Representations of physical plausibility revealed by event-related potentials

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Maintaining an accurate mental representation of the current environment is crucial to detecting change in that environment and ensuring behavioral coherence. Past experience with interactions between objects, such as collisions, has been shown to influence the perception of object interactions. To assess whether mental representations of object interactions derived from experience influence the maintenance of a mental model of the current stimulus environment, we presented physically plausible and implausible collision events while recording brain electrical activity. The parietal P300 response to 'oddball' events was found to be modulated by the physical plausibility of the stimuli, suggesting that past experience of object interactions can influence working memory processes involved in monitoring ongoing changes to the environment. *NeuroReport* 20:1081–1086 © 2009 Wolters Kluwer Health | Lippincott Williams & Wilkins.

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Introduction

Examples abound of how existing knowledge derived from previous experience can influence the processing of incoming information. The visual system assumes that illumination of scenes is from above [1], and that faces are convex [2], leading to particular interpretations of ambiguous visual input. Information about how objects, bodies, and faces move is also represented in the brain and can be used to guide perception and action and anticipate future movements even from relatively impoverished visual information [3]. The present investigation extends the range of factors found to influence the processing of new information to include experience of the dynamic 'interactions' of objects.

Knowledge of how moving objects interact affects both the drawing of inference about, and the perception of, object interactions, such as collisions. The schema-matching hypothesis [4] proposes that information about physical mechanisms is associated in memory with visual information about the typical motions of objects and other sensory information in 'schemas' derived from experience. When an observer is presented with visual input, the kinematic properties of perceived objects are matched to the schema that gives the best fit. The schema-matching hypothesis posits that experience with colliding objects will create a representation that characterizes collisions as contiguous and with angles of motion that obey physical laws.

The hypothesis is supported by the observation that collision events are perceived as causal interactions only when the kinematic properties of the stimulus can be mapped onto a physically plausible mechanism [5]. Moreover, observers misperceive dynamic stimulus interactions in concordance with a plausible mechanism [5,6], suggesting that the human perceptual system is tuned to apply assumptions and recover percepts of dynamic interactions between objects that conform to the real world.

Integrative long-term schematic representations of object interactions may also be revealed by their effect upon short-term functions, such as the maintenance in memory of a mental model of the current environment. Information about recently encountered stimuli, such as their type, their frequency, and their probability of reoccurrence, may be biased towards existing representations. To investigate whether individuals hold schematic representations of physically plausible interactions between objects, we presented individuals with animations of collision events that either conformed to, or violated, basic laws of physics while recording brain electrical activity. We then examined an event-related potential (ERP) index of processes responsible for updating and maintaining a model of the current environment, namely the parietal P300 component.

The parietal P300, or P3b [7], is a large positive scalp ERP that peaks in amplitude 300–500 ms after a task-relevant

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event, embedded in a train of task-irrelevant events, is detected. The P300 component is most commonly elicited by infrequent target 'oddball' events presented randomly in a series of nontarget 'standard' events. Typically, the standard and oddball events differ along a single-stimulus dimension, such as pitch, although complex events, such as a change in strategy in a bargaining task, can elicit the response [8,9].

The context updating model of P300 proposes that a system, that includes a continually updated representation in memory of the current environment, exists to serve the strategic processing of information to influence priorities, biases, and the allocation of attentional resources [8,9]. Current events are compared with representations in memory and, if deviant, the online model is updated evoking a P300, the amplitude of which is proportional to the amount of change required in the model of the environment [10]. In the two-stimulus paradigm, physical deviance of stimuli affects the amplitude of earlier negative components but not the P300 [11], which is instead modulated by conceptual factors such as task instructions, subject motivation, and the subjective probability of events [8,12]. The P300 is therefore best described as a cognitive, rather than sensory, component that is elicited not by stimuli but by events [9].

Several findings suggest that P300 is susceptible to conceptual knowledge derived from experience outside of the experimental context. For instance, self-relevant [13] and emotive [14] events elicit enhanced P300s. The observation that musically experienced individuals with absolute pitch did not produce a P300 to auditory oddballs [15] was interpreted as evidence for the existence of 'internal standards' that allowed these individuals to name tones without comparing them to a mental model. In a similar vein, this study investigated the interaction of preexisting knowledge of interactions between physical objects and representations derived from recent experience.

