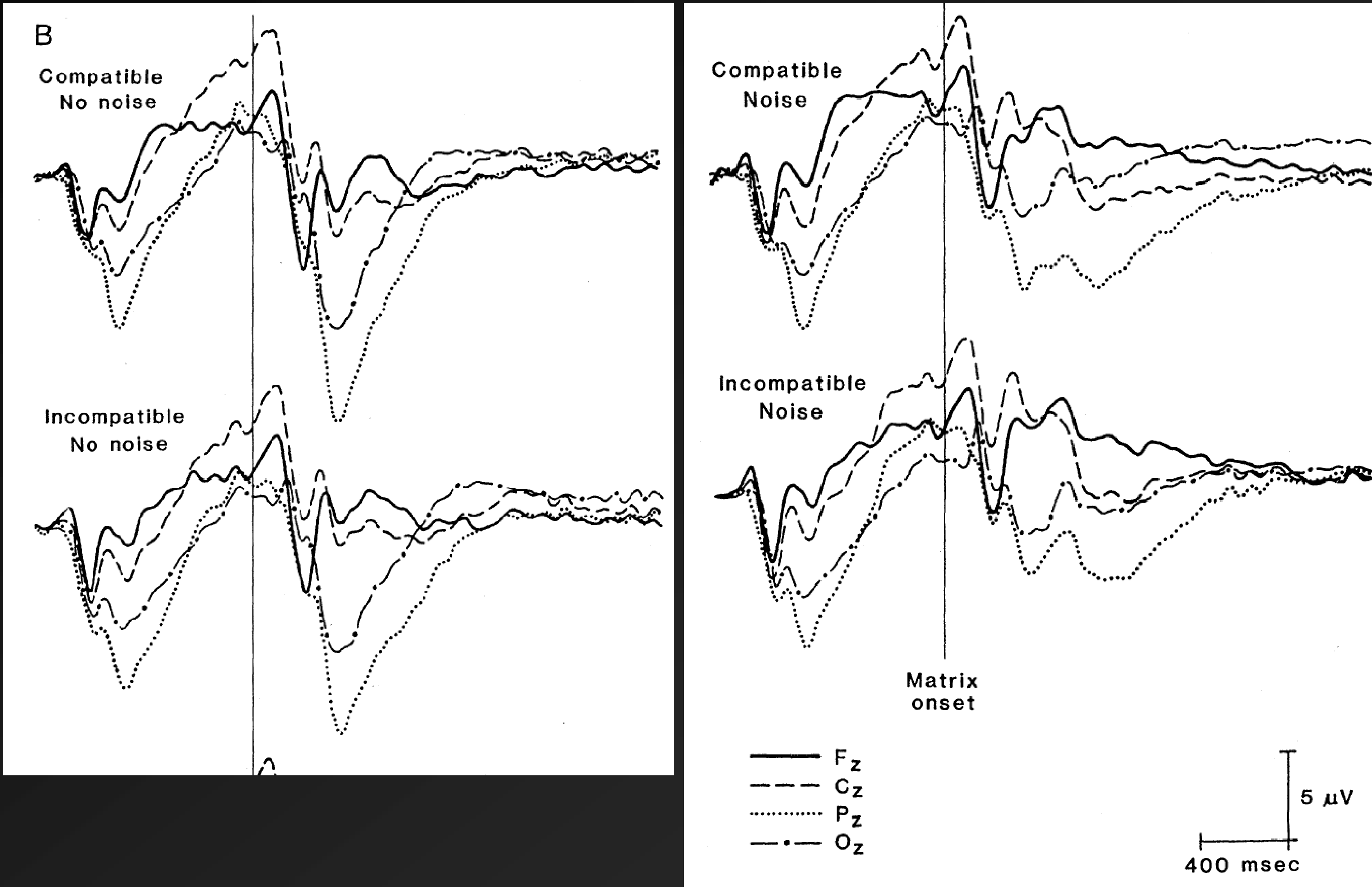
Figure 2. Grand-mean waveforms (N = 7) from F_Z, C_Z, and P_Z from three different tasks. The ERPs elicited in an oddball paradigm run under two different task conditions, Counting (solid line) and Reaction Time (dashed line), are superimposed on the ERP elicited when the same stimulus signified correct performance in a feedback paradigm (dotted line). The waveforms were all elicited by a 1000 Hz, 50dB SL tone ($p = .50$).

P3 Latency

- An index of processing time, independent of response requirements
  - RT measures confounds the two
  - McCarthy & Donchin (1981) experiment:
    - The words "RIGHT" or "LEFT" embedded in a matrix of letters of X's
    - Compatible condition: respond with hand indicated in matrix; Incompatible condition: respond with opposite hand (e.g., LEFT signals right hand response);
    - Results:
      - P300 latency delayed when discriminability more difficult
      - Response compatibility had no effect on P300 latency
      - **Note amplitude reduction as function of noise--information transmission)**



A
No noise
######
#RIGHT
######
######
a
######
######
##LEFT
######
b
Noise
NRIGHT
BMJUKM
EQEIKM
KEHEHG
c
KWSMNT
UYRMUD
VTFMZS
ILEFTA
d
1°



B
Compatible
No noise
Incompatible
No noise
Compatible
Noise
Incompatible
Noise
Matrix
onset
Fz
Cz
Pz
Oz
5 µV
400 msec

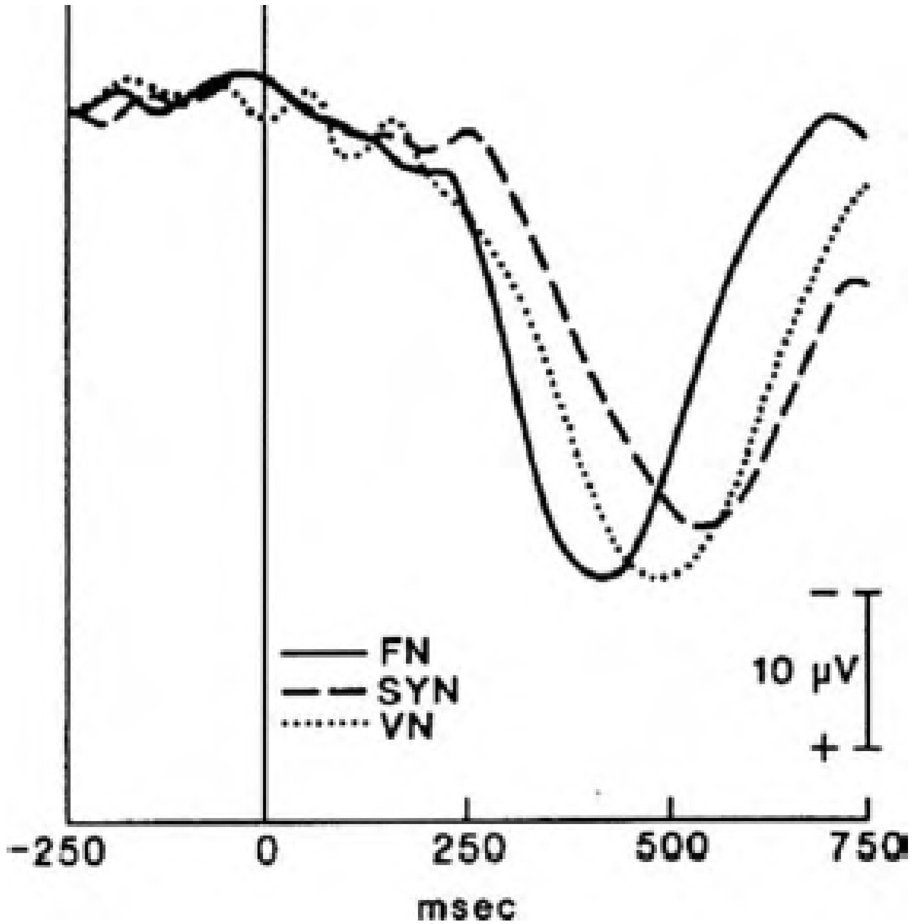


Figure 4.10. ERP waveforms at Pz averaged across subjects for three different semantic categorization tasks. The solid line indicates ERPs obtained during a task in which the subjects had to distinguish between the word DAVID and the word NANCY (the FN condition). The dotted line indicates ERPs obtained during a task in which the subjects had to decide whether a word presented was a male or a female name (the VN condition). The dashed line indicates ERPs obtained during a task in which the subjects had to decide whether a word was or was not a synonym of the word PROD (SYN condition). These three tasks were considered to involve progressively more difficult discriminations. Note the latency of P300 peak is progressively longer as the discrimination is made more difficult. (Copyright 1977, AAAS. Adapted with permission of the author and publisher from Kutas, McCarthy, & Donchin, 1977.)

Not only difficulty in physical discrimination, but difficulty in cognitive categorization

Construct Validity?

- What, then, does the P300 mean in very general terms?
  - A stimulus (or class of stimuli) is "important"; denotes information that is necessary or useful to the task
  - Stimulus is meaningful, important, noticeable
  - Evaluated within context of working memory? (cf. Donchin & Coles, 1988; Verlager 1988; Polich, 2007; Verlager, 2008)
- The P3a (Squires, Squires, and Hillyard, 1975): P3-like component with a frontal maximum and occurs to improbable stimuli in the "to-be-ignored" class of stimuli; a novelty response.
  - More later…

ERPs and Memory

- Sensitive to both Recognition
  - Likely episodic recollection
- Sensitive to Encoding

Repetition Priming Effects

- Robust effect that repeated items produce an enhanced late positivity across a broad latency range
- Magnitude of effect related to strength of memory trace

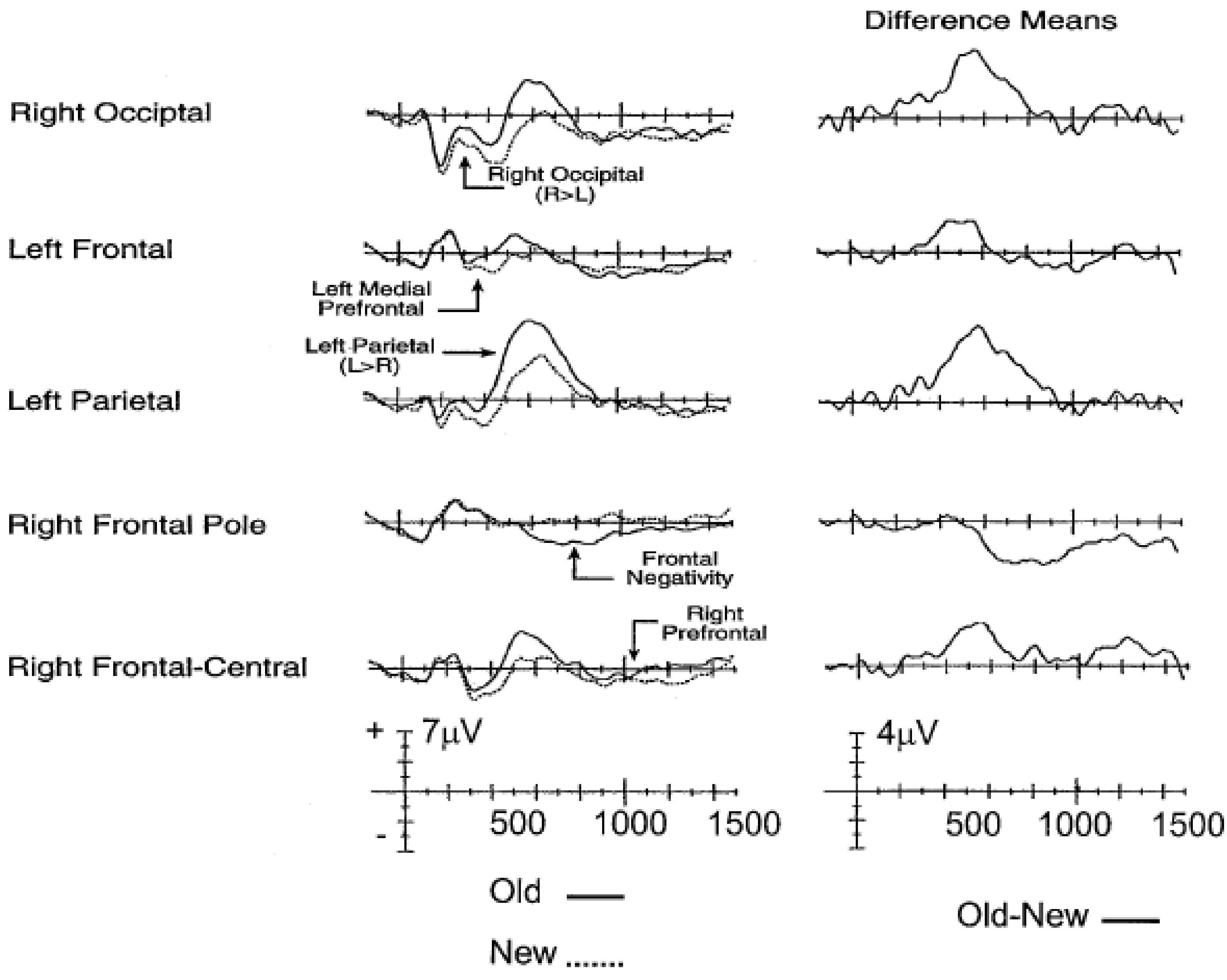
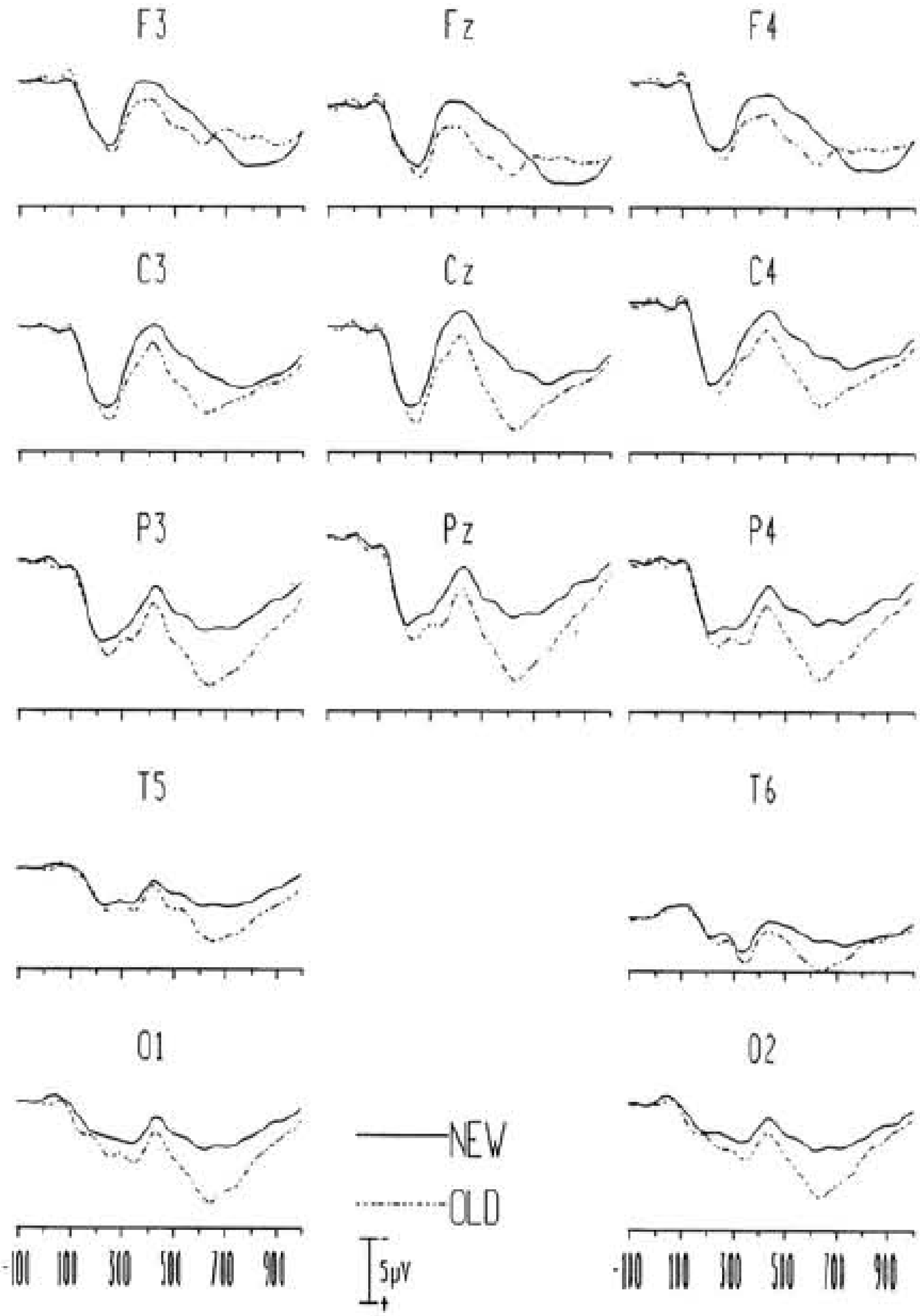
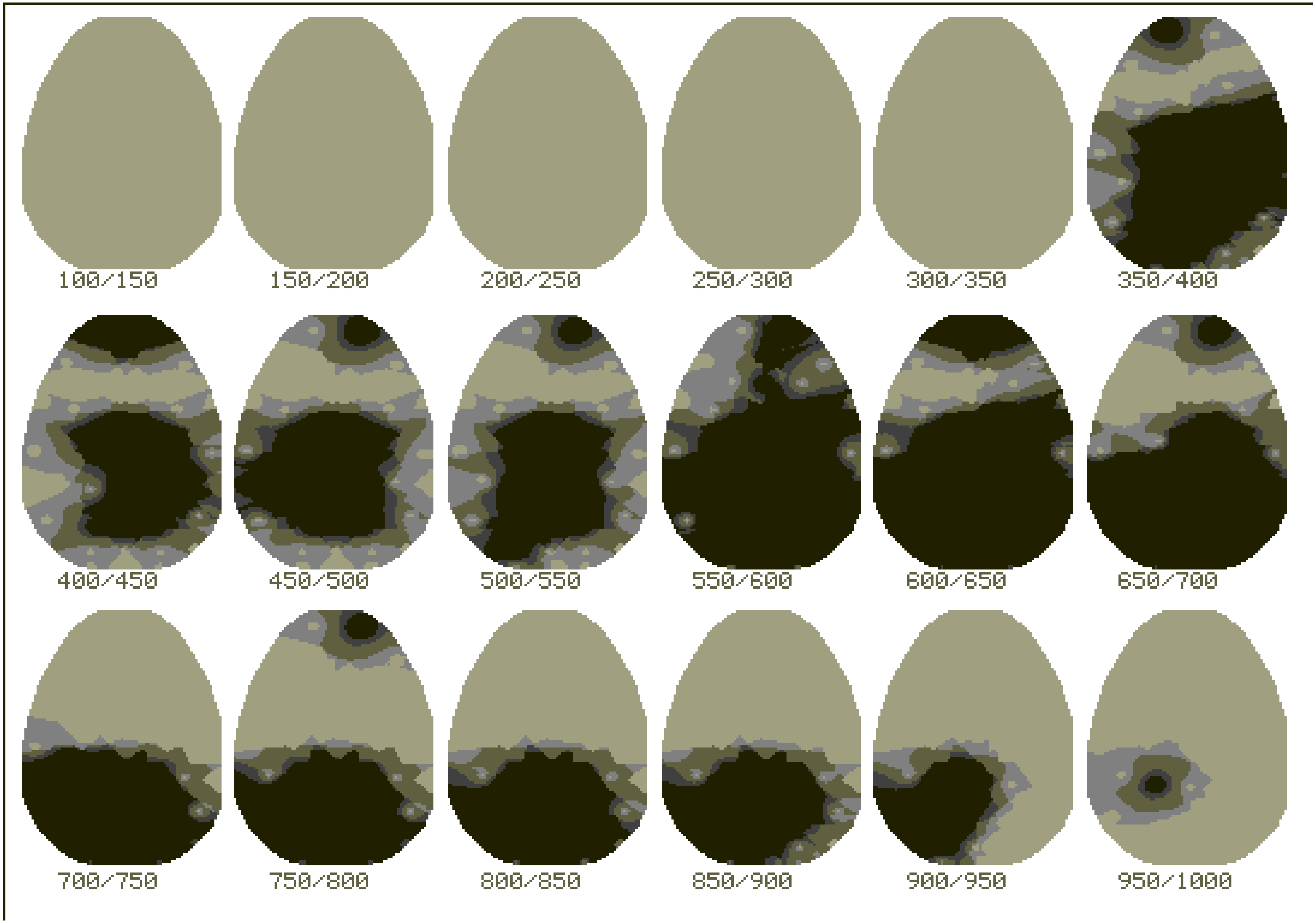


Fig. 4. Grand mean ERP waveforms elicited by correctly recognized old and correctly rejected new items from Johnson et al. (1998a). The left column depicts the old and new waveforms at the electrode site and hemiscalp where that subcomponent was largest. Repoduced from Johnson et al. (1998a) with permission of the publisher.