Our experiment manipulated the plausibility of the target oddball event to determine whether the amplitude of the elicited P300 was affected by conceptual knowledge of object interactions. We predicted that physically implausible oddball events would elicit a P300 of greater amplitude than physically plausible oddball events, as the former deviates both from a mental model based on the within-experiment environment and from latent representations of how objects interact in the real world. This finding would inform about the existence of mental representations (schemas) of the kinematic properties of object interactions derived from real-world experience and the susceptibility of online mental models to extraexperimental factors.

Methods

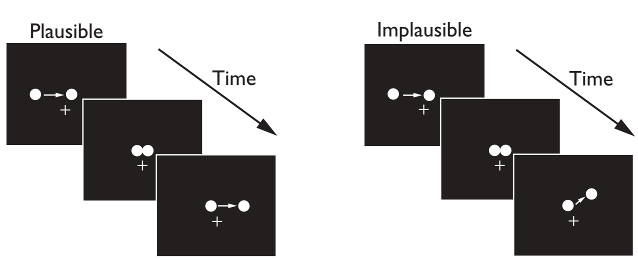
Participants

Nine participants (five females, four males; approximate mean age 25 years, SD 1.9 years) took part in the experiment for academic credit. All but one were predominantly right handed. Each participant provided written informed consent before participating.

Stimuli

Stimuli were presented on a computer screen using Presentation software (Version 9, *www.neuro-bs.com*), situated approximately 100 cm from the participant and refreshed at 60 Hz. A white fixation cross subtending approximately 0.4° visual angle was presented throughout the experiment. On each trial, a white disk, subtending approximately 1.8° visual angle, was presented immediately above the fixation cross with one edge (right or left) adjacent to the vertical meridian (see Fig. 1). Another white disk was simultaneously presented with its center moved to the opposite side of the fixation point by approximately 2.9°. At the outset of each trial, this eccentric disk moved towards the central disk. After 418 ms, the moving disk was adjacent to the stationary stimulus. Up to this point on each trial, stimuli representing physically plausible or physically implausible collision events were identical. After contact, the impacted disk moved immediately in either a horizontal direction for plausible events or upward at an angle of 45° for implausible events. Movement of the second disk was at half the velocity of the movement of the first to create the strongest causal impression [16]. The stimuli were

Fig. 1



Stimulus display for plausible and implausible collision events. Arrows indicate smooth movements of the first ball to move and the impacted ball for 418 and 835 ms, respectively.

removed from the screen 835 ms after the collision of the two disks.

Procedure

Participants were instructed that the disks represented colliding balls. Stimulus events were presented according to a two-stimulus oddball paradigm in which standard events were presented on 90% of trials and target oddball events were presented on the remaining 10%. The experiment was run in 12 blocks of 40 trials, within which the event probabilities were preserved. Participants maintained fixation and pressed a response button when presented with the target oddball stimulus. The direction of movement of the stimuli on each trial was randomized. On half of the blocks (plausible-oddball condition) the target oddball event was the plausible collision stimulus, in which the impacted ball moved horizontally across the screen in a manner consistent with basic laws of physics, and the standard event was the implausible stimulus, in which the impacted ball moved upward at an angle of 45°. In the other half of the blocks (implausible-oddball condition), these arrangements were reversed so that the implausible stimulus was the oddball and the plausible stimulus was the standard. The balanced design held the perceptual distinctiveness, and the degree of physical deviance, of the target and standard stimuli constant across the two conditions but varied the physical plausibility of the two event types. Targets (either plausible or implausible) were therefore equally discriminable in the two conditions. The target condition and the hand used for response were randomized across blocks. Participants completed six blocks in each of the target conditions, yielding a total of 480 trials (48 oddball and 432 standard).

Event-related potential recording

Scalp potentials were recorded from 24 tin electrodes mounted on a custom elastic cap and covering the entire head, and from the left and right mastoids. Electroencephalographic activity was recorded relative to a reference electrode on the cap situated just anterior to FZ and a ground electrode located below the left eye. Activity was amplified with a band pass of 0.1–30 Hz (half-amplitude cutoffs) and digitized at 256 samples per second. The electrooculogram was recorded from the canthi and from an electrode inferior to the right eye. Offline computerized artifact rejection was used to eliminate trials during which detectable eye movements, blinks, muscle potentials, or amplifier blocking occurred. This was assessed by measuring peak-to-peak amplitude over a time window encompassing the period of interest. No participant had more than 5% of their total number of trials rejected because of these signal artifacts. For each participant, ERPs were averaged into 3000-ms epochs, beginning 1500 ms before the collision of the two stimuli, which was the point when target oddballs diverged from standard stimuli. All ERPs were algebraically re-referenced to the average of the left and right mastoid signals and filtered with a low-pass Gaussian filter (25 Hz half-amplitude cutoff) to eliminate high-frequency artifacts in the waveforms and high pass RC filtered (1.3 Hz cutoff) to remove slow-wave and DC components.

Results

Behavioral

Reaction times were calculated as the difference in time between the collision of the two stimuli and the response. There was negligible difference between mean reaction times to targets in the two conditions (plausible 599 ms, SD 242 ms; implausible 594 ms, SD 257 ms).

Event-related potentials

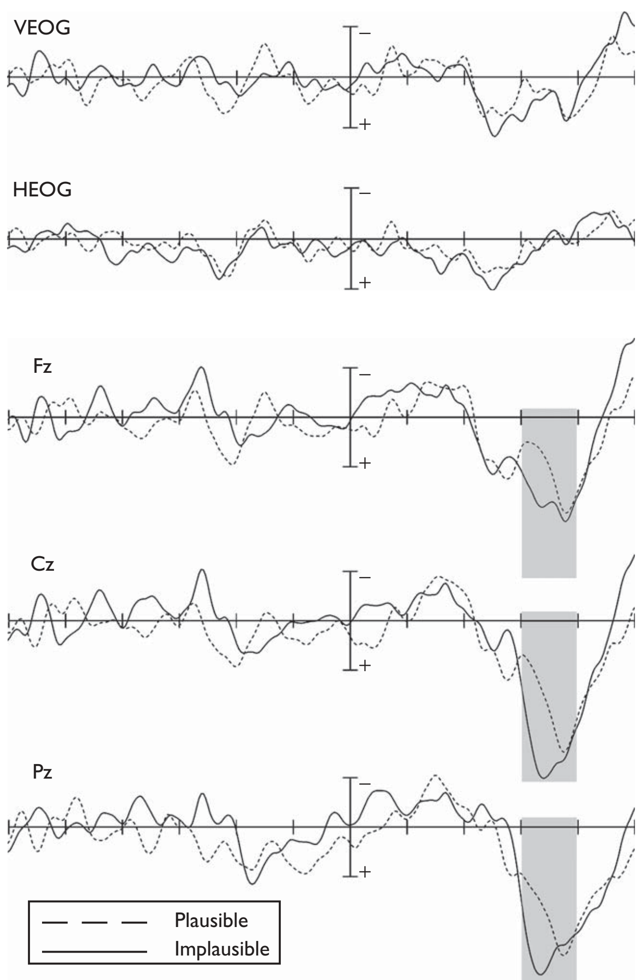
Visual inspection of the ERP waveforms indicated a P300-like response, peaking around approximately 300 ms post-collision for the standards and peaking around 350 ms post-collision for the oddballs, which was maximal at midline electrode sites Fz, Cz, and Pz. Not only was the overall amplitude of this positive-going response greater for oddballs relative to standards, the response within each stimulus condition appeared to be greater for implausible collisions relative to plausible collisions. This pattern was confirmed through an omnibus repeated-measures analysis of variance (ANOVA) on the mean amplitudes of these P300-like responses that included factors of time window (250–350 ms post-stimulus vs. 300–400 ms post-stimulus), stimulus frequency condition (standard vs. oddball), and collision type (plausible vs. implausible). Analyses were restricted to the electrodes at which the P300 was maximal and well defined. Electrode (Fz, Cz, PZ) was also included as a factor in all ANOVAs, but we found no consistent effect of this factor or systematic interactions with any other factor and will not be discussed further. We found significant main effects of stimulus frequency [$F(1,8) = 14.06$; $P = 0.006$], indicating that oddballs produced a larger amplitude P300-like response relative to standards, and collision type [$F(1,8) = 105.37$; $P = 0.0001$], indicating that the implausible collisions produced larger amplitude P300-like responses than the plausible collisions. We also found a significant interaction between stimulus frequency and time window [$F(1,8) = 83.76$; $P = 0.0001$], indicating an overall larger P300-like response in the later time window for oddballs relative to standards.