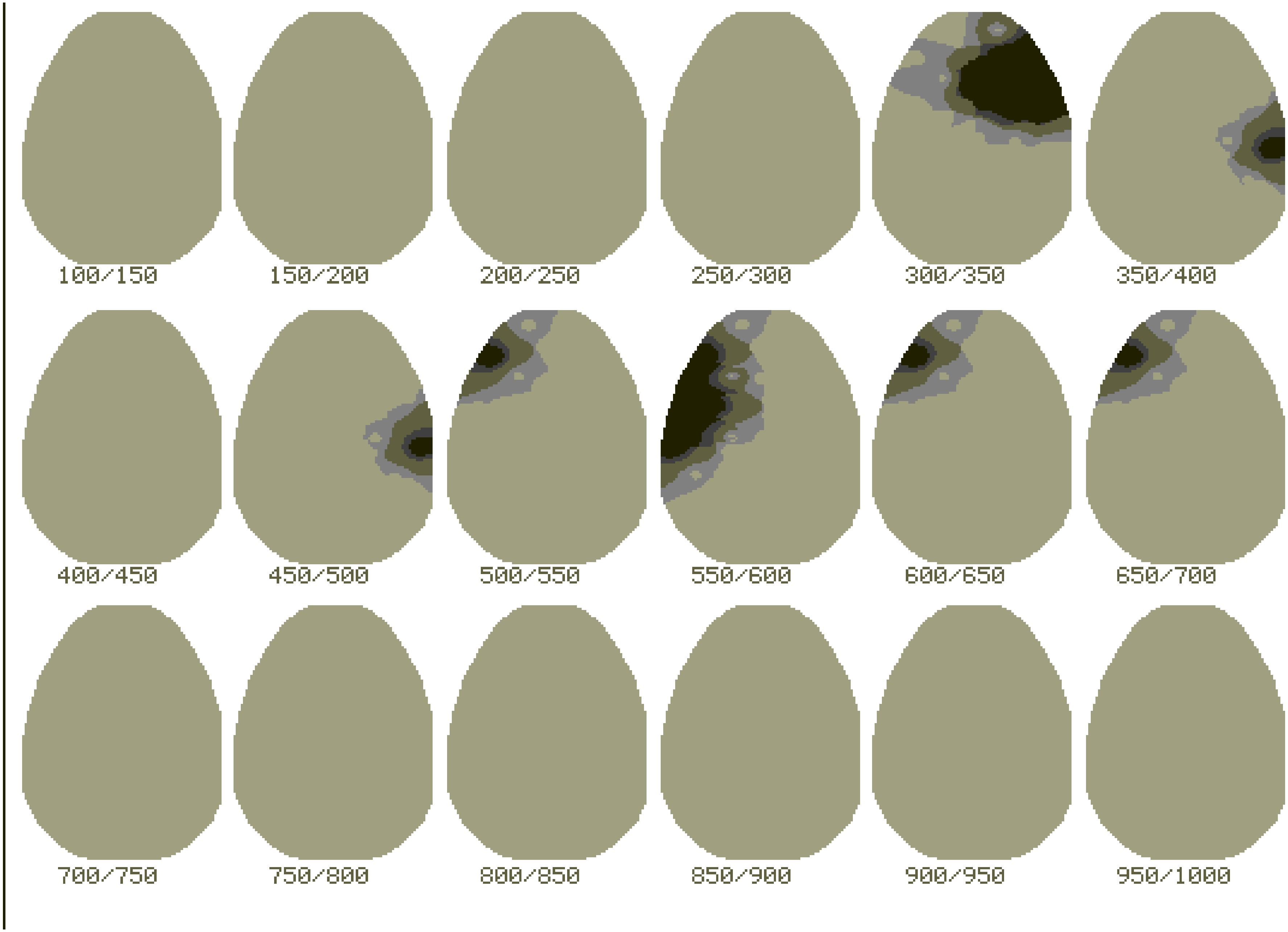
Repetition Priming

- Are there repetition effects that do not depend on the subjective awareness of the subject?
  - Can use Mask Priming to examine (Schnyer, Allen, Forster, 1997)

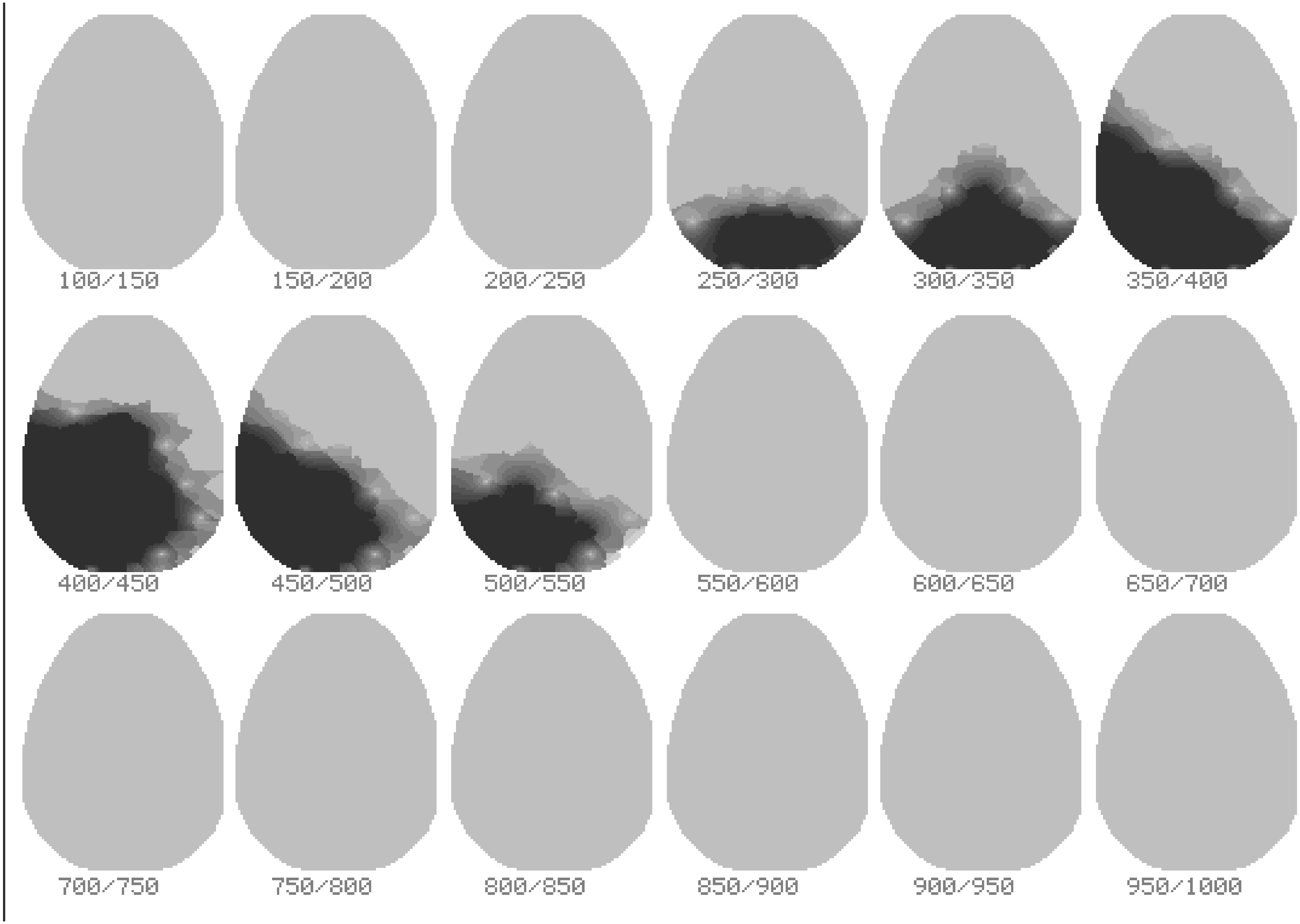

F3
Fz
F4
C3
Cz
C4
P3
Pz
P4
T5
T6
O1
O2
NEW
OLD
5μV
-100
100
300
500
700
900



Standard Repetition Effect for Words Seen Unmasked in Previous Blocks
Task is to make OLD-NEW decision



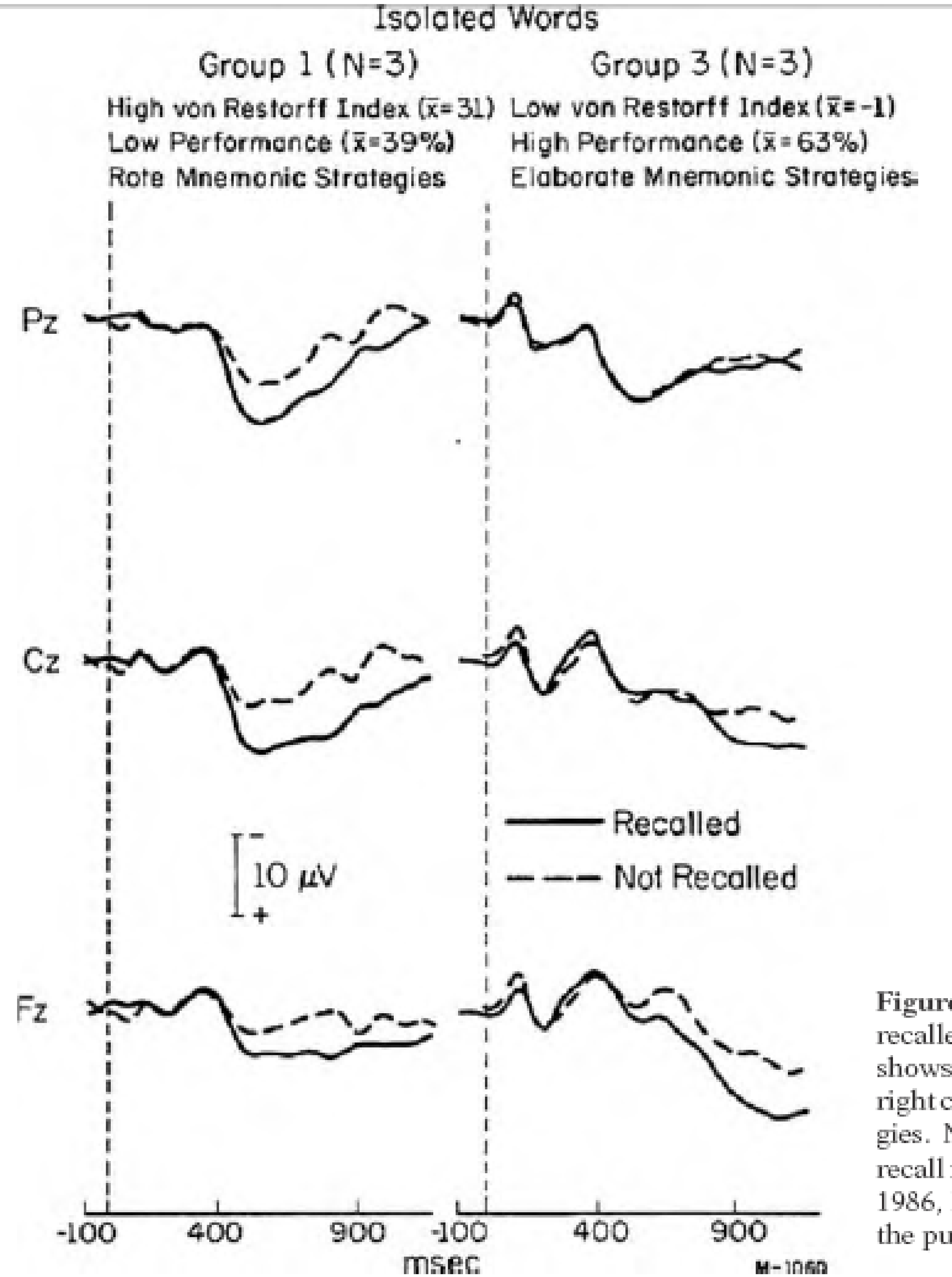
Standard Repetition Effect for Words Seen Unmasked in Previous Blocks
But Task is to make WORD-NONWORD decision



Masked Repetition Priming Effect for Words Presented only a Trial Previously

Memory Encoding

- Words subsequently remembered show enhanced positivity at encoding
- Strategy interacts, however



Note prototypic DM effect on left, but not on right for those that used elaborative strategies. Note enhancement over frontal lead for these latter subjects.

Figure 4.12. ERPs elicited by "isolated" words that were later recalled (solid line) or not-recalled (dashed line). The left column shows ERPs for subjects who used rote mnemonic strategies; the right column shows ERPs for subjects who used elaborative strategies. Note that the amplitude of P300 is related to subsequent recall for the rote memorizers, but not for elaborators. (Copyright 1986, Elsevier Science Publishers. Reprinted with permission of the publisher from Fabiani, Karis, & Donchin, 1986b.)

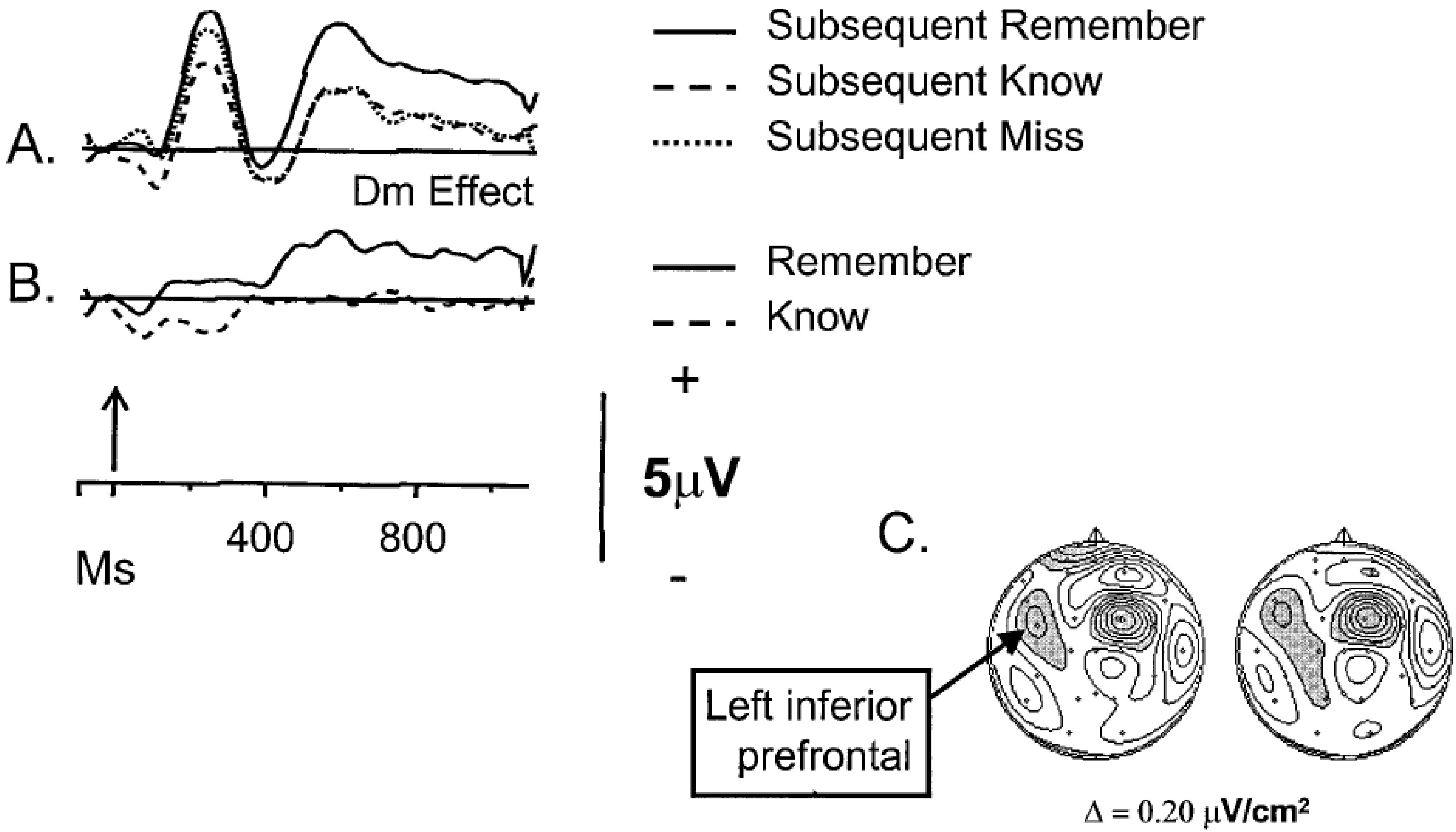


Fig. 3. **A:** Grand mean ERPs elicited by study items that were subsequently associated with remember or know judgments (hits) or were unrecognized (misses) during the subsequent recognition test. **B:** Grand mean difference waveforms computed by subtracting the ERPs to study items subsequently missed from those that were subsequently associated with either a remember or know judgment (Modified from Friedman and Trott, 2000). **C:** CSD maps for 2 intervals (500–800; 810–1,100 ms) measured in the Dm waveform associated with a subsequent Remember judgment. Data in A and B recorded at a left inferior prefrontal scalp site.

Indirect Assessments of Recognition

- Can the ERP detect recognition, independent of subjects' overt responses?
- Two applications
  - Clinical Malingering
  - Forensic Assessment

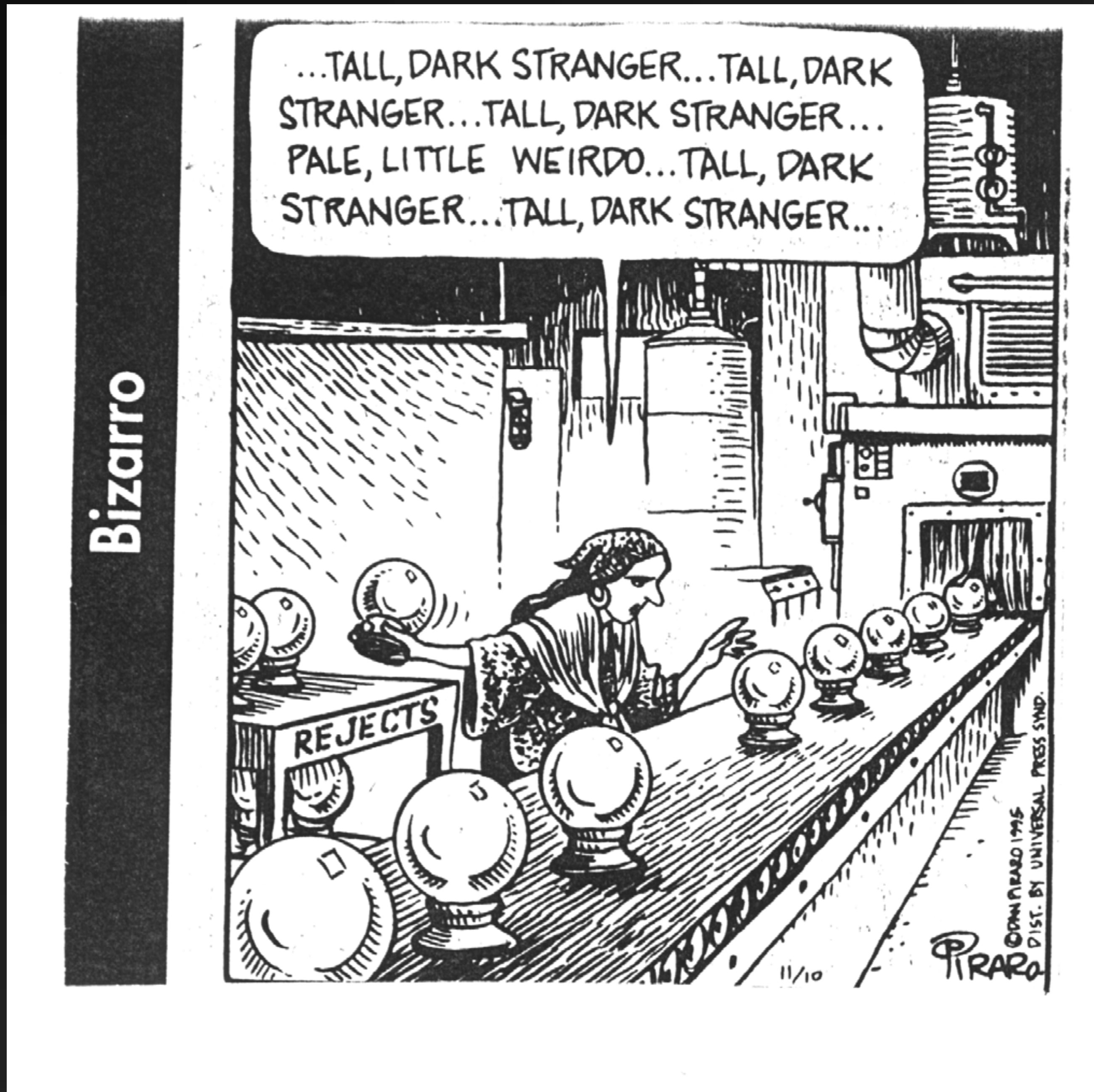
ERP Memory Assessment Procedures

- Learn a list of words
- Learn a second list of words
- Task: Concealed (1st list) and Nonconcealed (2nd list) words appear infrequently

Item Type	Probability	Response	P3 Amplitude
Nonconcealed	1/7	"Yes"	Large
Concealed	1/7	"No"	Large if Recognized Small if not Recognized
Unlearned	5/7	"No"	Small

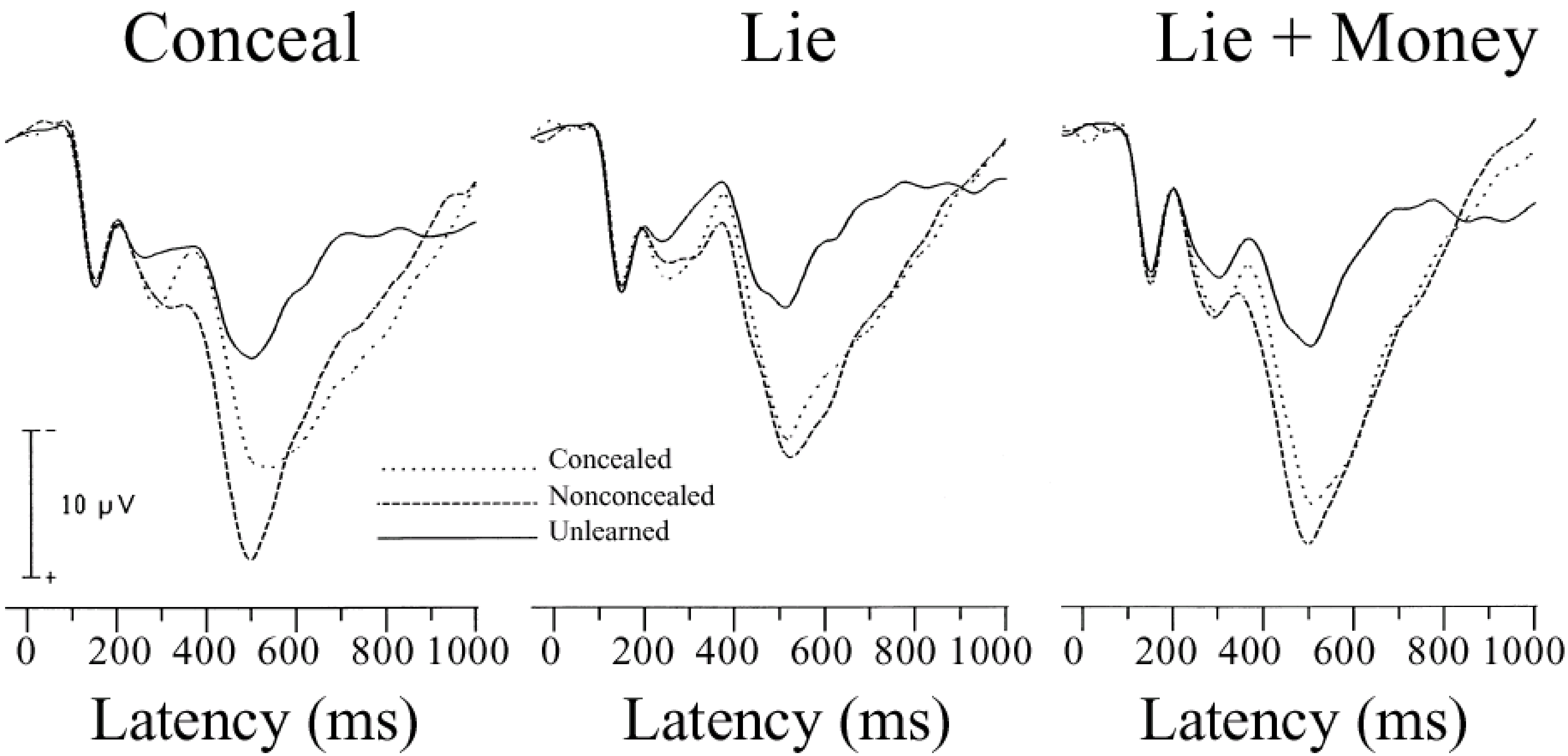
- Similar to procedures by Rosenfeld et al, Farwell & Donchin

The Classic Oddball Experiment



Motivational Variations

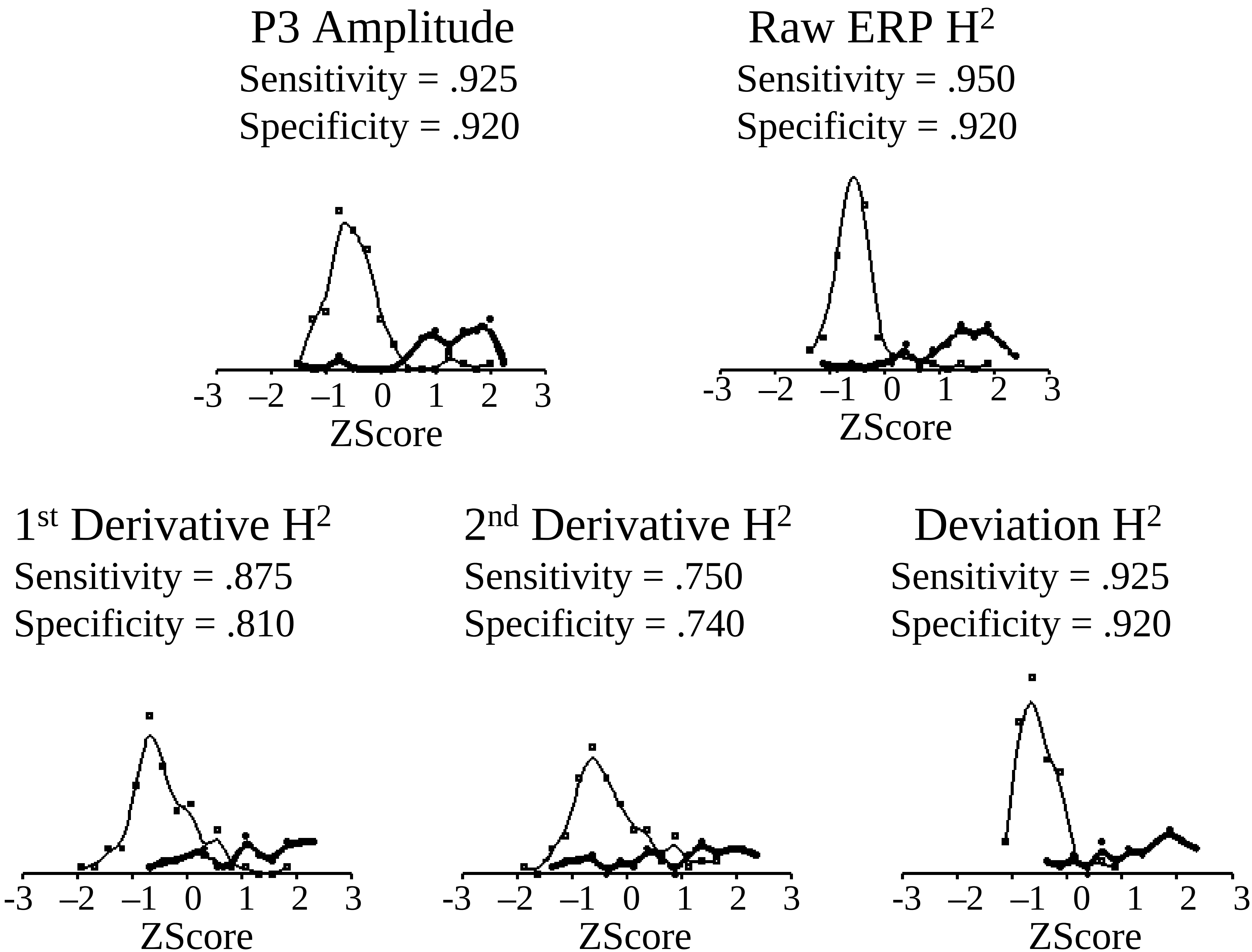
Conceal	Lie	Lie + $$
➢"YES" for words <u>*JUST*</u> learned, "NO" for all others	➢"YES" for words learned	➢"YES" for words learned
➢*Try to hide the fact that you learned the first list of words I taught you*	➢*Lie about words from the first list I taught you*	➢*Lie about words from the first list I taught you*
		➢*$5.00 incentive*



After Allen & Iacono, 1997

The Challenge

To provide statistically supported decisions for each and every subject, despite considerable individual variability in ERP morphology



P3 Amplitude
Sensitivity = .925
Specificity = .920
-3 –2 –1 0 1 2 3
ZScore
Raw ERP H2
Sensitivity = .950
Specificity = .920
-3 –2 –1 0 1 2 3
ZScore
1st Derivative H2
Sensitivity = .875
Specificity = .810
-3 –2 –1 0 1 2 3
ZScore
2nd Derivative H2
Sensitivity = .750
Specificity = .740
-3 –2 –1 0 1 2 3
ZScore
Deviation H2
Sensitivity = .925
Specificity = .920
-3 –2 –1 0 1 2 3
ZScore

Bayesian Combination of ERP Indicators: Probability that an ERP was elicited by Learned Items

	List						
	Learned		Unlearned				
Subject	NonConceal	Conceal	U1	U2	U3	U4	U5
#01	1.0	0.999	0.000	0.000	0.000	0.000	0.001
#02	1.0	1.0	0.000	0.000	0.000	0.000	0.000
#03	1.0	0.999	0.000	0.000	0.000	0.002	0.000
#04	1.0	1.0	0.000	0.001	0.002	0.000	0.000
#05	1.0	0.971	0.002	0.000	0.000	0.000	0.000
#06	1.0	0.999	0.000	0.000	0.000	0.000	0.000
#07	0.983	1.0	0.000	0.000	0.000	0.000	0.000
...							
#18	0.996	0.983	**0.874**	0.001	0.000	0.000	0.000
#19	**0.009**	**0.214**	**0.971**	0.000	0.002	0.189	**0.983**
#20	1.0	0.999	0.002	0.000	0.009	0.000	0.214

Note: Only trials in which subjects did not acknowledge concealed items included

Classification Accuracy based on ERPs

	Learned (true pos)	Unlearned (true neg)
Conceal	0.95	0.96
Lie	0.93	0.94
Lie + $$	0.95	0.98
Combined	0.94	0.96

Allen, Iacono, & Danielson, *Psychophysiology*, 1992

Brain Fingerprinting:
A New Paradigm in Criminal Investigations and Counterterrorism

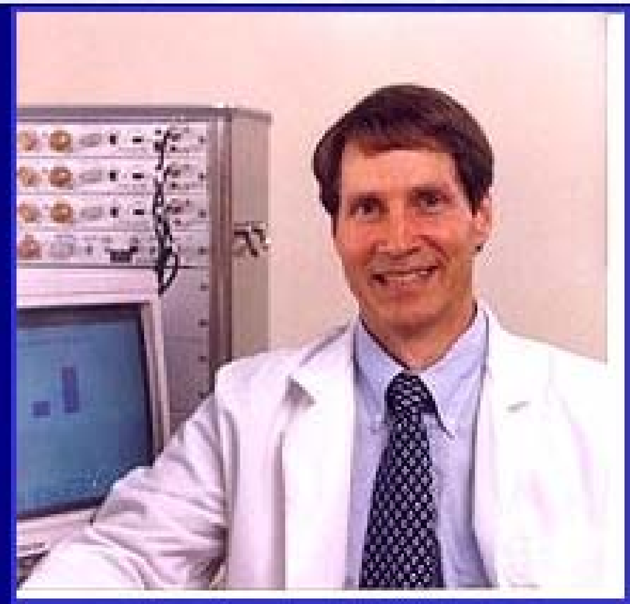
Executive Summary

Farwell Brain Fingerprinting is a revolutionary new technology for investigating crimes and exonerating innocent suspects, with a record of 100% accuracy in research on FBI agents, research with US government agencies, and field applications.

The technology is proprietary and patented. Brain Fingerprinting fulfills an urgent need for government, law enforcement agencies, corporations, and individuals. Over a trillion dollars are spent annually on crime fighting worldwide.

Brain Fingerprinting solves the central problem by determining scientifically whether a suspect has the details of a crime stored in his brain. It has received extensive media coverage around the world. The technology is fully developed and available for application.

Brain Fingerprinting is a powerful tool for the investigation of suspected terrorists. Measuring the brain wave activity while suspects are shown words or pictures related to specifics of the September 11, 2001 attacks can help determine if they are members of terrorist cells. Brain Fingerprinting can identify trained terrorists before they strike



Larry Farwell, PhD

Chairman & Chief Scientist
Brain Wave Science
Human Brain Research Laboratory, Inc.

www.brainwavescience.com

The Claim

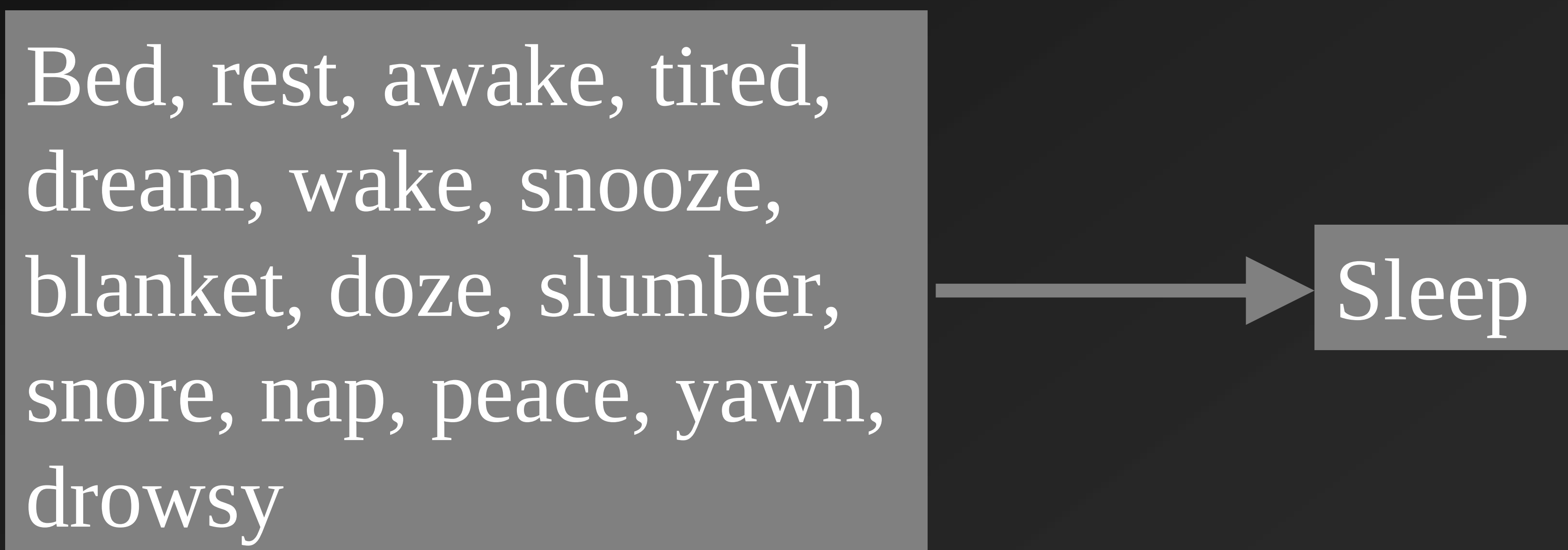
- Brain Fingerprinting can determine "scientifically whether a suspect has details of a crime stored in his brain"

- Thus these ERP-procedures should be able to identify memories in laboratory studies

- Two tests of the robustness of this procedure:
  - False recollections
  - Virtual Reality Mock Crime

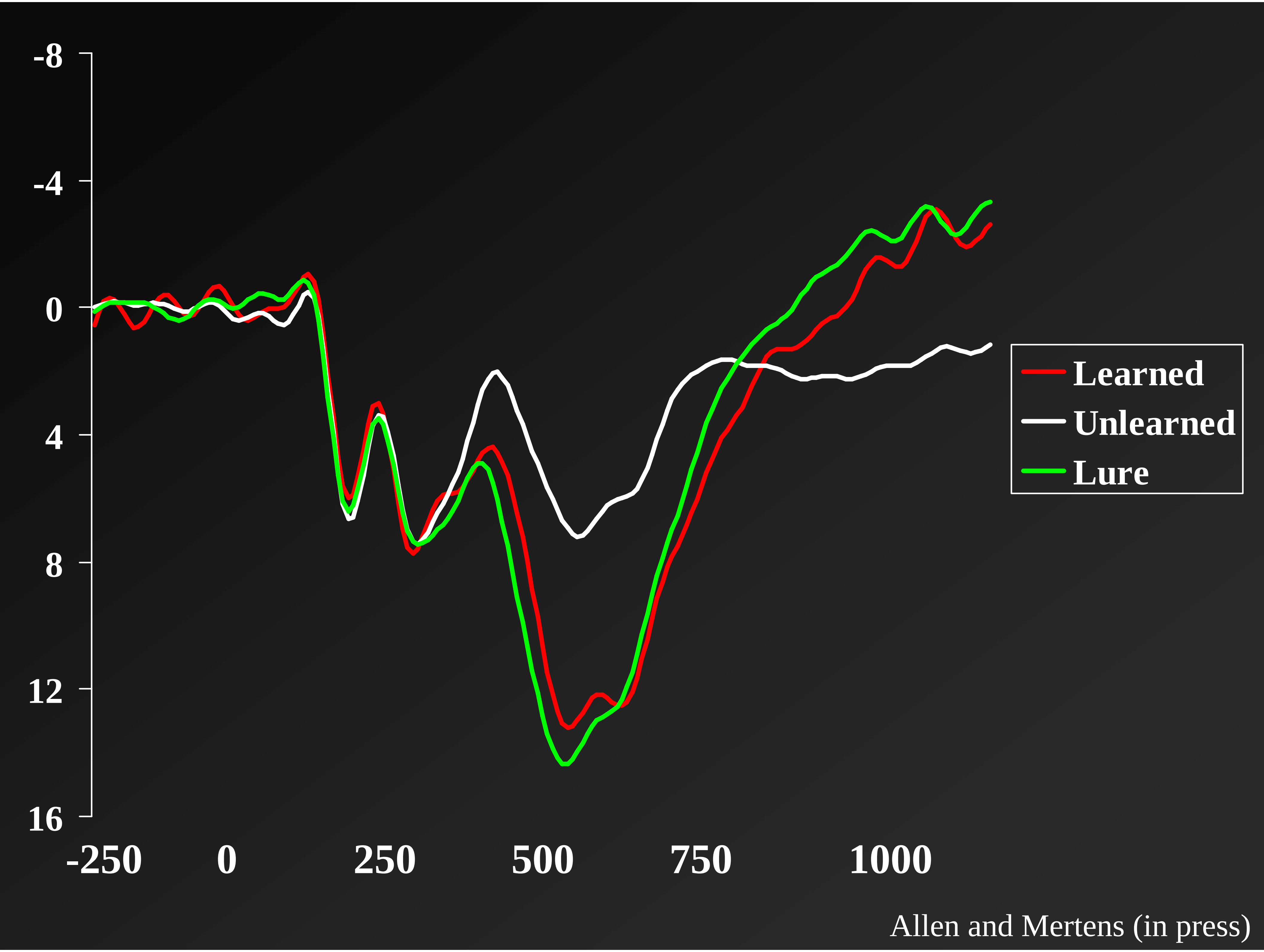
A Laboratory Paradigm for False Recollections: DRM

- Subjects presented with 15 words highly associated with an omitted critical item



Reported Rates of Recogntion

Allen and Mertens (in press)



-8
-4
0
4
8
12
16
-250
0
250
500
750
1000
Learned
Unlearned
Lure
Allen and Mertens (in press)

The Box Score Blues

	Test Verdict
Ground Truth	Recognized
Actually Learned	56%
Critical Lure	72%
Unlearned	4%

- ❑ Highlights the need to have memorable items in the test
- ❑ Suggests limited utility in substantiating disputed memories; e.g., claims regarding recovered memories
- ❑ Still has low false positive rate when person denies knowledge

Current and Future Directions

- Develop realistic laboratory models for mock crime investigations

Virtual Reality Mock Crime

- Subjects received email detailing their “Mission”
- Sneak into graduate student office to break in to virtual apartment
- Apprehended and interrogated using ERP-based procedure
- Some subjects given details about utilizing countermeasures
- Innocent subjects tour the same virtual apartment, but with different objects and details.

SCALED ENVIRONMENTS

ARIZONA DAILY WILDCAT online

Friday December 6, 2002 | wildcat.arizona.edu | online since 1994

POLICE BEAT

Police Beat

By David Halperin
Arizona Daily Wildcat
Friday December 6, 2002

Suspicious e-mail sent

An employee reported that he received an e-mail Wednesday stating he is supposed to commit a crime today, reports stated.

At about 11:35 a.m., the employee told police he had received the suspicious e-mail while in his office at the Arizona Health Sciences Center, 1501 N. Campbell Ave.

The employee told police he did not know the sender of the message or why he received it. He decided to report the incident after his supervisor advised him to do so.

The message read: "This message is simply a reminder of the crime you are to commit on December 6th at 9:00a.m. You should have carefully read over your mission plan and memorized all relevant information in order to carry out your mission. Remember, do not bring materials with you related to the crime and maintain your innocence at all times. Good luck. Dispose of this message once understood," reports stated.

Results of Mock Crime Brainwave Procedure

Group	N	Verdict: Guilty	Verdict: Innocent
Guilty	15	47%	53%
Guilty (countermeasure)	45	17%	83%
Innocent	15	6%	94%

Note: Using Bootstrapping approach, Guilty detection drops to 27%, but innocent subjects classified correctly in 100% of cases. Allows indeterminate outcomes

New Handout

Sources of P3

- Likely distributed
- Candidates found in (nonexhaustive list):
  - bilaterally in the anterior superior temporal gyrus
  - inferior and middle frontal gyrus
  - inferior and superior parietal lobules
  - anterior and posterior cingulate
  - thalamus
  - Caudate
  - Amygdala/hippocampal complex
  - Insula
  - Among others!

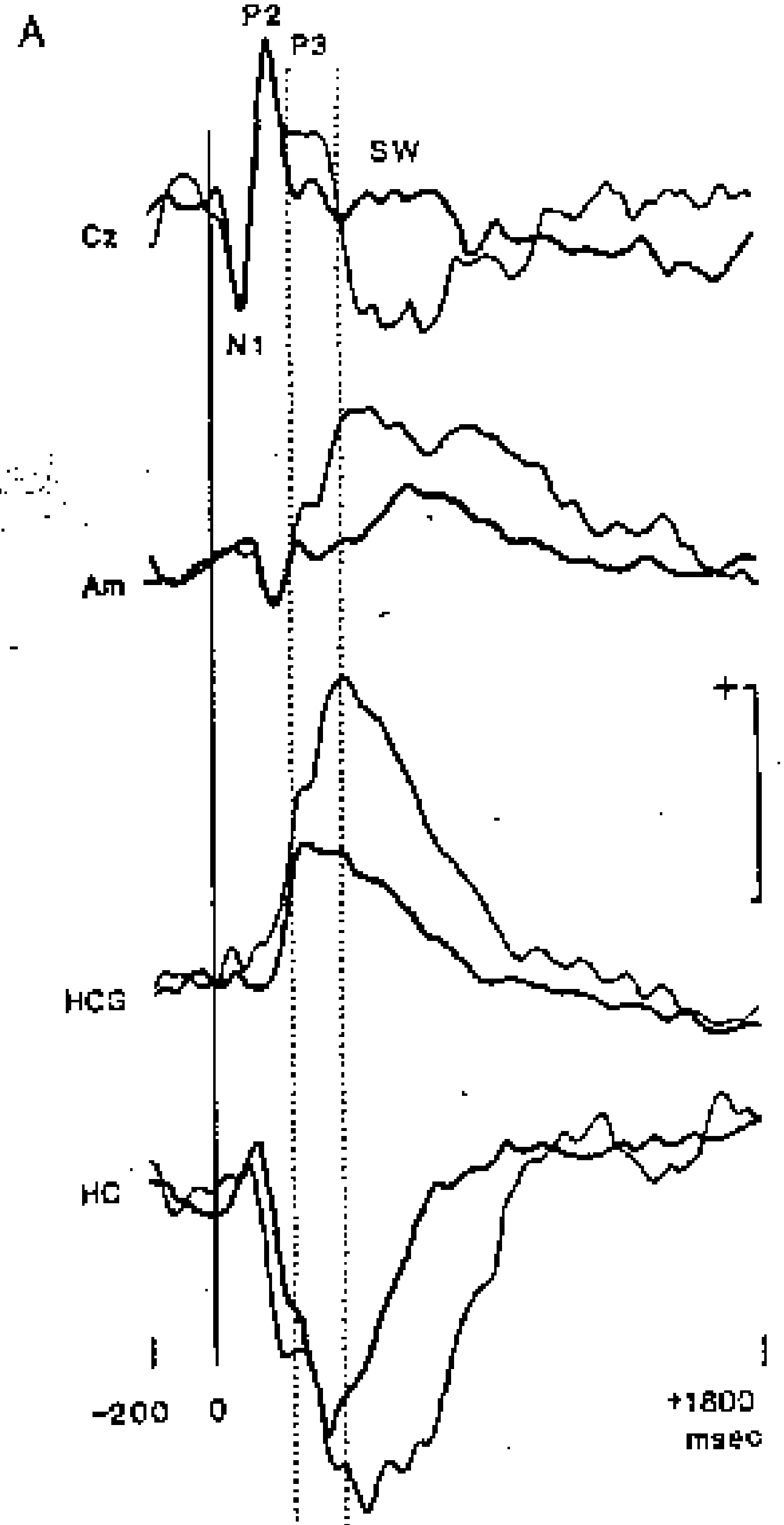
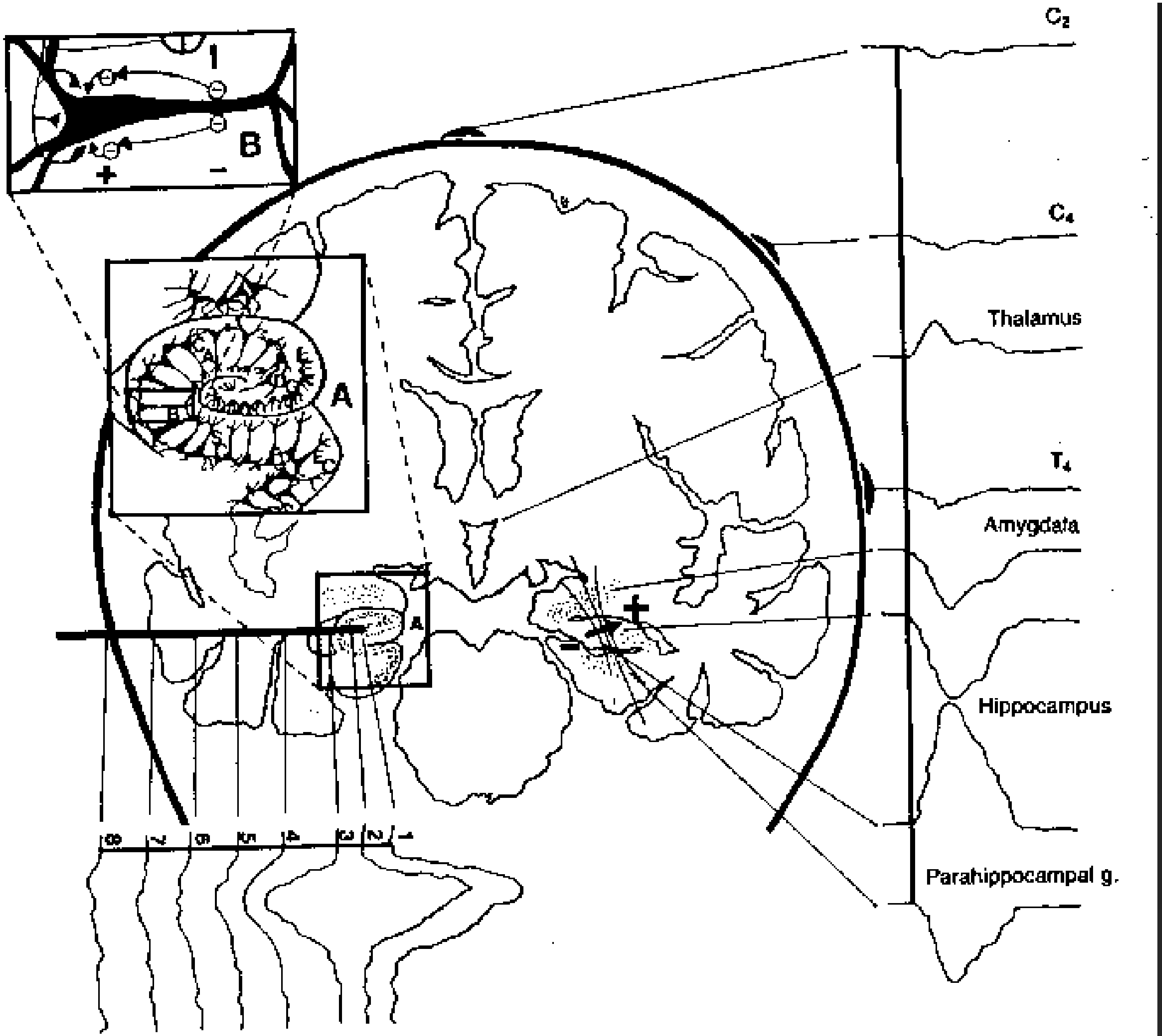


Fig. 1 (left). (A) Characteristic potentials evoked in limbic sites during an auditory paradigm (*3*). The largest negative potential was recorded in the hippocampus (*HC*) after rare tone bursts. Phase reversal occurred 9 mm posteromedial in the hippocampal gyrus (*HCG*) and 26 mm anterior in the amygdala (*Am*). The vertical dotted lines, 265 and 430 msec after stimulus onset, indicate the approximate onsets of the P3 and slow wave (*SW*) at the vertex (*Cz*). In all graphs, the thin lines represent the average of 35 to 45 responses evoked by rare stimuli, and the thick lines the averages to 155 to 165 frequent stimuli (*15*). Scale: 100 μV depth; 25 μV scalp.

Halgren, *Science*, 1980



Note polarity reversal as enter and exit the hippocampus

Yet hippocampus not likely to be a major contributor to surface-recorded P3

Polich and Squires (1993) find P3 in patients with bilateral hippocampal lesions!