Given these initial findings and the interaction between stimulus type and time window, we separately examined the effect of collision type (plausible vs. implausible) for oddballs and standards, each within the respective time window when the P300-like response was maximal for each stimulus condition (250–350 ms for standards, 300–400 for oddballs). For the standards, we found a significant main effect of collision type [$F(1,8) = 87.66$; $P = 0.0001$], indicating a larger response for implausible conditions relative to plausible conditions. For the oddballs, we also found a significant main effect of collision type [$F(1,8) = 35.11$; $P = 0.004$], again indicating an overall larger response for implausible conditions relative to plausible collisions. Taken together, these analyses were consistent with the conclusion that although the P300-like response was consistently larger for oddballs relative to standards, the implausible collision reliably produced larger responses than the plausible collisions, regardless of the frequency manipulation.

Waveforms for target oddball events and standard events, for electrodes submitted to analysis, are shown alongside recordings for the eye-movement channels in Figs 2 and 3, respectively. Waveforms are plotted for the period from 600 ms before the collision of the two balls until 500 ms after the collision. The vertical bar represents the moment of collision, which was the point at which oddball and standard events diverged. As the stimulus onset preceded the collision by 418 ms, the part of these plots to the left of the bar includes a period in which visual stimuli were displayed but a collision had not yet occurred. Waveforms are plotted relative to a 200-ms prestimulus baseline. The baseline period was measured relative to stimulus onset, not to object collision.

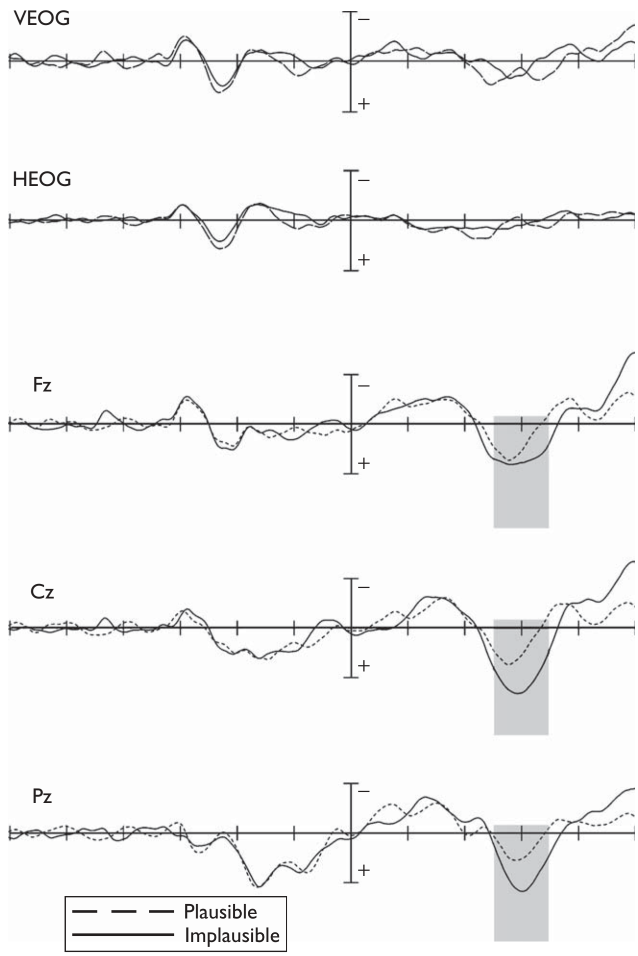
Finally, we examined the control issue of whether any effects attributed to implausible versus plausible collisions could actually be because of physical differences in the stimuli themselves. In most investigations using the oddball paradigm, oddballs and standards are differentiated by a physical difference, such as tone pitch.