Distributed sources likely

Menon, Ford et al, Neuroreport, 1997

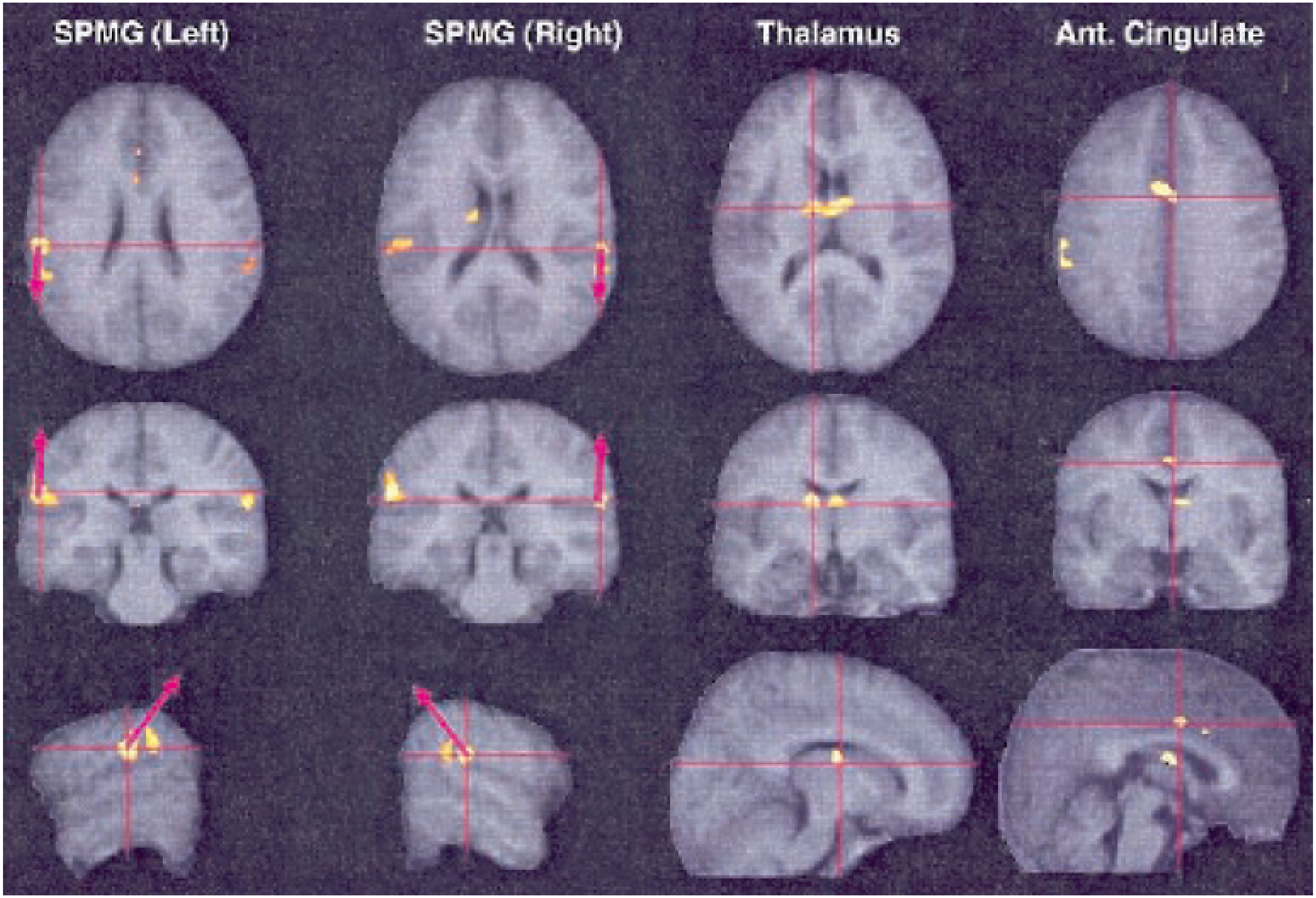
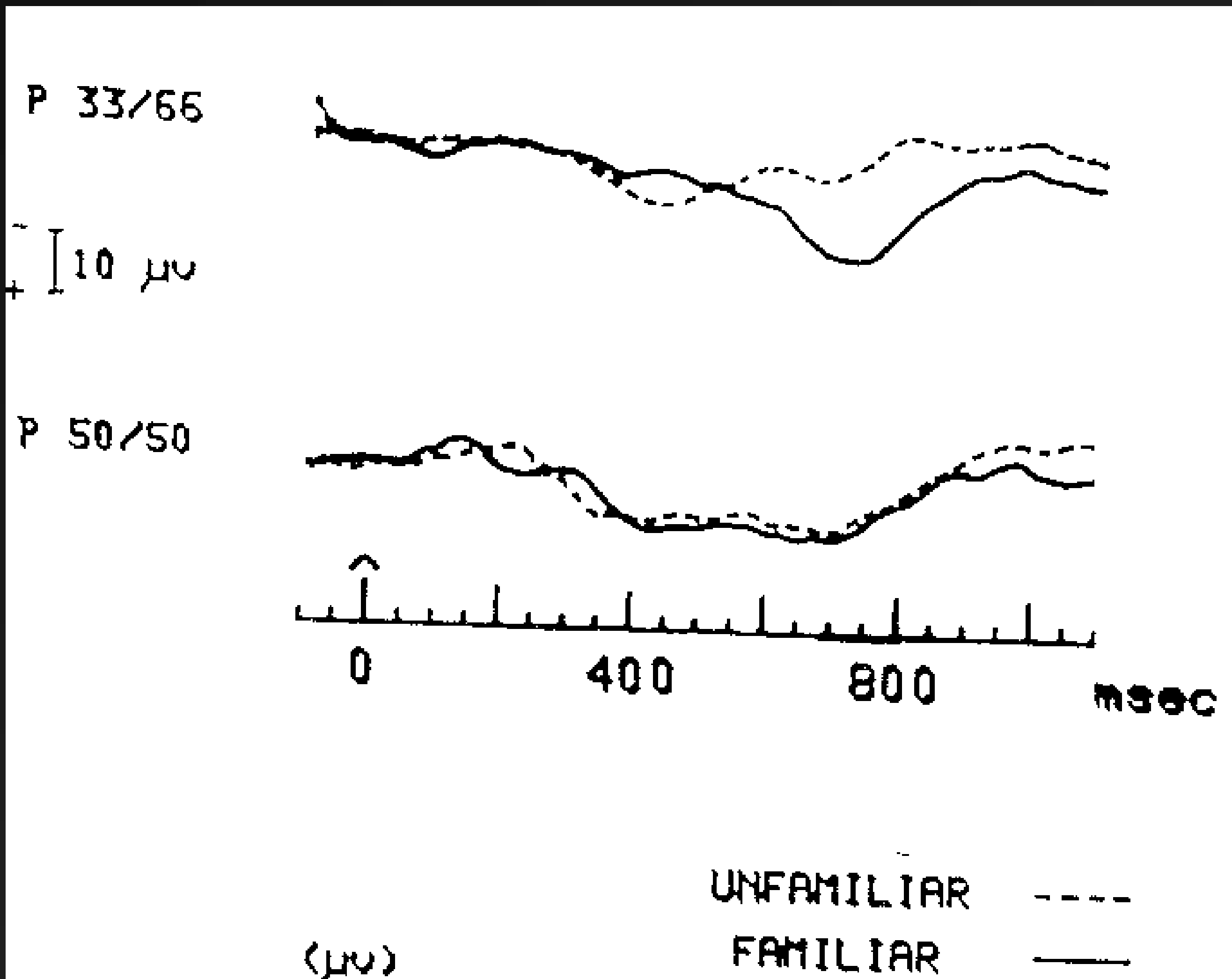


FIG. 1. Brain areas that showed significant fMRI activation to target stimuli are shown superposed on average MRI in Talairach space: left and right supramarginal gyri (SPMG), thalamus and anterior cingulate. Cross hairs mark locations of peak activation. Bilateral symmetric dipole sources (indicated by arrows) in the left and right supramarginal gyri are the main generators of the P3b component of ERP to infrequent target stimuli. Note that the dipole orientations are approximately perpendicular to the cortical gray matter. The dipole sources are active 285–610 ms following target stimulus onset. The length of the arrows indicate the relative strengths of the dipoles in the three orthogonal planes.

P3 without awareness? Assessing Recognition in Prosopagnosia



Renault et al.

How Many P3s?

- The Classic P3/P300
  - Parietal Central Maximum
  - Largest when stimuli rare and task-relevant
- The P3a (Squires et al., 1975) or Novelty P3 (Courchesne et al., 1975)
  - More anterior scalp distribution
  - Slightly earlier latency
  - Responsive to rare, unexpected, unattended stimuli

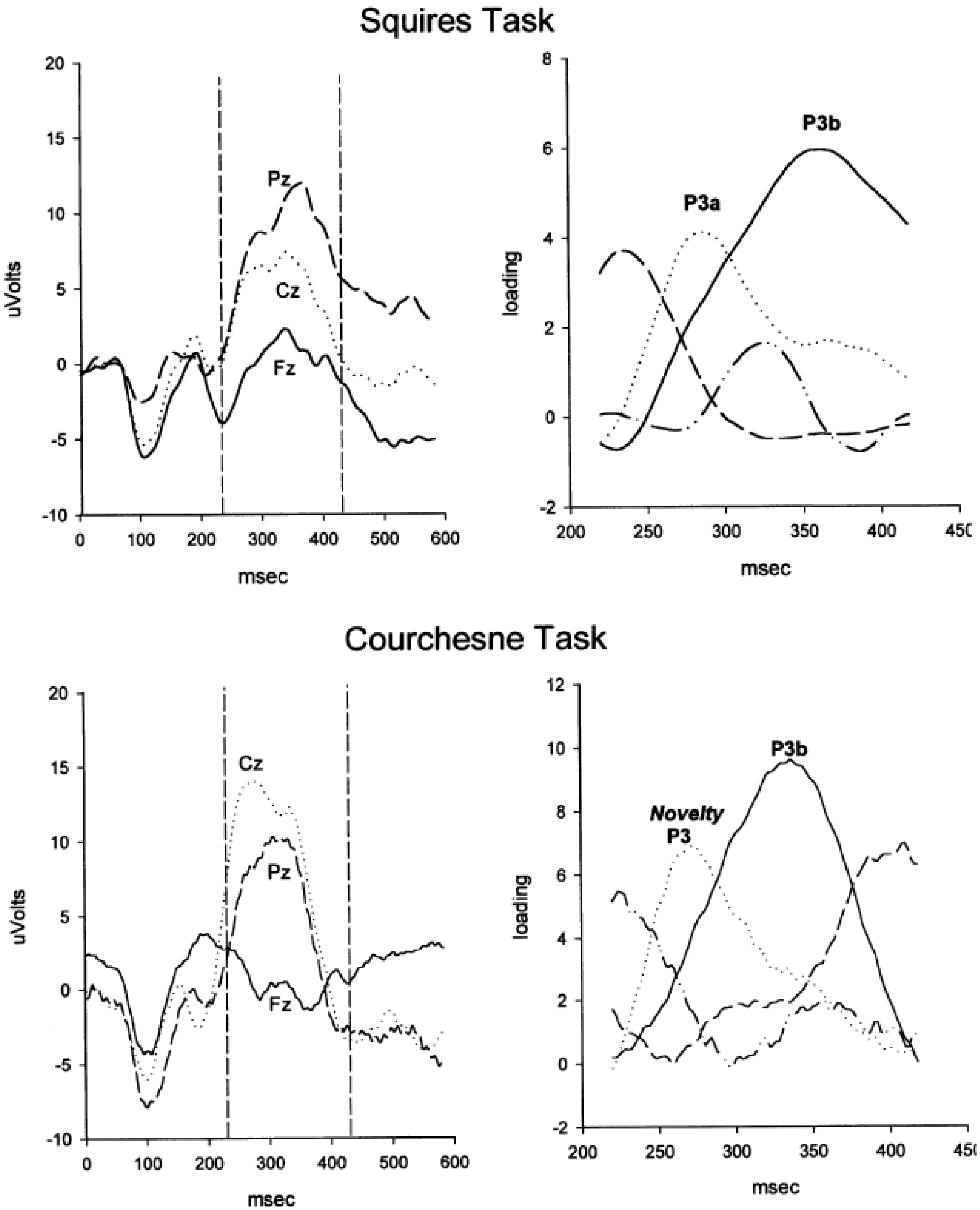


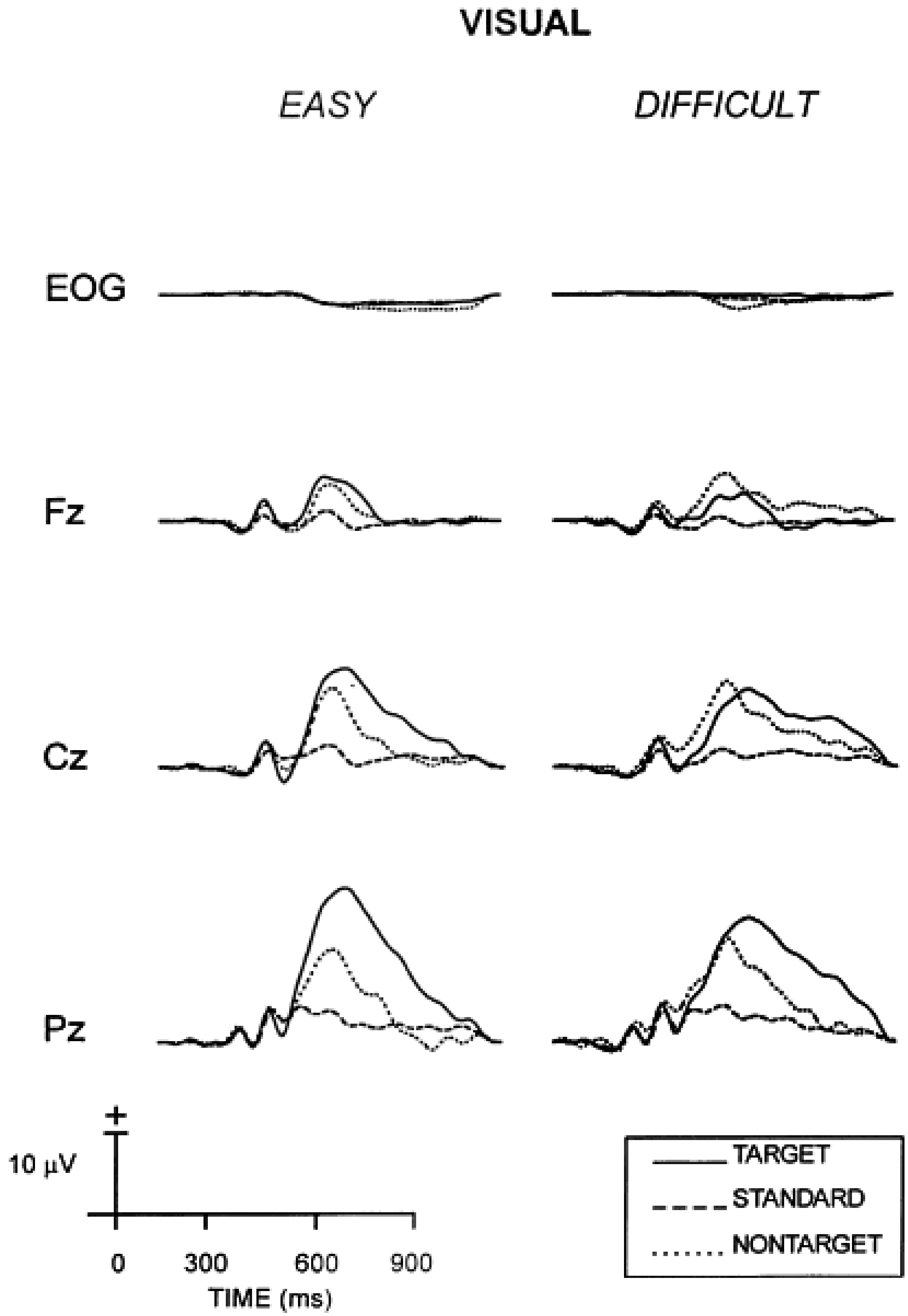
Fig. 1. ERP waveforms (left) and PCA basis waves (right) obtained from infrequent targets during the Squires (top) task and infrequent nontargets/novels during the Courchesne (bottom) task. PCA was conducted during the 220–420 ms epoch following stimulus onset and four factors were extracted from each data set.

Simons et. al, 2001

- Squires Task was tones (two tones)
- Courchesne task was digitized speech (“me” “you” and collection of naturally occurring sounds
- In all cases subjects merely counted Tones

P3a – Can you see it?

- Some inconsistencies in finding P3a following the initial Squires, Squires and Hilyard 1975 report
- Comerchero & Polich (1998) may have resolved the enigma
  - P3a highly dependent on foreground discrimination



Note: Nontarget peak amplitude was earlier and larger at the frontal electrodes than those from the target stimuli, but especially when foreground discrimination is difficult

Comerchero & Polich (1998), *Clinical Neurophysiology*

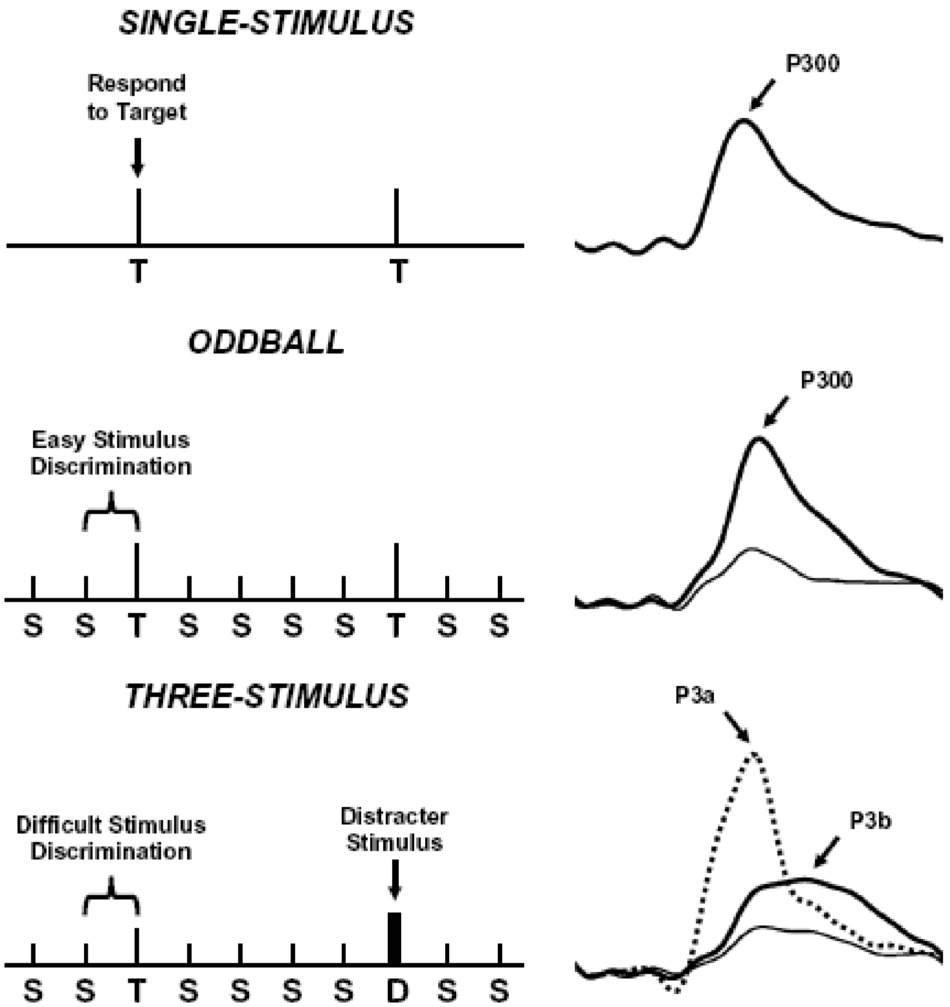


Fig. 1. Schematic illustration of the single-stimulus (top), oddball (middle), and three-stimulus (bottom) paradigms, with the elicited ERPs from the stimuli of each task at the right (Polich and Criado, 2006). The single-stimulus task presents an infrequent target (T) in the absence of any other stimuli. The oddball task presents two different stimuli in a random sequence, with one occurring less frequently than the other (target = T, standard = S). The three-stimulus task is similar to the oddball with a compelling distracter (D) stimulus that occurs infrequently. In each task, the subject is instructed to respond only to the target and otherwise to refrain from responding. The distracter elicits a P3a, and target elicits a P3b (P300). Reprinted with permission of the authors and from Elsevier (Copyright 2006).

Polich, *Clin Neurophys*, 2007

Synopsis

"…the manipulation of target-standard stimulus discriminability produced a stimulus environment in which the infrequently occurring nontarget engaged focal attention in a manner similar to that observed previously for 'novel' stimuli.

"If stimulus context is defined primarily by a difficult target-standard discrimination, attentional redirection to the nontarget would occur because of the frontal lobe activation that generates P3a."

Comerchero & Polich 1998, p. 47

Polich V. Verlager

Clinical Neurophysiology 118 (2007) 2128–2148

Invited review

Updating P300: An integrative theory of P3a and P3b

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Abstract

The empirical and theoretical development of the P300 event-related brain potential (ERP) is reviewed by considering factors that contribute to its amplitude, latency, and general characteristics. The neuropsychological origins of the P3a and P3b subcomponents are detailed, and how target/standard discrimination difficulty modulates scalp topography is discussed. The neural loci of P3a and P3b generation are outlined, and a cognitive model is proffered: P3a originates from stimulus-driven frontal attention mechanisms during task processing, whereas P3b originates from temporal–parietal activity associated with attention and appears related to subsequent memory processing. Neurotransmitter actions associating P3a to frontal/dopaminergic and P3b to parietal/norepinephrine pathways are highlighted. Neuroinhibition is suggested as an overarching theoretical mechanism for P300, which is elicited when stimulus detection engages memory operations.

Polich V. Verlager

Verlager Clinical Neurophysiology 119 (2007) 968–970

(1) There is a double dissociation between brain areas related to memory and brain areas related to generation of P3b.
(2) Items later remembered do not reliably differ in P3b from items not remembered.
(3) If there is a link between memory-related areas of the brain and the P300 complex then this link is to P3a.
(4) Obvious candidates for what P3b reflects become apparent by P3b's relation to the decision about what to do with the stimulus, one possible candidate being the monitoring whether the decision to classify some stimulus is appropriately transformed into external or internal action (Verleger et al., 2005).

ERPS and Affective Processing

- IAPS = International Affective Picture System
  - Pleasant, Neutral, Unpleasant
  - Vary in Arousal: Pleasant and Unpleasant tend to be more arousing
- Predict more significant stimuli produce larger P3

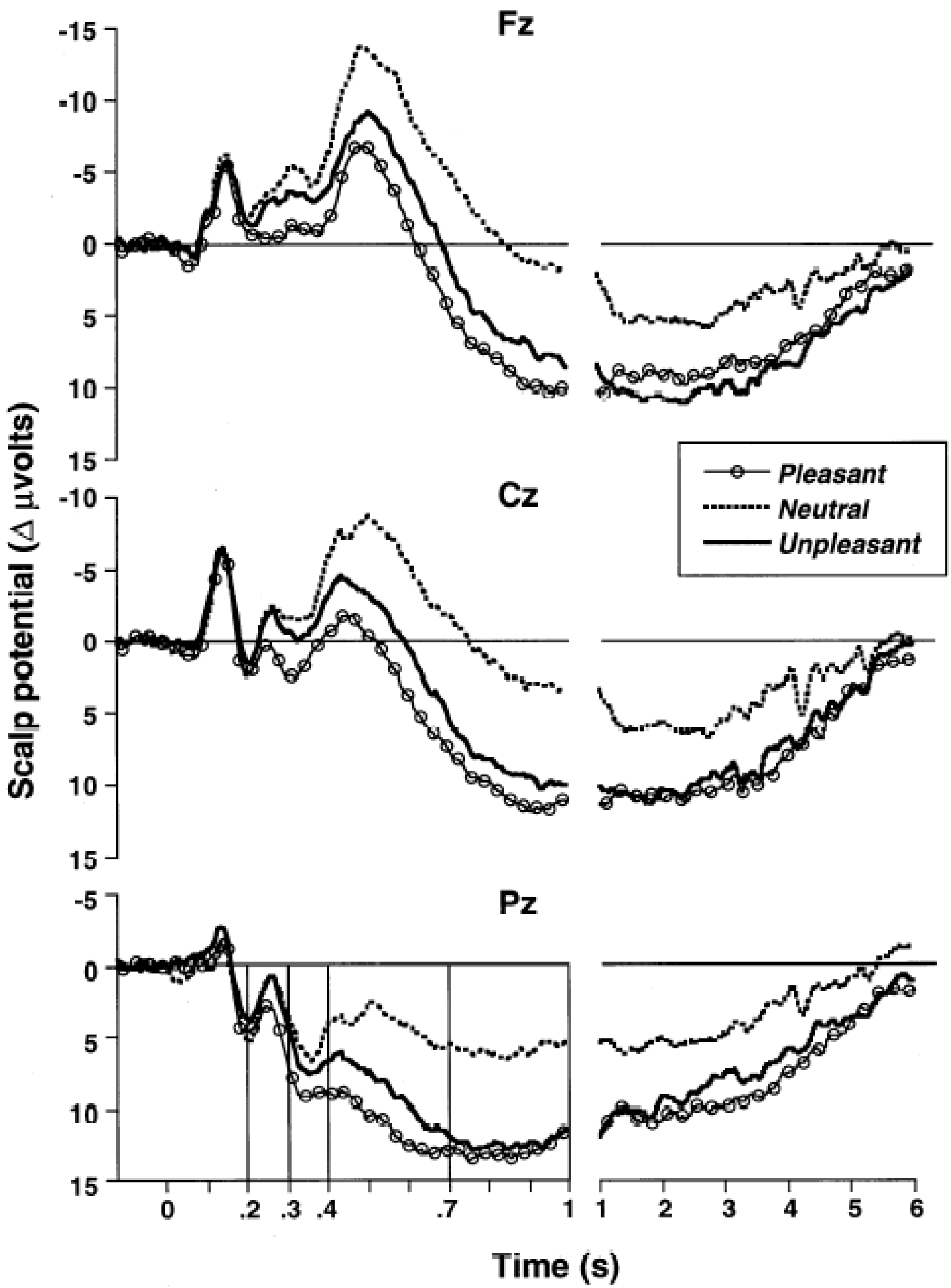


Fig. 1. Stimulus synchronized grand average ERP waveforms for Fz, Cz, and Pz electrodes during viewing of affective pictures, separately for each valence category (pleasant, neutral and unpleasant). The left panel illustrates the picture onset potentials on a finer time scale, and the vertical lines at Pz illustrate the time areas subjected to statistical analysis (i.e. 200–300, 300–400, 400–700, 700–1000 ms). The right panel shows the subsequent 5 s of slow potential change.

Long (6 sec)
Presentation Duration

Schupp et al (2000),
Psycholophysiology

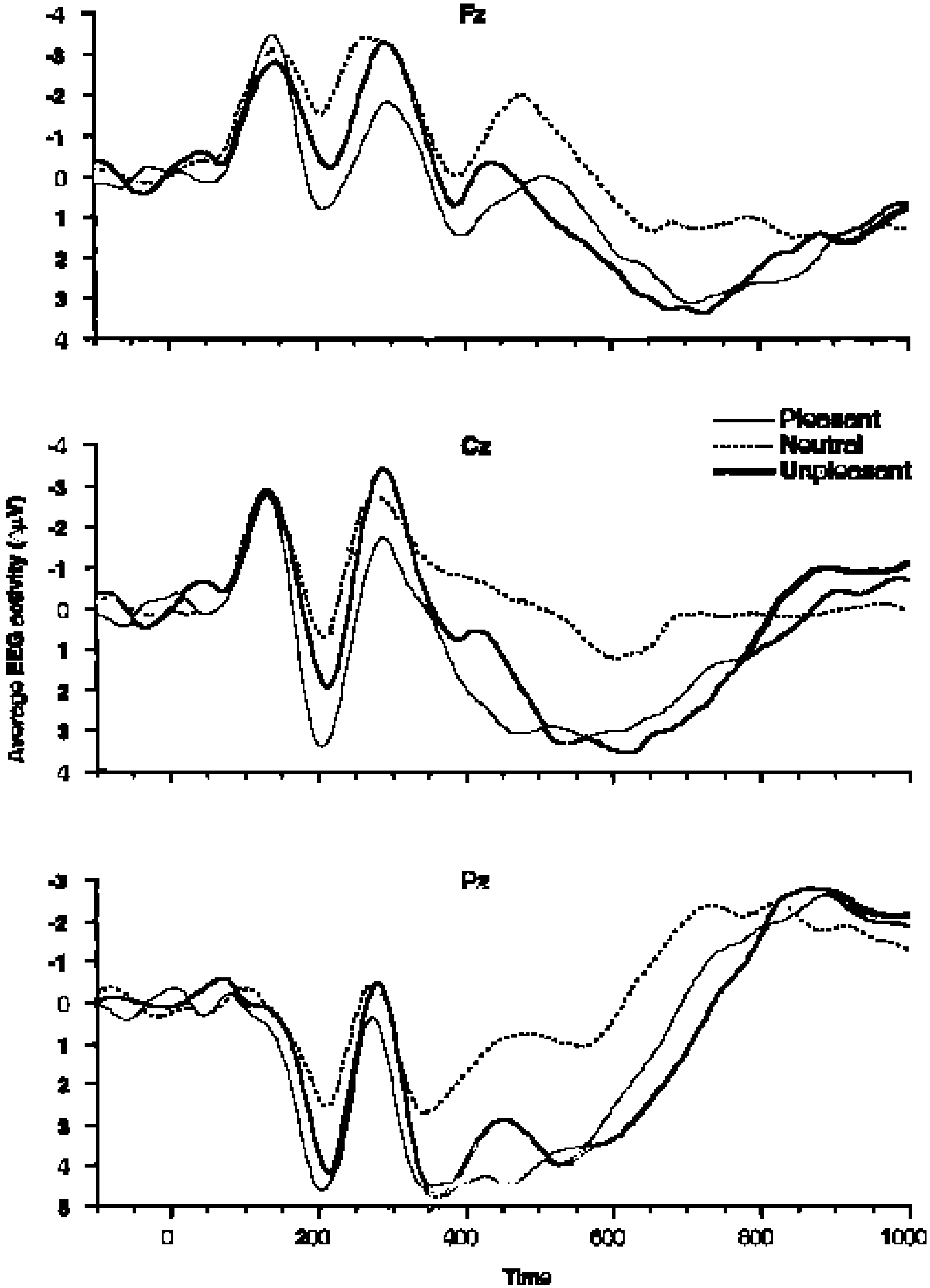
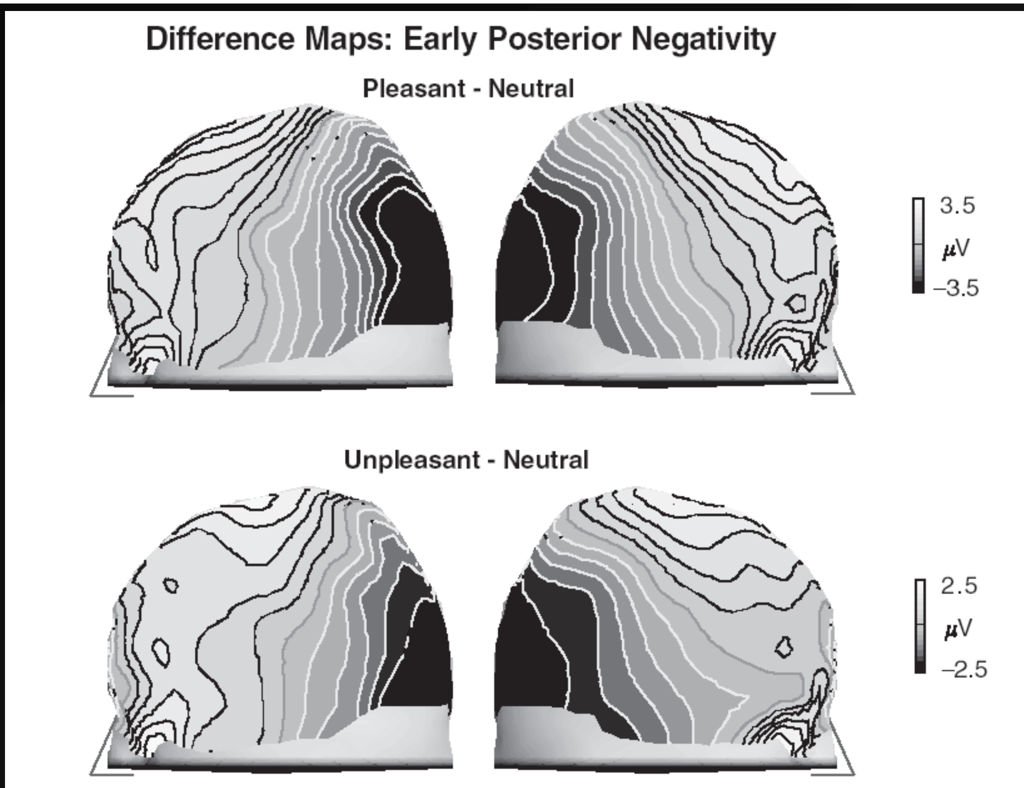


Figure 1. Picture onset synchronized grand-average event-related potential (ERP) waveforms for each valence category (pleasant, neutral, and unpleasant) from midline electrodes Fz, Cz, and Pz.

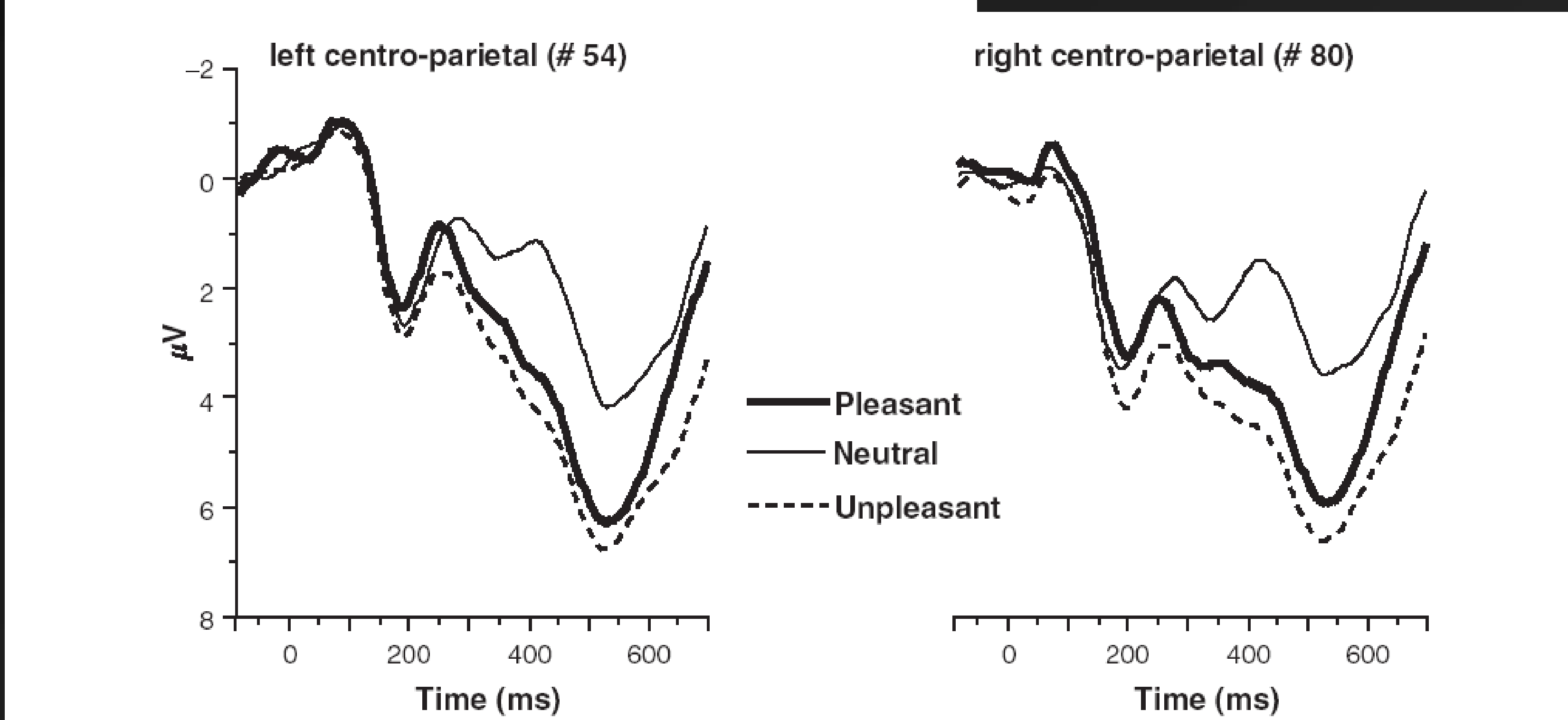
1.5 sec Presentation Duration

Cuthbert et al (2000), *Biological Psychology*



120 msec Presentation Duration

Schupp et al
Psycholophysiology



ERPS and Implicit Affective Processing

- Ito & Cacioppo (2000) *JESP*
  - Evaluative Processing (positive vs negative)
  - Nonevaluative (people vs no-people)

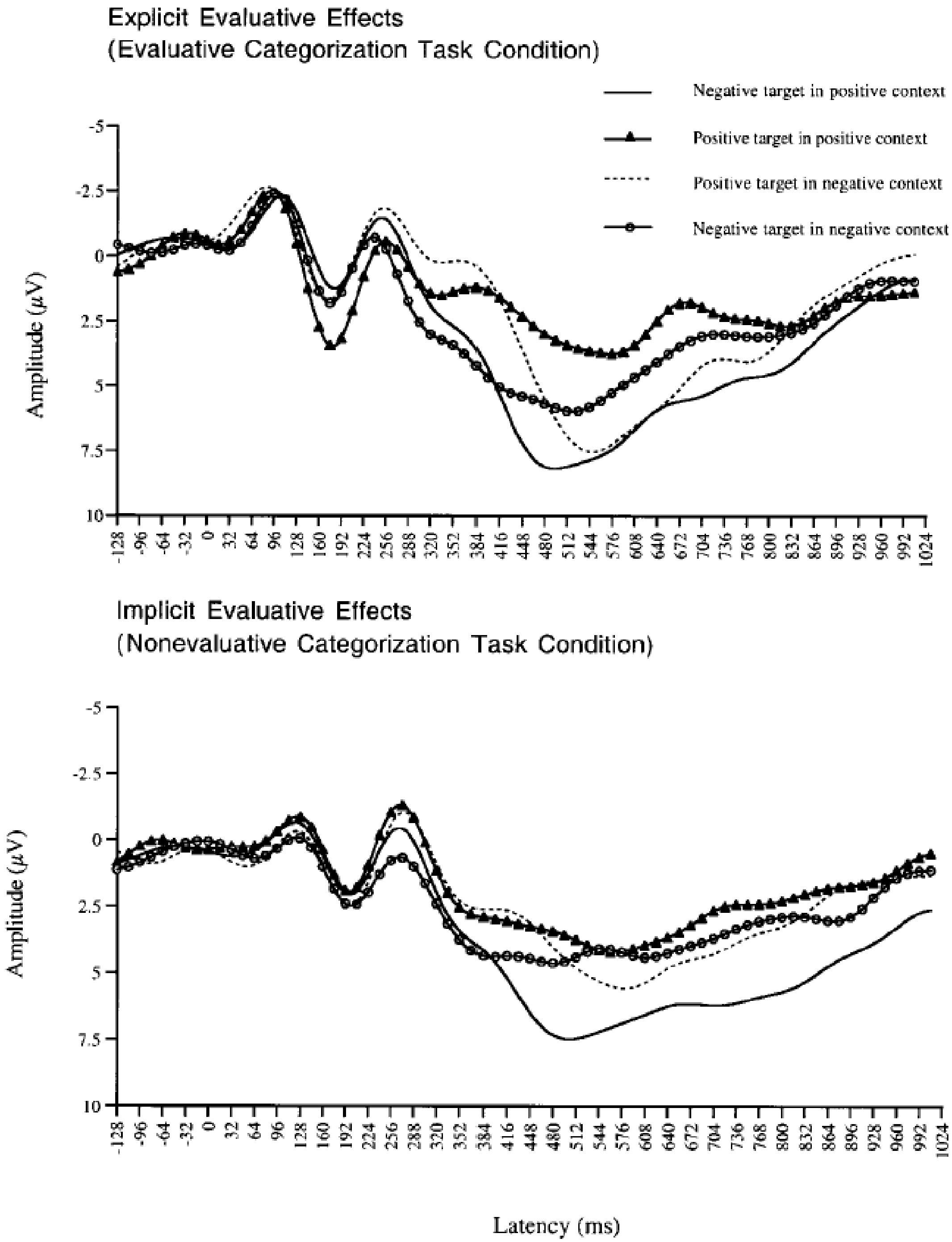


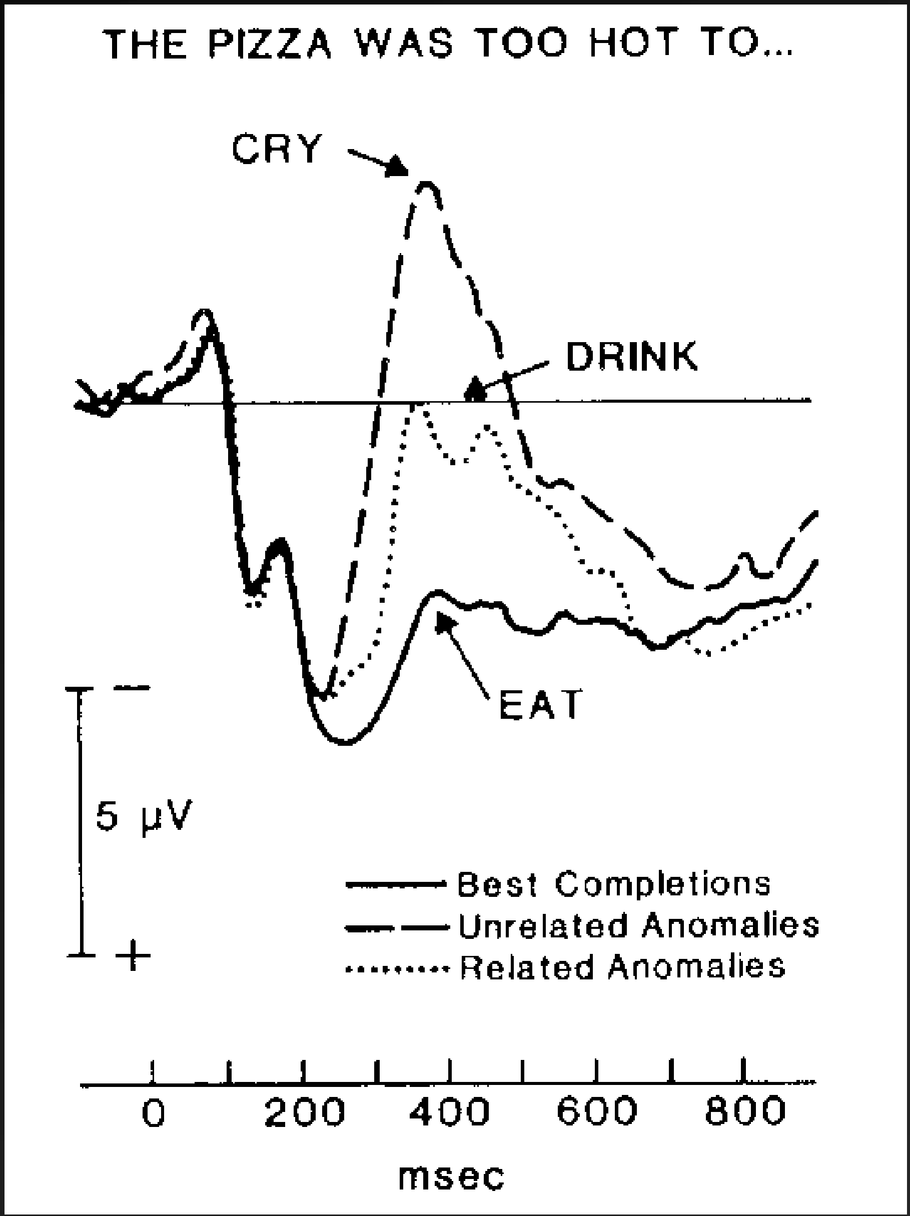
FIG. 2. Averaged event-related potential waveforms at electrode Pz as a function of target and context valence. The top panel depicts explicit evaluative categorization effects (data from participants in the evaluative task condition). The bottom panel depicts implicit evaluative categorization effects (data from participants in the nonevaluative task condition). The late-positive potential is the positive (downward) deflection peaking at approximately 450–550 ms.

Explicit – categorize as positive or negative

Implicit – categorize as with or without people

Ito & Cacioppo (2000) *JESP*

N400 and Language



- Originally reported by Kutas & Hillyard, 1980.
- Semantic Incongruity is separable from other forms of deviations (e.g. large font)
  - N400 Semantic Deviation
  - P300 Physical Deviation
- Also seen in semantic differentiation tasks (Polich, 1985); APPLE, BANANA, ORANGE, MANGO, *TRUCK*
- Subject-Object mismatch (the Florida group)
- NOTE: N400 will appear before P3 (which will be ~P550 in word tasks)

Political Evaluations!

- Morris Squires et al. *Political Psychology* 2003

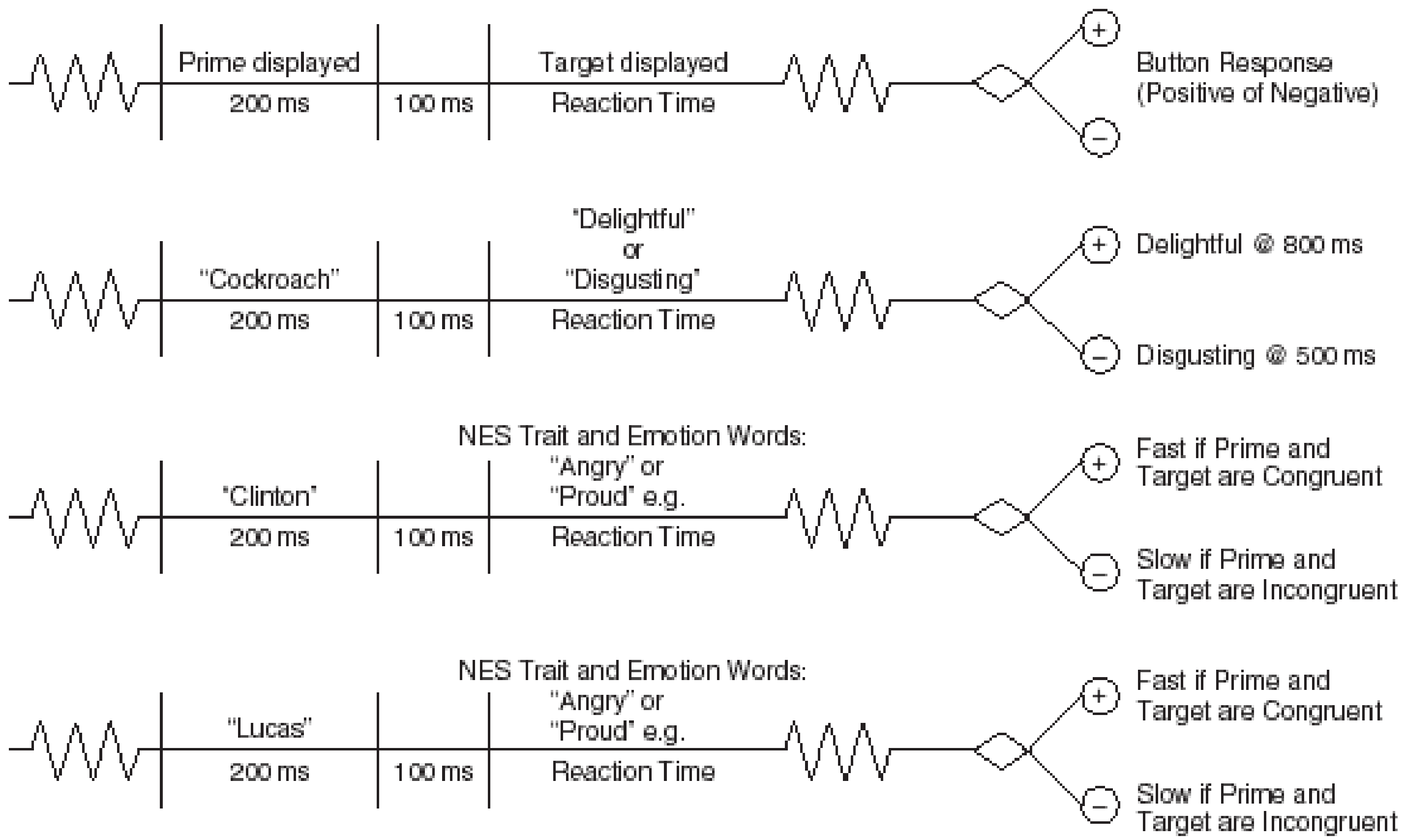


Figure 2. Attitude-priming paradigm and examples of its use.

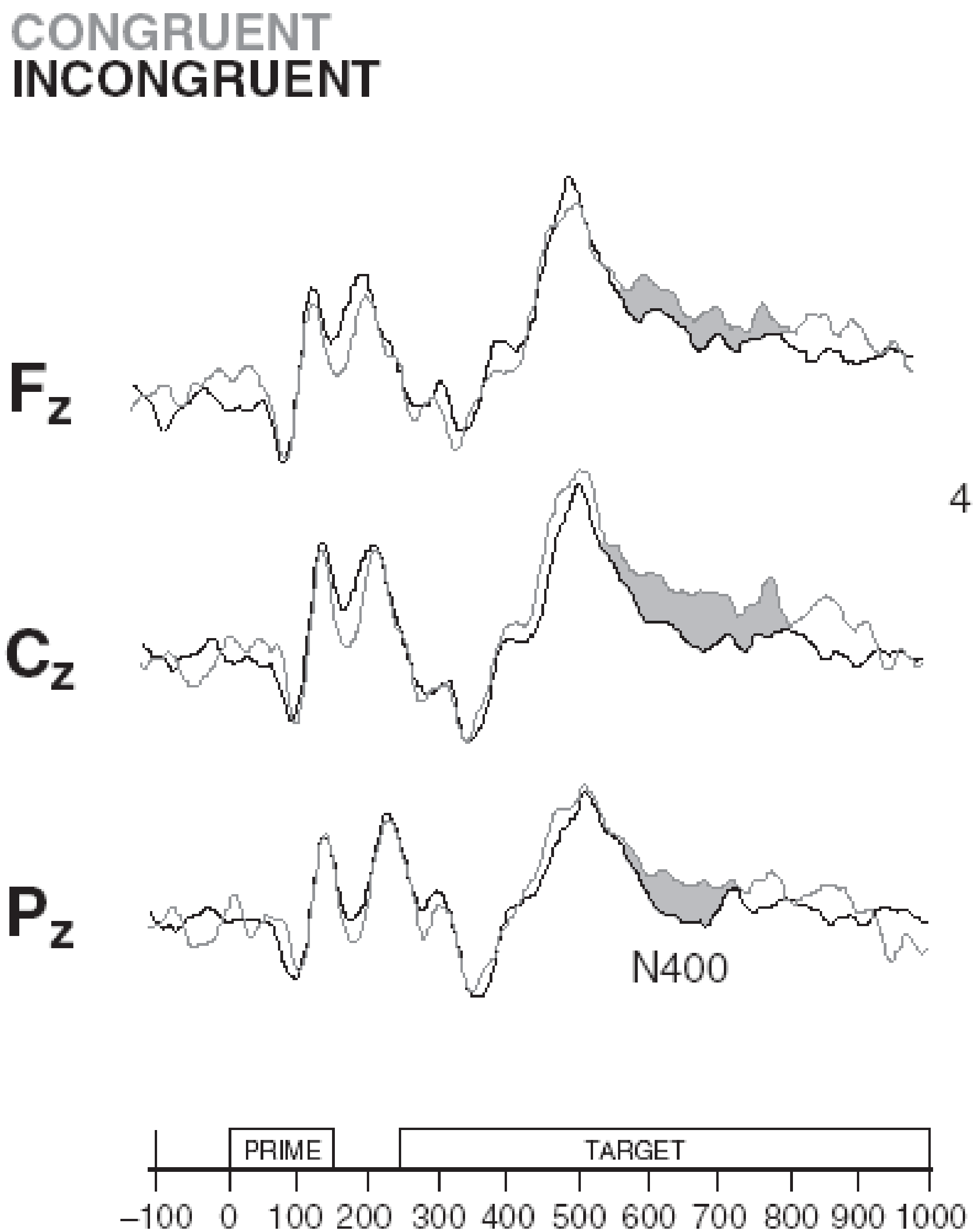
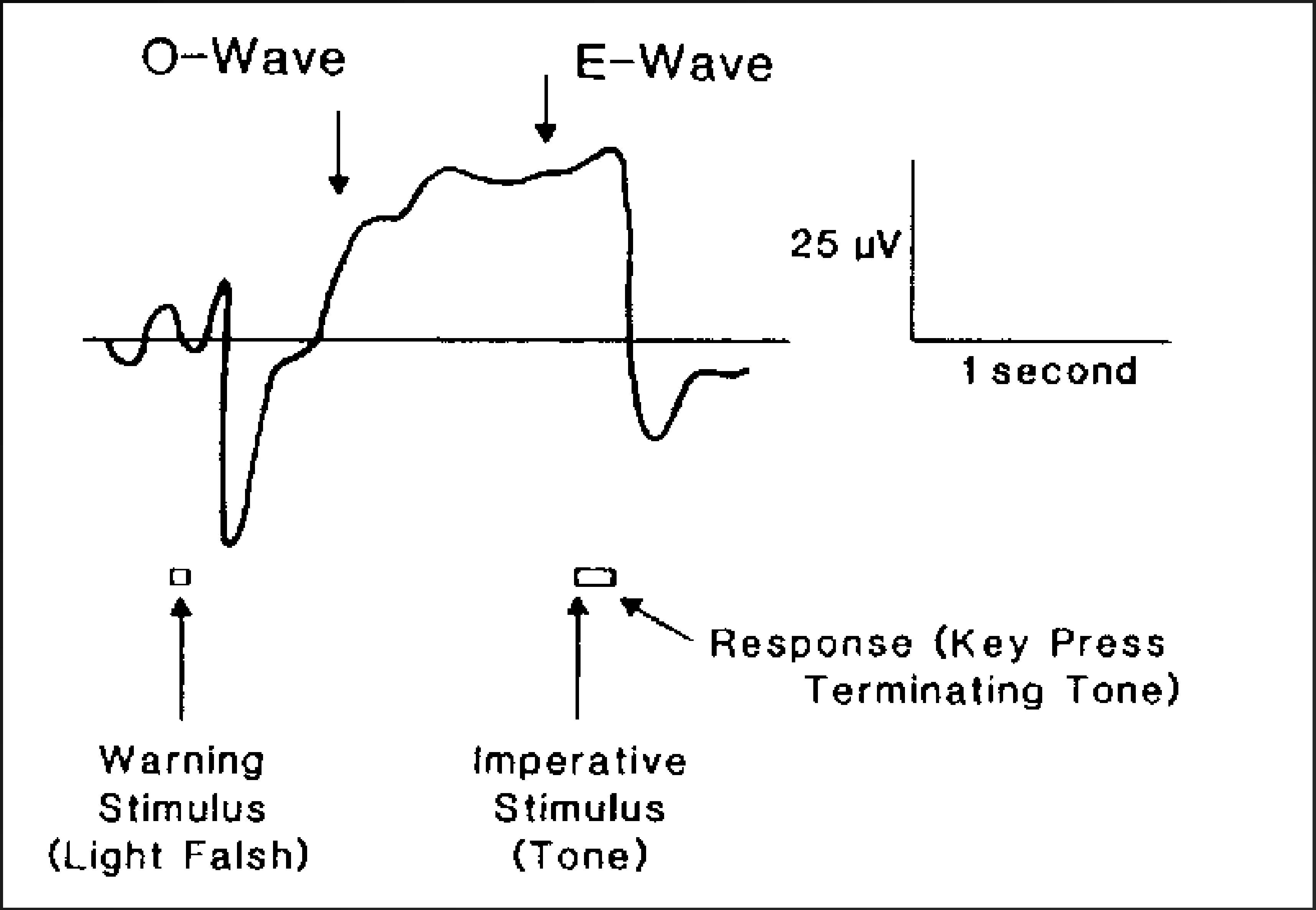


Figure 4. ERPs to congruent and incongruent prime/target pairs.

Congruent or incongruent defined base in idiographic data from pretest

Morris Squires et al. *Political Psychology* 2003

Contingent Negative Variation



O-wave = Orienting; E-Wave = Expectancy, arguably motor-related

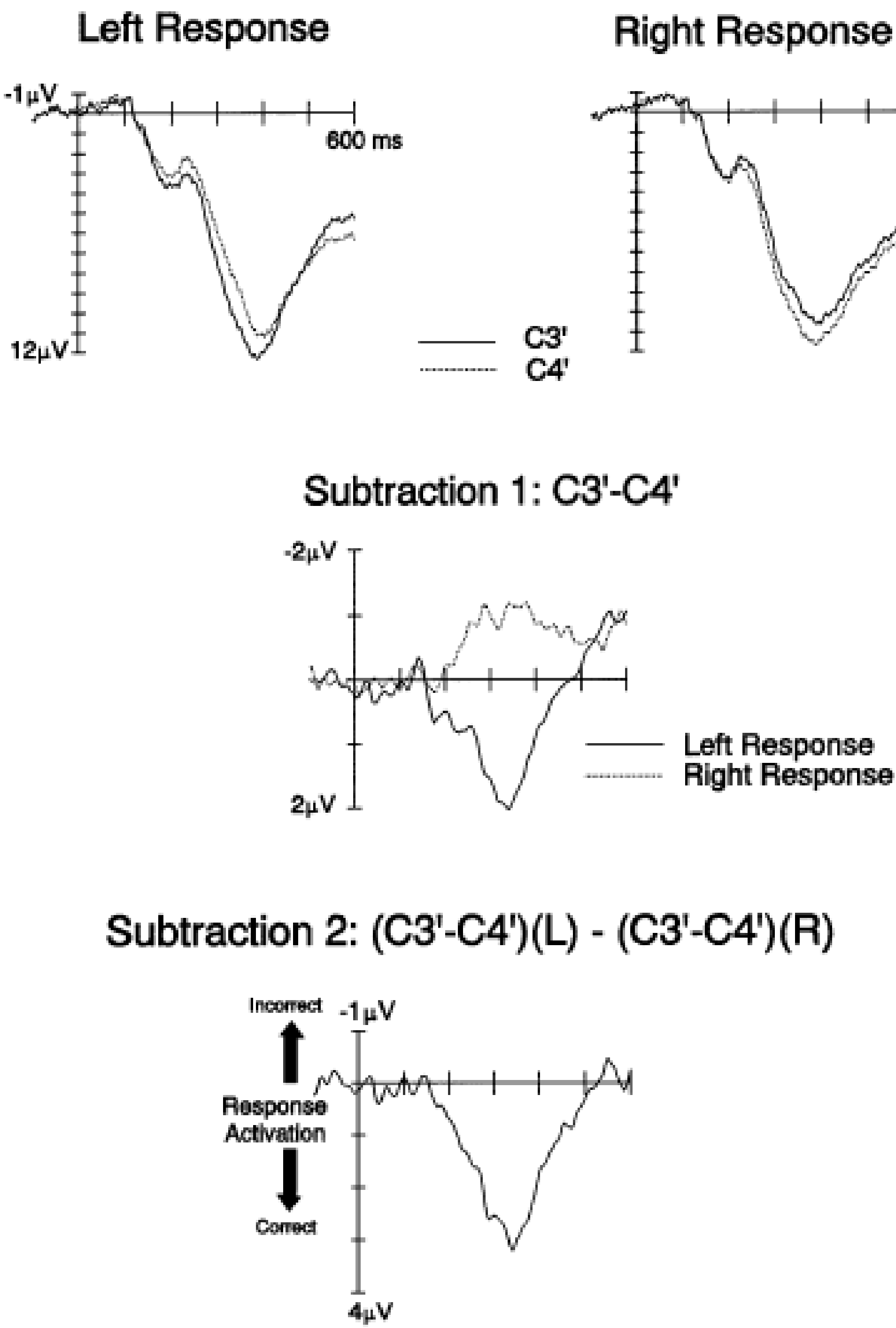
Response-locked potentials

- Lateralized Readiness Potential (LRP), a special case of movement-related potentials
- Error-related Negativity (ERN, aka N_E)

148 EIMER

Eimer 1998, *Beh Res Methods*

Lateralized Readiness Potential



- LRP can be stimulus-locked or response-locked
- For stim-locked, latency is time between stimulus onset
- and LRP onset
- For rsps-locked latency is time between an LRP deflection and the overt response.

Figure 1. Computation of the lateralized readiness potential (LRP) with the double subtraction method on the basis of event-related brain potential (ERP) waveforms elicited at electrodes C3′ (left hemisphere) and C4′ (right hemisphere). Top panels: Grand-averaged ERP waveforms from 10 subjects elicited at C3′ (solid lines) and C4′ (dashed lines) in response to stimuli requiring a left-hand response (left side) and to stimuli requiring a right-hand response (right side). Middle panel: Difference waveforms resulting from subtracting the ERPs obtained at C4′ from the ERPs obtained at C3′ separately for left-hand responses (solid line) and right-hand responses (dashed line). Bottom panel: LRP waveform resulting from subtracting the C3′ − C4′ difference waveform for right-hand responses from the C3′ − C4′ difference waveform for left-hand responses. A downward-going (positive) deflection indicates an activation of the correct response; an upward-going (negative) deflection indicates an activation

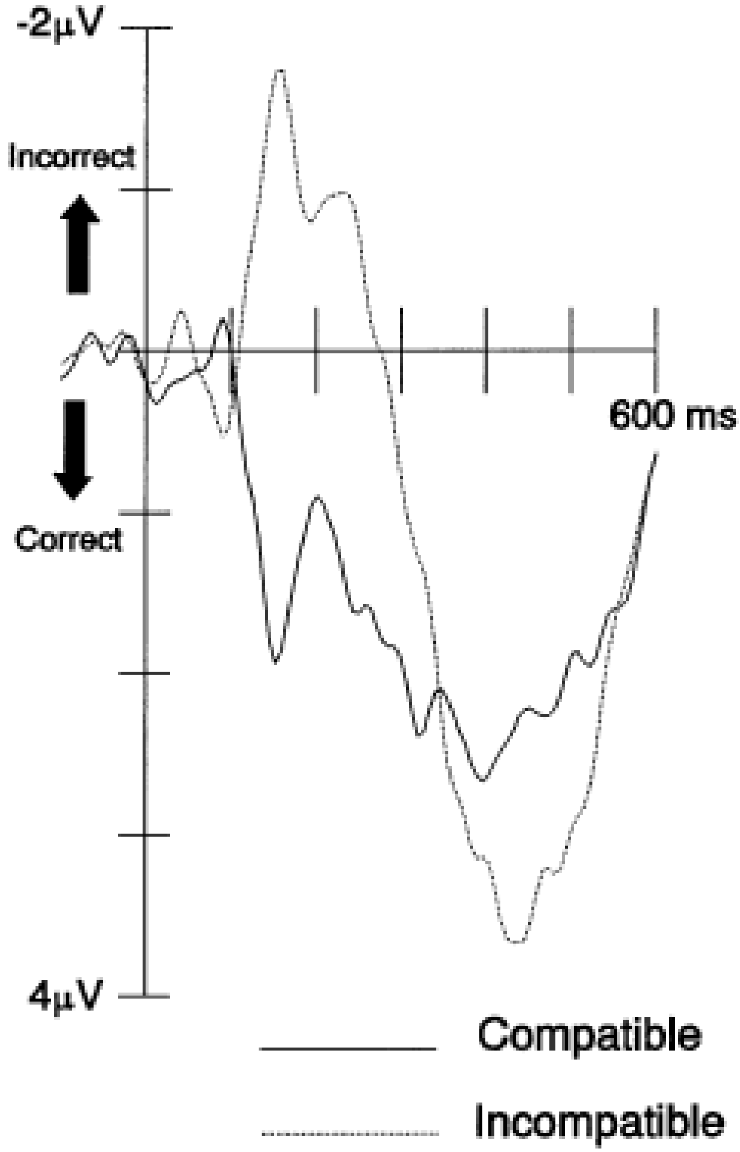


Figure 2. Top: Examples of stimulus displays in an experiment on spatial stimulus–response compatibility (Eimer, 1993, Experiment 1a) in which stimulus and response sides could either be compatible (left side) or incompatible (right side). Bottom: Grand-averaged LRP waveforms from 10 subjects, elicited in compatible trials (solid line) and in incompatible trials (dashed line).

Response conflict in the LRP

Eimer 1998, *Beh Res Methods*

The ERN

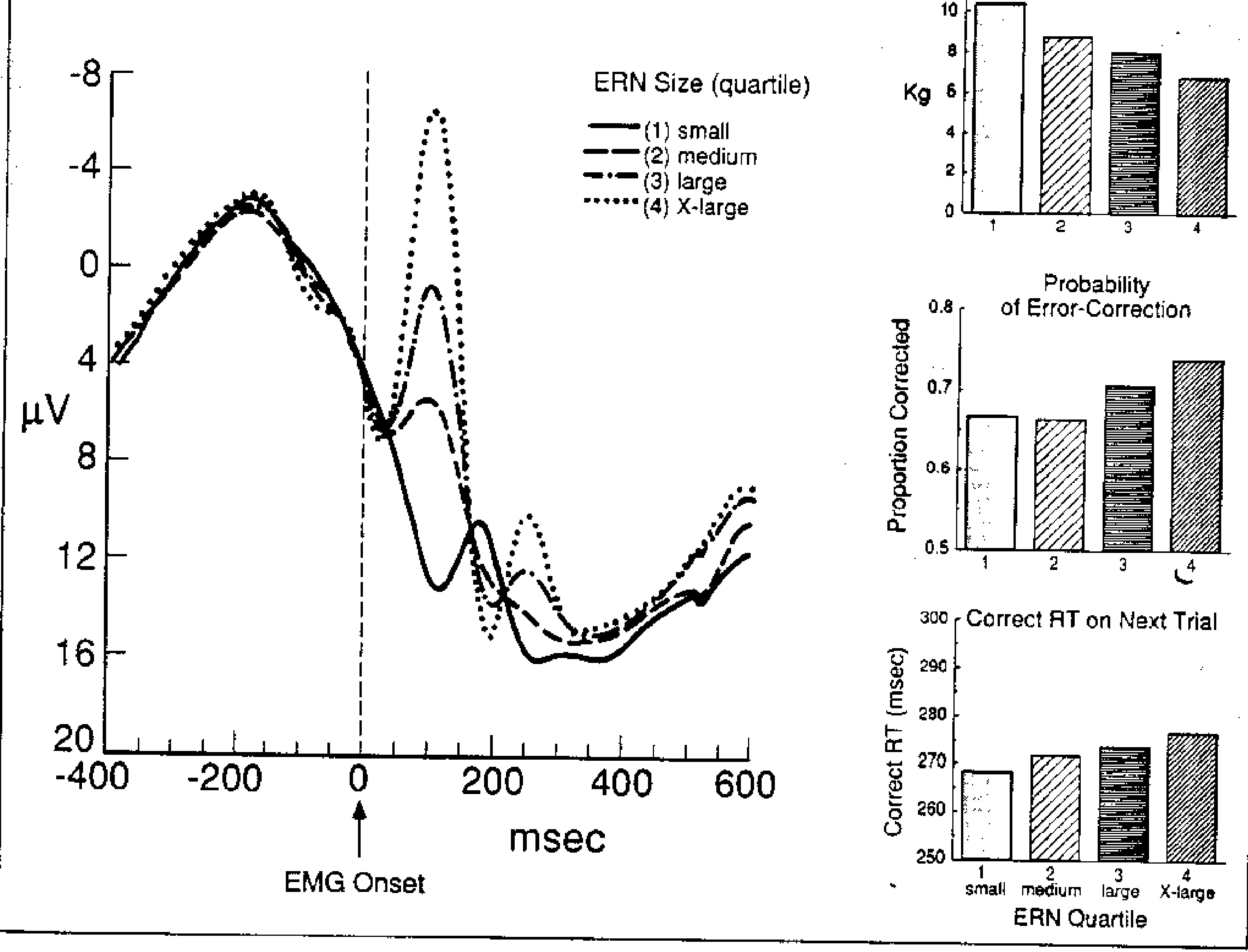


Fig. 3. Relationship between error-related negativity (ERN) amplitude and three measures of compensatory behavior. Left panel: Average event-related potentials at the C_z electrode as a function of the four levels of the posterior probability measure of ERN amplitude. Right panel, top: Error squeeze force in Kg as a function of the four ERN levels. Right panel, middle: Probability of error correction as a function of the four ERN levels. Right panel, bottom: Correct reaction time on the trial following an error as a function of the four ERN levels.

Gehring et al., 1993

Modality Specific?

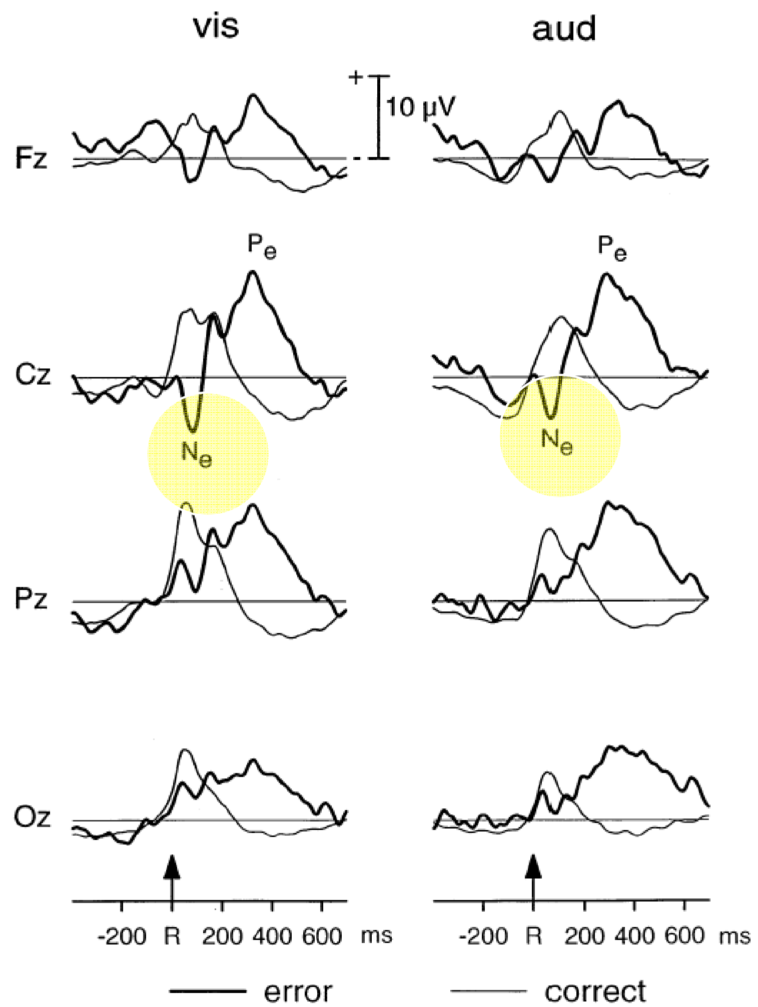
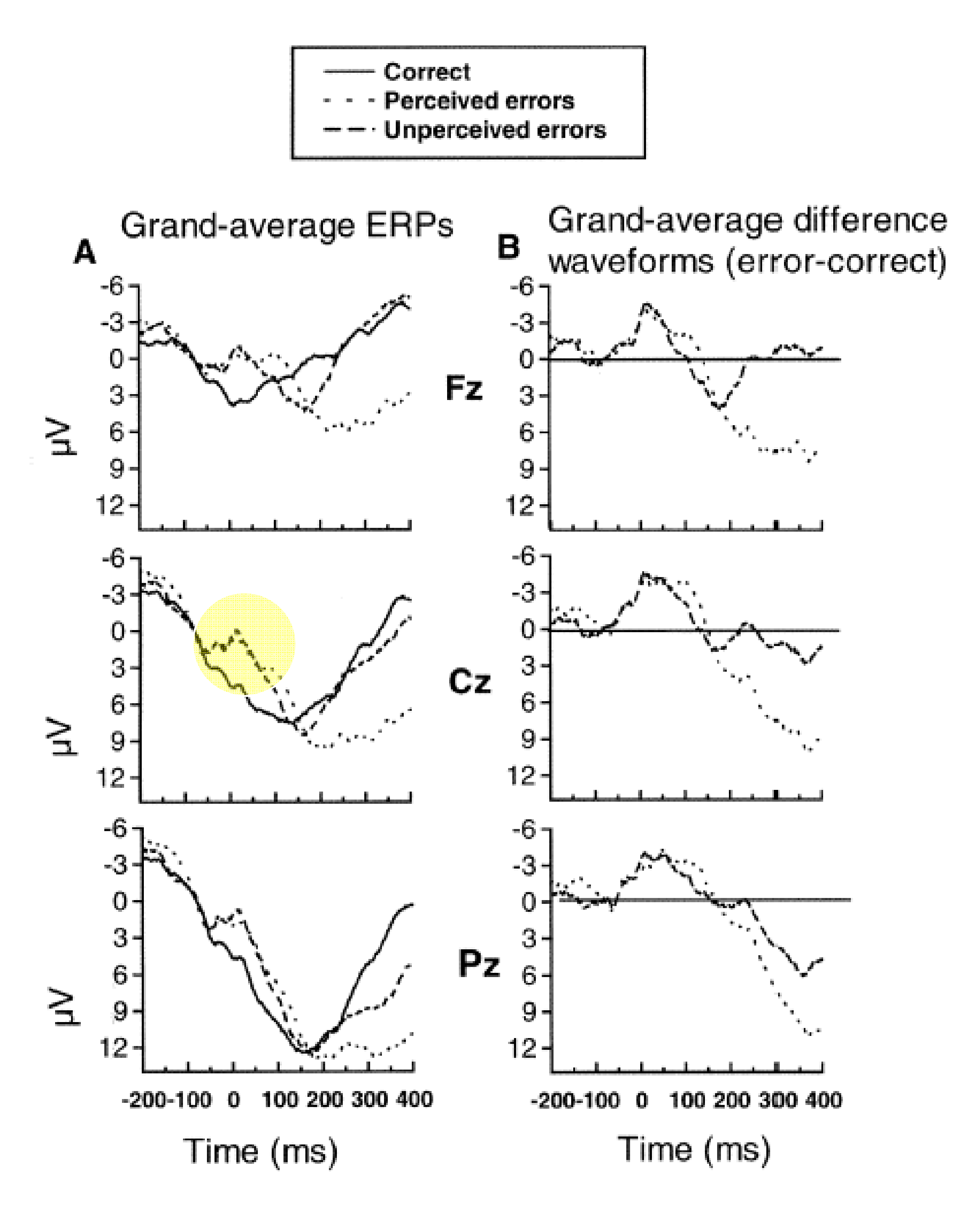


Fig. 1. Grand averages (Experiment 4; $n = 12$) of the RTA for errors (heavy lines) and correct trials (light lines) after visual (vis) and auditory letter stimuli (aud) in a 2-CR task. The error negativity ('Ne') is seen as a sharp negative deflection with central maximum peaking at about 80 ms after the incorrect key press (R). The error positivity ('Pe') is seen as a late parietal positivity with Cz maximum peaking at about 300 ms after the incorrect key press. On correct trials a positive complex with Pz maximum is seen.

- Does not matter what modality stimulus was presented



- Does not matter what modality response was made
- Eye

Nieuwenhuis et al., 2001: Saccade Task

C.B. Holroyd et al. / Neuroscience Letters 242 (1998) 65–68

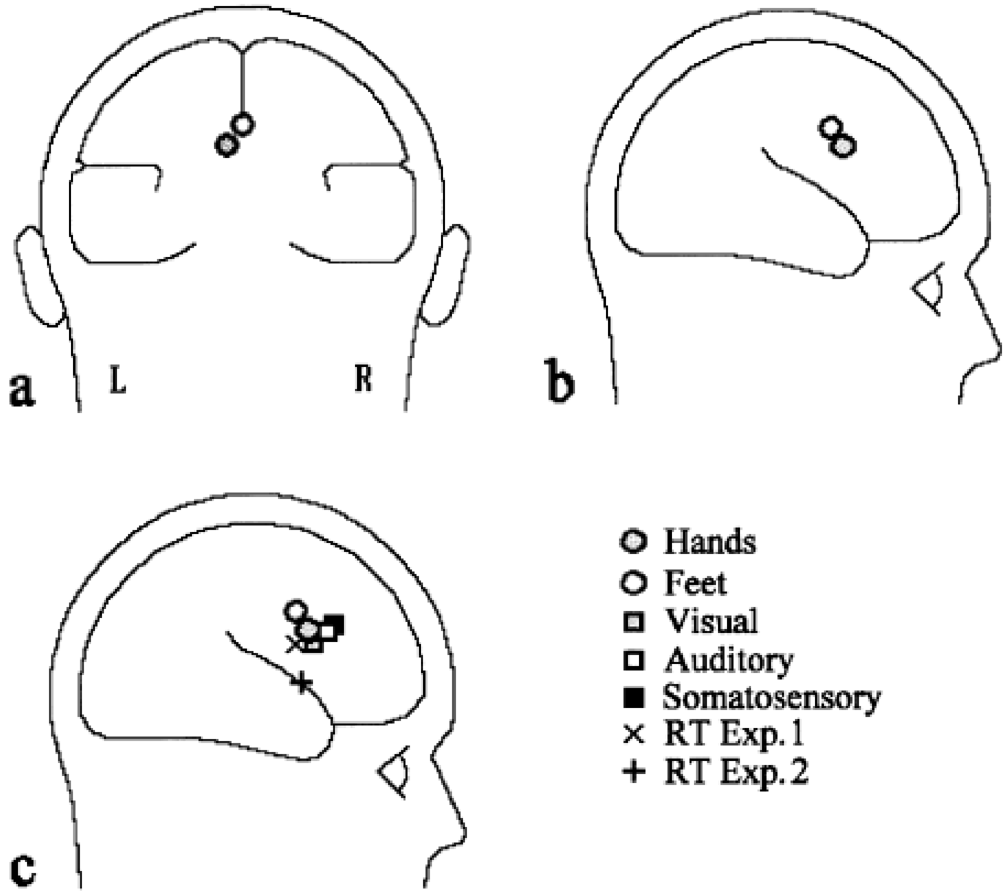


Fig. 2. Source localization of the error-related negativity. Circles represent locations of sources determined for hand and foot responses: (a) coronal view; (b) sagittal view; (c) for comparison, source locations of the ERN determined in previous studies are depicted along with the locations of the ERN obtained in the present study. Squares represent locations of sources found for ERNs elicited by visual, auditory, and somatosensory feedback [10]. Crossed symbols represent locations of sources found for ERNs elicited by errors in two reaction time experiments [2].

- Does not matter what modality response was made
- Eye
- Hand
- Foot

Theoretical Squabble #1: Error Detection Vs. Error Compensation

- If Error Compensation, ERN/Ne should not be present in tasks where compensation impossible
- Ergo…
  - the Go-Nogo!
  - Play along… press only for X following X

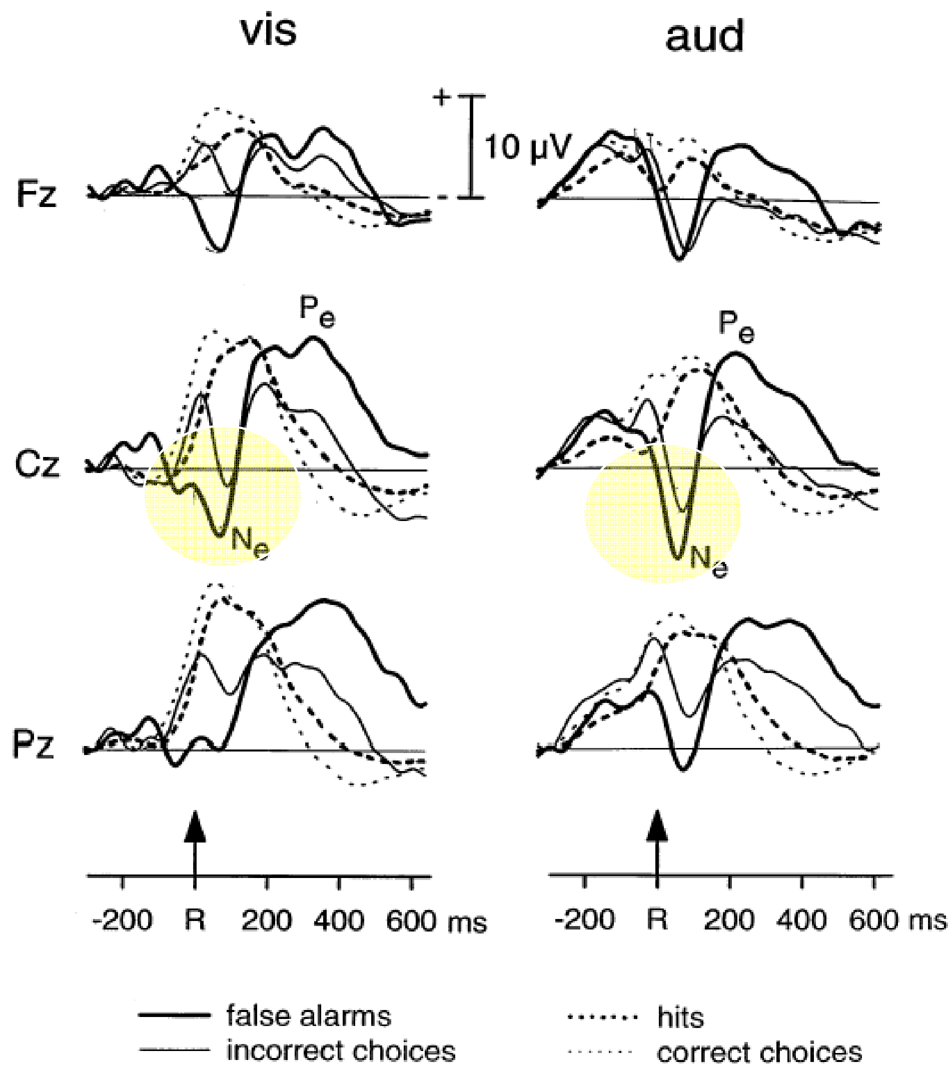


Fig. 5. Grand averages (Experiment 2; $n = 10$) of the RTA for false alarms and hits in Go/Nogo tasks (heavy lines), and choice errors and correct choice trials in two-way choice tasks (thin lines). Errors continuous lines, correct responses broken lines. The Ne is delayed relative to the incorrect key press, and the Pe is smaller, for choice errors compared to false alarms. In correct trials a positive complex with Pz maximum is seen, which is larger after visual than after auditory stimuli. However, this complex is not larger for hits than for correct choice trials.

Falkenstein Hoormann Christ & Hohnsbein, *Biological Psychology,* 2000, Summary of Falkenstein et al 1996

Theoretical Squabble #2: Error Detection Vs. Outcome Impact

- Might the “cost” or “importance” or “salience” of an error be relevant to this process?
- Studies relevant to error salience
  - Speed-accuracy trade off
  - Individual differences

Speed Vs. Accuracy

M. Falkenstein et al. / Biological Psychology 51 (2000) 87–107

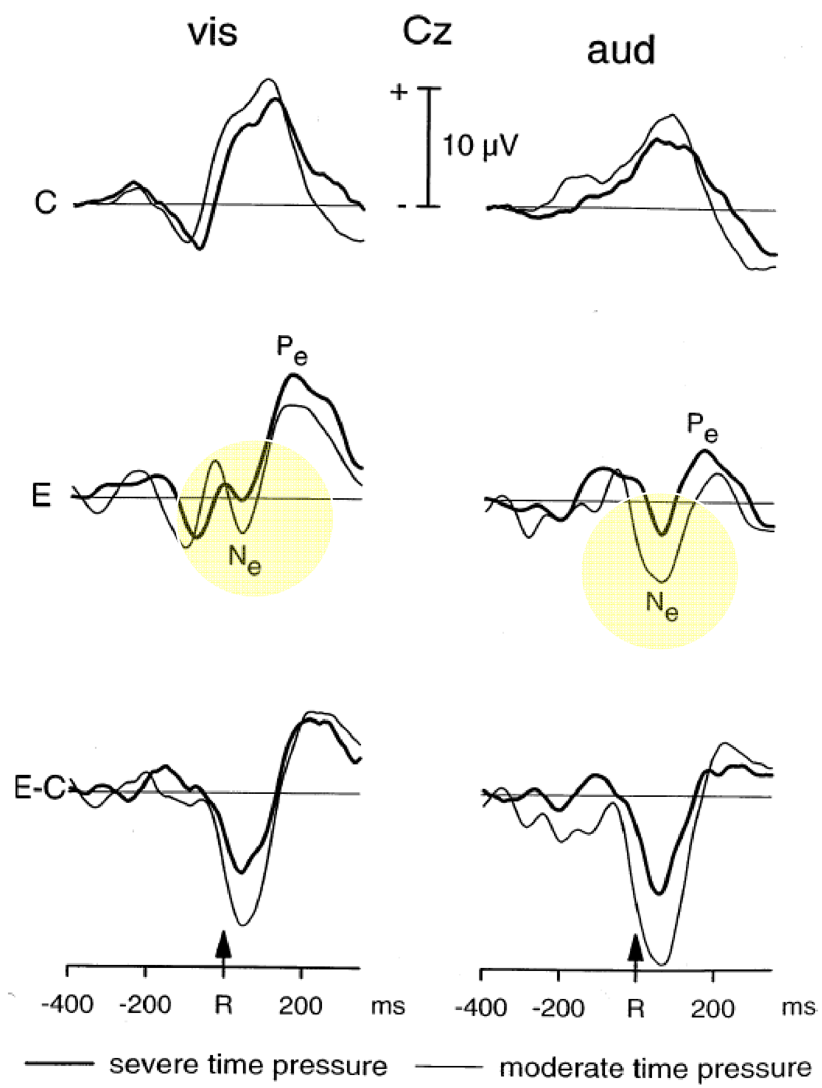


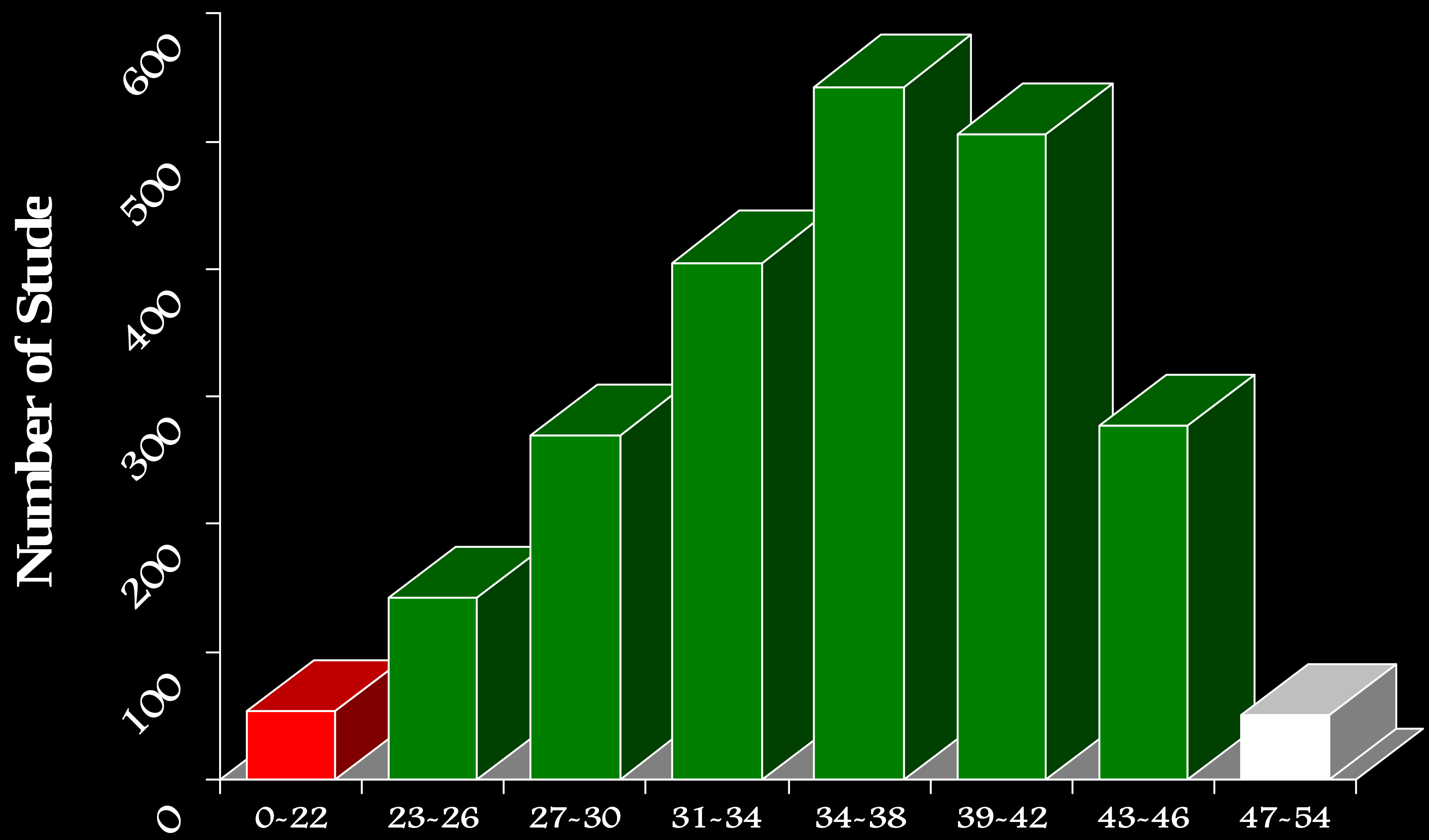
Fig. 4. Grand averages (Experiment 1; $n = 9$) of the RTA for correct responses (C), errors (E), and difference waveshapes (error minus correct; E − C) in a 2-CR task under moderate (light lines) and severe time pressure (heavy lines). The error rates were 15% (moderate) and 30% (severe); the number of error trials used was equalised for the two conditions. The Ne is smaller for severe time pressure/high error rate.

Individual Differences

- Psychopathy (or analog)
- OCD

Deficits in Error Monitoring in Psychopathy

- Psychopaths appear unable to learn from the consequences of their errors
  - Avoidance learning deficits
  - In the context of rewards *and* punishments
  - Deficient anticipatory anxiety



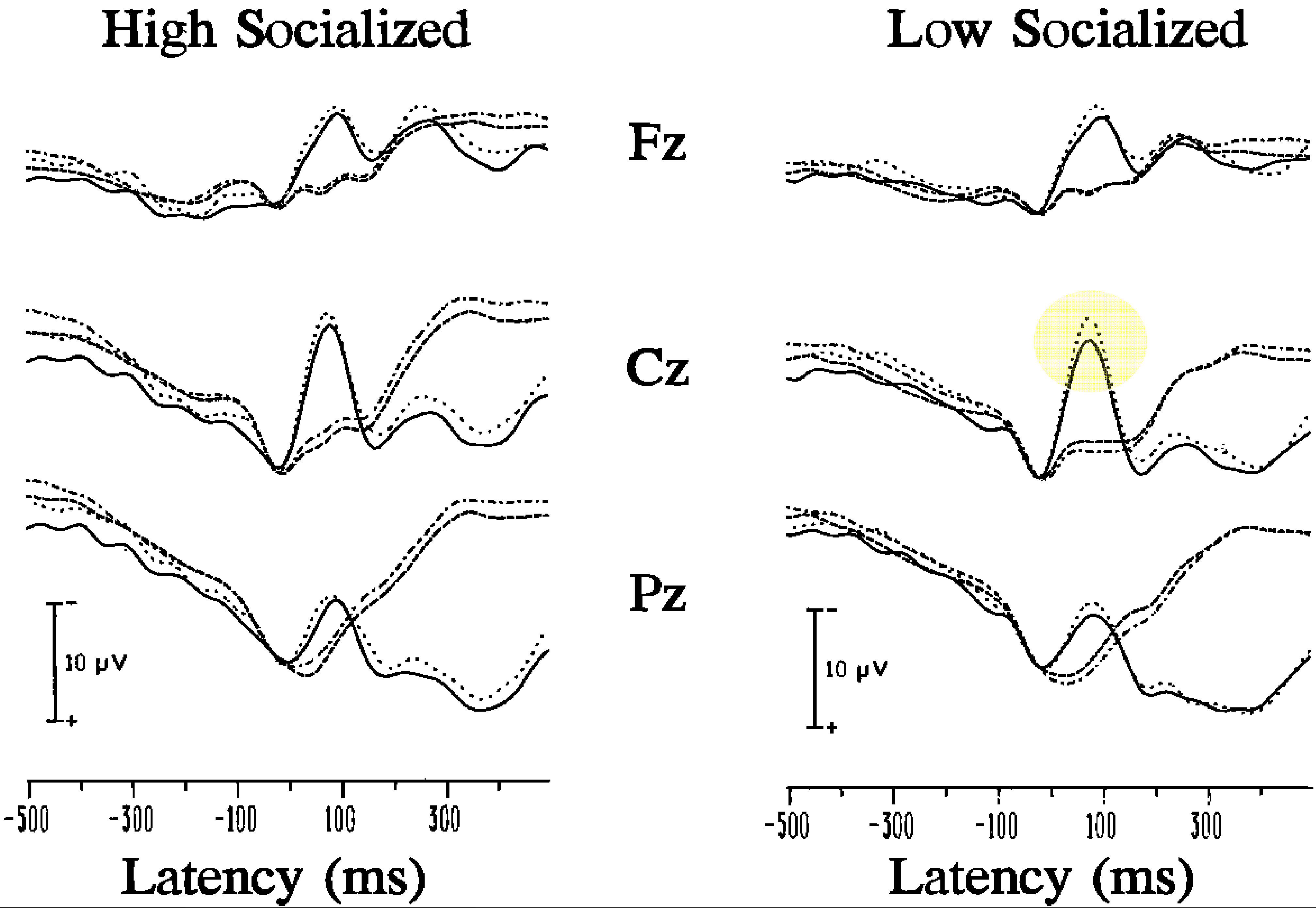
Thirty participants selected: **15 high SO**

15 low SO

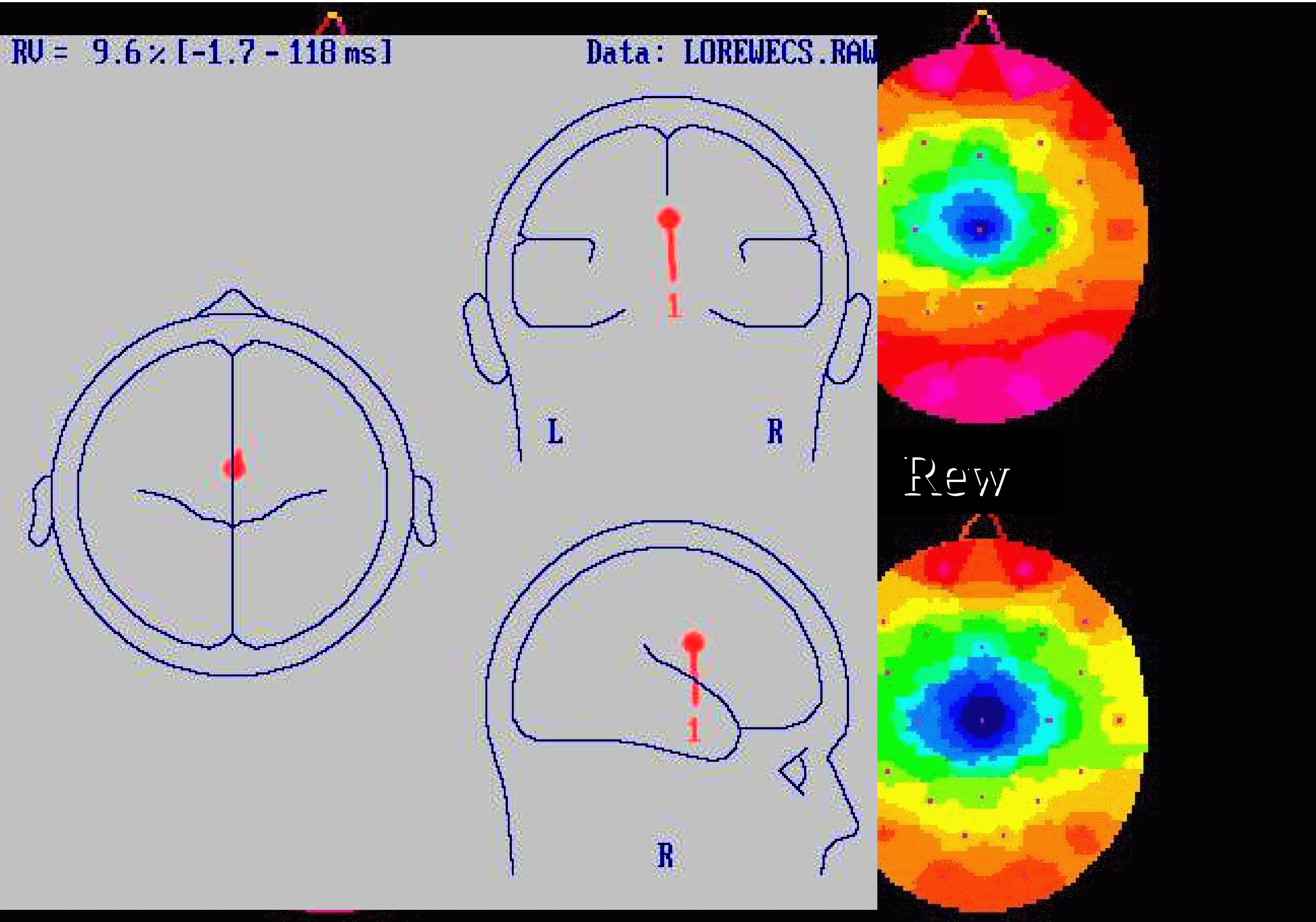
Dikman & Allen, 2000, *Psychophysiology*

Procedure

- Eriksen flanker task: SSHSS
- Two conditions for each subject
  - Reward (REW), errors “No $”
  - Punishment (PUN), errors 95 dB tone
- Consequences of errors could be avoided by self-correcting response within 1700 msec window
- Response mapping switched at start of each of 10 blocks, total trials 600
- Only corrected error trials examined



Dikman & Allen, 2000, *Psychophysiology*


RV = 9.6% [-1.7 - 118 ms]
Data: LOREWECS.RAW
L
R
R
Rew

ERN in OCD

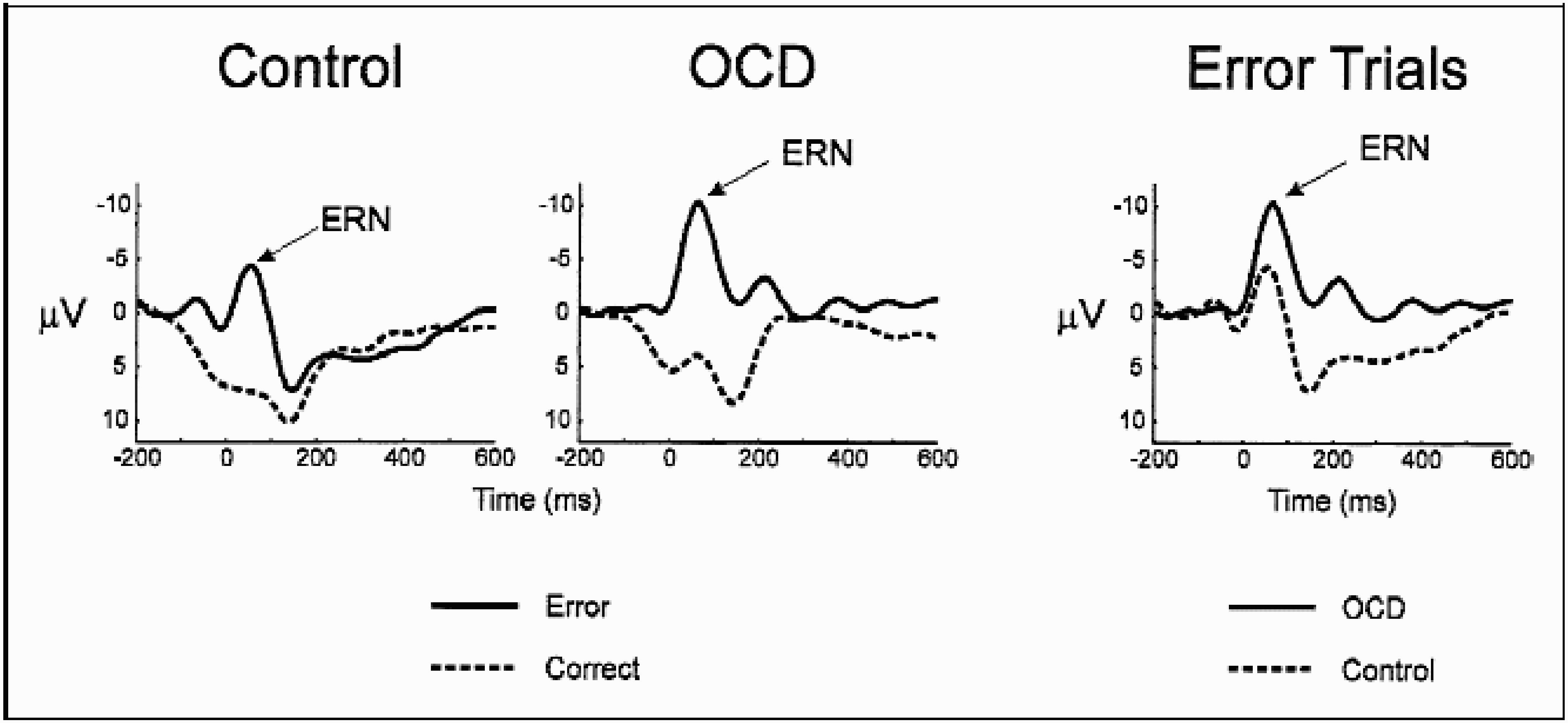


Fig. 1. Response-locked event-related potential waveforms at the Cz electrode location. The left panel compares correct-trial and error-trial waveforms for control participants and for individuals with obsessive-compulsive disorder (OCD). The right panel compares error-trial waveforms for the two groups. Times are plotted relative to the latency of the button-press response. ERN = error-related negativity.

And amplitude of ERN correlates with Symptom severity (correlation magnitude ~.50); Gehring et al. (2000)

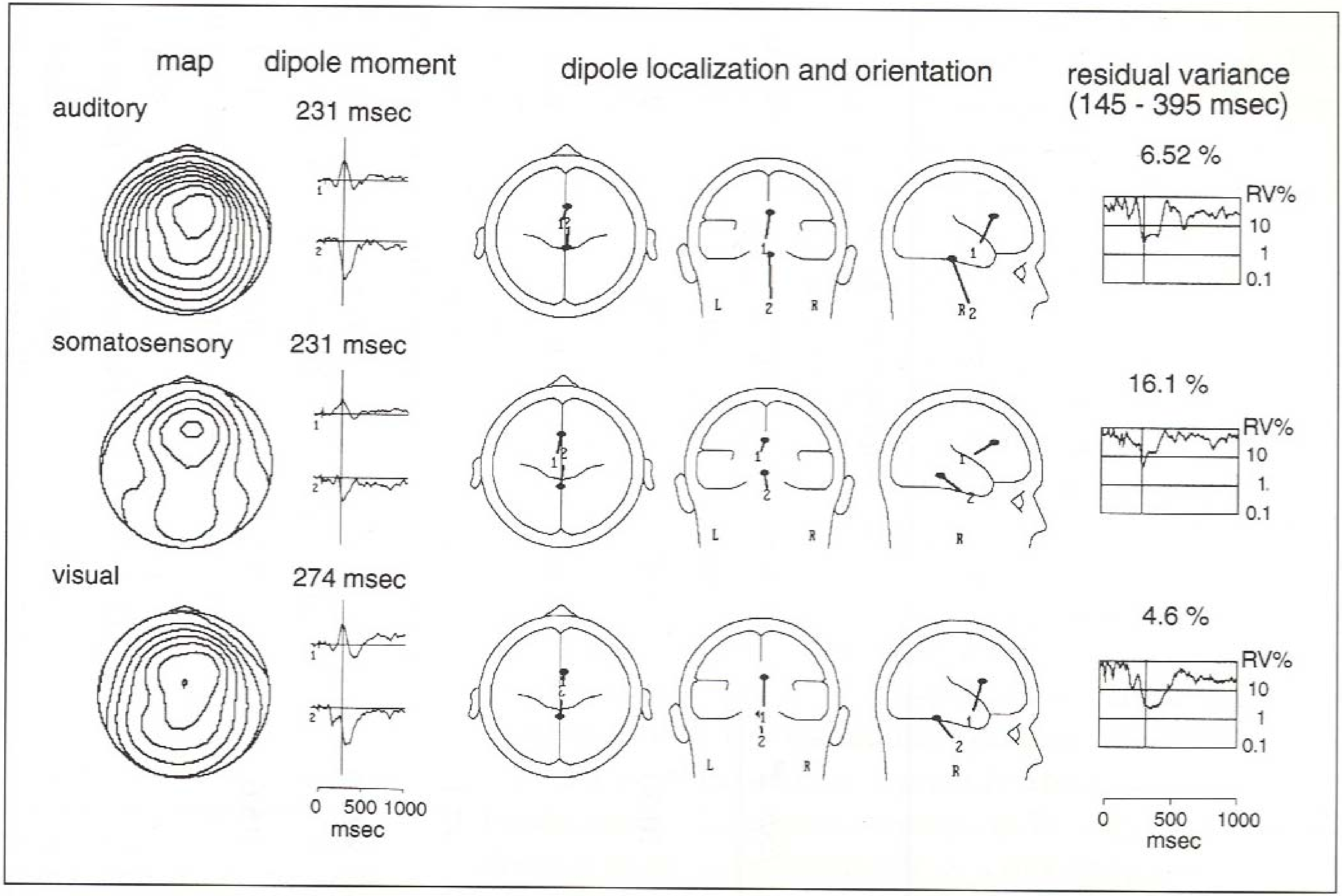
Theoretical Squabble #3: Error Detection Vs. Conflict

- Trials on which errors occur will entail greater response conflict than those without errors
- So, is it error detection, or response conflict?
- Stay tuned…

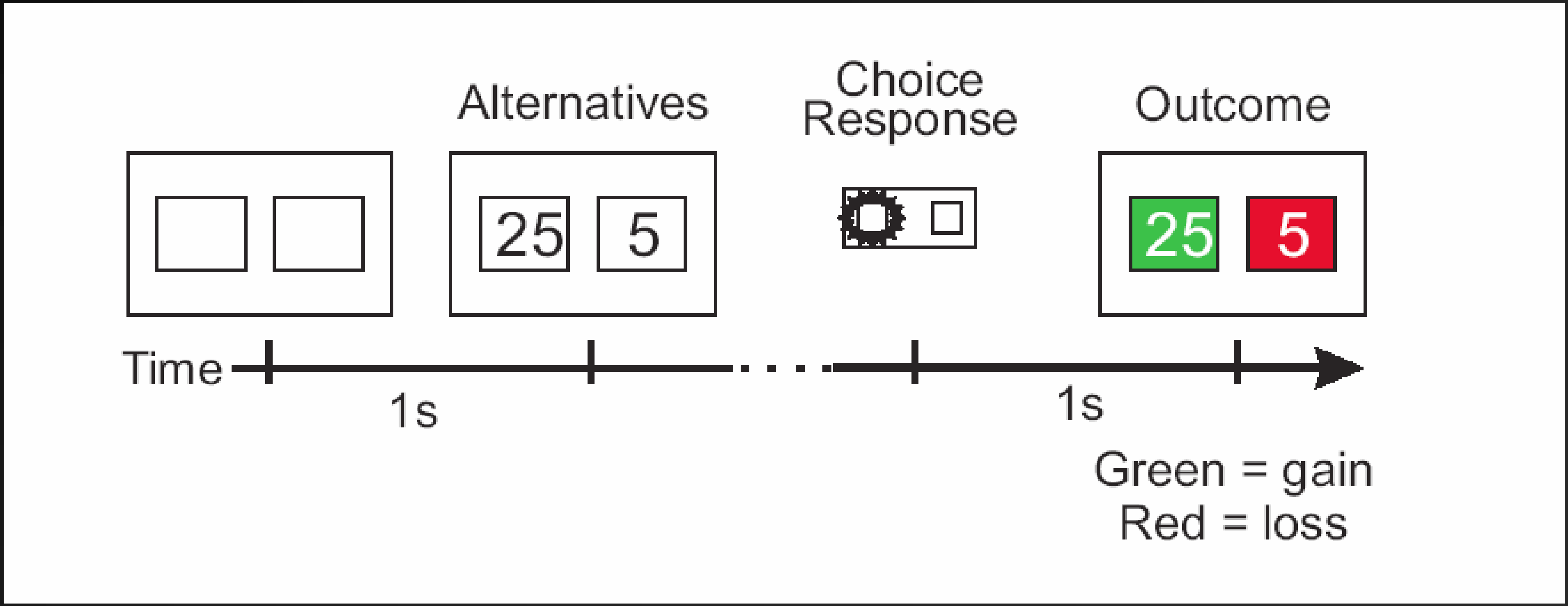
Errors and Feedback

- Endogenous Error Detection
- Exogenous Error Feedback
- Common Mechanism?

The Feedback Medial Frontal Negativity



The Gambling Task



Gehring and Willoughby, 2002 *Science*

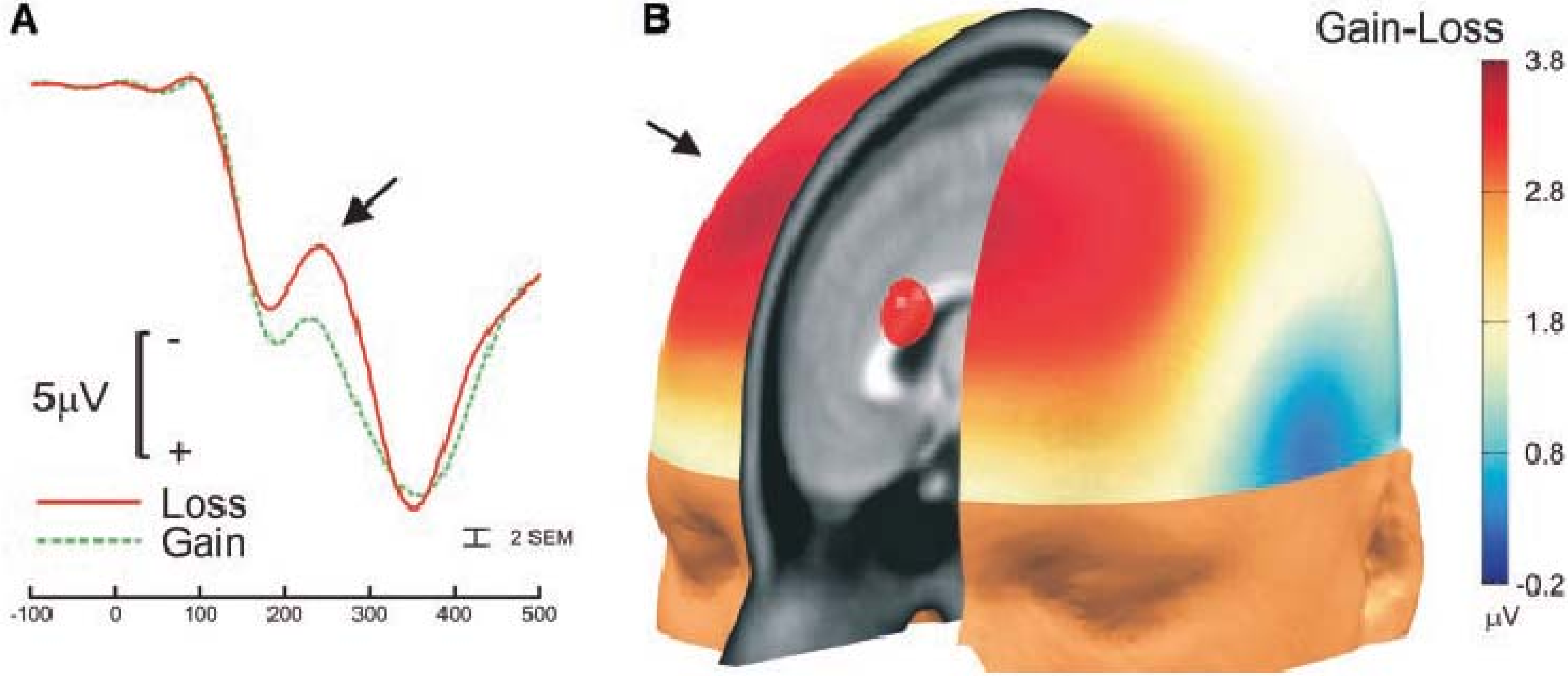
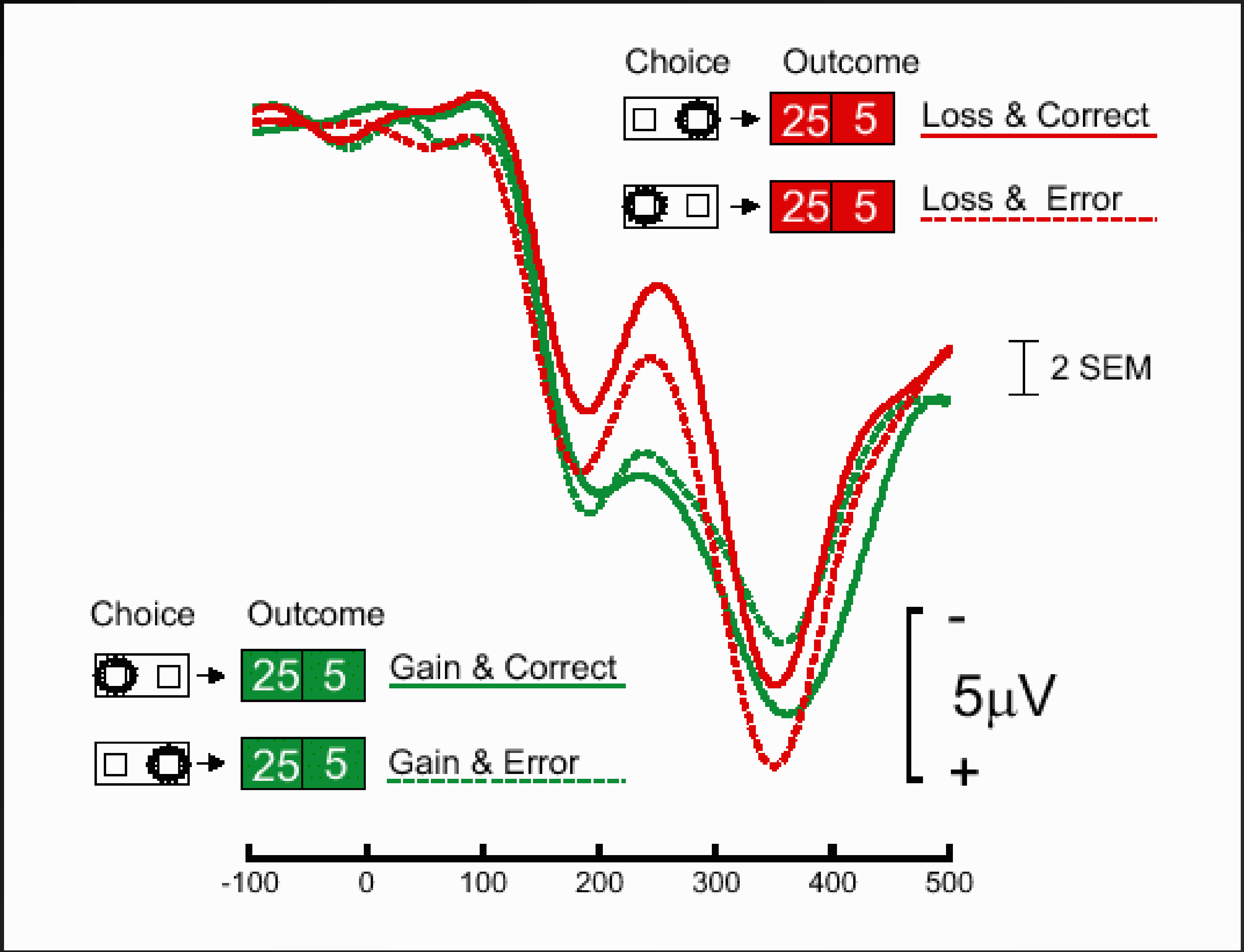


Fig. 2. ERP waveforms, scalp topography, and likely neural generator of the MFN. (**A**) The waveforms are shown at the Fz (frontal) electrode site. The solid red line corresponds to the average ERP waveform for all trials in which the participant lost money. The dashed green line corresponds to those trials in which the participant gained money. The MFN is indicated by the arrow. The error bar represents two standard errors of the mean, based on the mean squared error from the ANOVA (9). (**B**) The map of scalp activity shows the voltages, derived by subtracting the loss-trial waveform from the gain-trial waveform, computed at 265 ms after the onset of the outcome stimulus. Larger positive values correspond to a greater MFN effect. The MFN is indicated by the focus of activity at the Fz electrode (designated by the arrow). The best-fitting dipole model of the generator of the MFN is shown as a red sphere centered in the ACC on a canonical magnetic resonance imaging template of the human head (9).

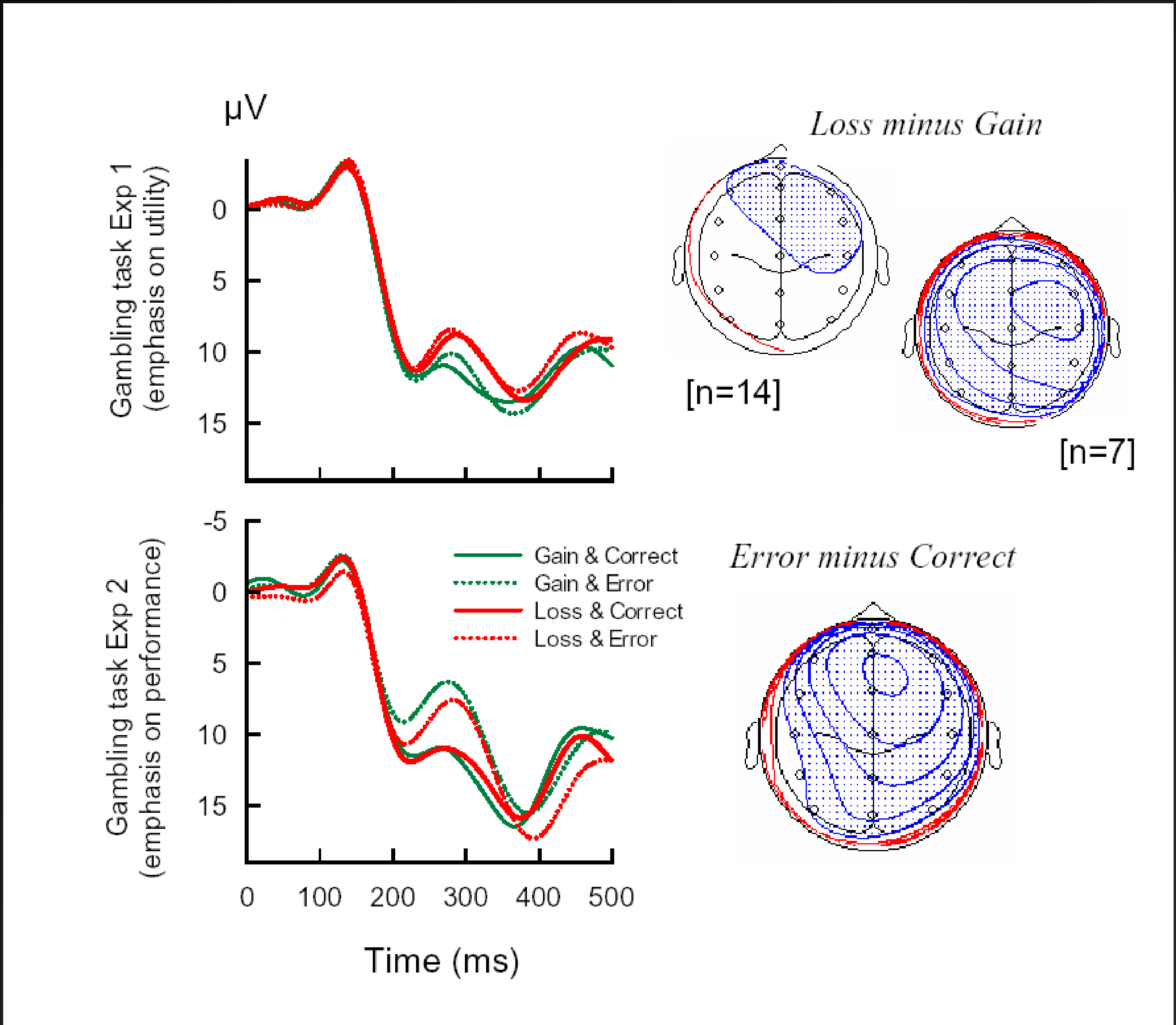
Gehring and Willoughby, 2002 *Science*

Error, or motivation?



Gehring and Willoughby, 2002 *Science*

Effect may depend on *relevant* dimension of feedback



Nieuwenhuis, Yeung, Holroyd, Schurger, & Cohen (2004), Cerebral Cortex

End of this lecture… **on to the next!**