Fig. 2



Waveforms for plausible and implausible oddball events plotted relative to a 200 ms prestimulus baseline for electrodes Fz (frontal midline), Cz (vertex), and Pz (parietal midline). Data from channels positioned to detect vertical electrooculogram (VEOG) and horizontal electrooculogram (HEOG) eye-movement are plotted alongside. The analysis window is indicated by a gray box (300–400 ms post-collision). Each tick on the horizontal axis is equivalent to 100 ms.

Fig. 3



Waveforms for plausible and implausible standard events plotted relative to a 200 ms prestimulus baseline for electrodes Fz (frontal midline), Cz (vertex), and Pz (parietal midline) and eye-movement channels. The analysis window is indicated by a gray box (250–350 ms post-collision). HEOG, horizontal electrooculogram; VEOG, vertical electrooculogram.

In this study, plausible collisions were associated with balls that continued to move laterally on the screen and implausible collisions were associated with balls moving at oblique trajectories. In short, might this basic difference in stimulus behavior produce differences in sensory processing that could account for the above results? If so, one might expect the initial response to the stimuli to diverge as a function of collision type, this being the portion of the ERP waveforms that is most sensitive to initial sensory/perceptual processing. To investigate this possibility, we ran an additional repeated-measures ANOVA on the 0–250 ms post-collision portion of the ERP waveforms, including factors of collision type (plausible vs. implausible) and stimulus frequency (oddball vs. standard). No main effects or interactions were observed (all F values <1.54; all P values >0.25), supporting our interpretation of effects on later cognitive components as because of manipulation of physical plausibility and not because of differences in movement *per se*.

Discussion

The enhancement of P300 by physical plausibility suggests that conceptual knowledge of object interactions can affect elicited components associated with updating and maintaining an online mental model of the recent past. After the context-updating model of P300, our result suggests that implausible oddballs deviate more from the representation of the series of stimulus events than do plausible oddballs.

This asymmetric deviance may result from the influence of existing knowledge upon the mental model of the stimulus environment. Experience of the kinematics of physically plausible collisions may serve to reduce the deviance of physically plausible oddballs by biasing the representation of repeated implausible object interactions towards physical plausibility. Thus, experiment-specific representations of dynamic object interactions may be biased toward environmental reality by past experience.

Alternatively, existing knowledge may interfere with the proper maintenance of an online mental model, reducing the strength of the representation, in a manner similar to the proactive interference by previously encountered information in working memory tasks [17]. Decaying representation strength has previously been proffered as an explanation for the observation of P300 components of reduced amplitude with increased interstimulus intervals [18]. The question of whether biasing or interference is involved remains open to future investigation. Our result suggests that the mental model of the current environment is strongest when incoming information and existing information are congruent.

Further to our predicted effect, we also observed a P300-like response to standard events, which was larger for implausible events than plausible events. The evocation of P300 by standard events is not unprecedented, as slowly presented standard events, like those used in this study, have been shown to evoke a P300 [19]. Their presence in this study is relevant to the question under investigation. Even when participants were exposed to blocks in which the implausible stimulus was the standard event, and occurring far more frequently than the target, we still observed a P300-like response to physical implausibility. This suggests that expectations for object interactions of this type cannot be adjusted to eliminate the effect of previous information, at least with the amount of experience provided by our task.

Conclusion

Together, these results provide evidence for the involvement of past experience and conceptual knowledge of the dynamic physical world in memory processes that keep track of the environmental context and generate expectations for object interactions. This finding is congruent with the view that the kinematic properties of physical interactions between objects are encoded into memory by experience of the physical world, as proposed by the schema-matching hypothesis [4]. These representations are then available to contribute to the interpretation of perceptual input and to the formation of causal impressions in the case of stimuli that include appropriate kinematic features.

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References

1. Kleffner D, Ramachandran VS. On the perception of shape from shading. *Percept Psychophys* 1992; **52**:18–36.
2. Hill H, Johnston A. The hollow-face illusion: object-specific knowledge, general assumptions or properties of the stimulus? *Perception* 2007; **36**:199–223.
3. Blakemore S-J, Decety J. From the perception of action to the understanding of intention. *Nat Rev Neurosci* 2001; **2**:561–567.
4. White P. The role of activity in visual impressions of causality. *Acta Psychol* (*Amst*) 2006; **123**:166–185.
5. White P. Visual causal impressions in the perception of several moving objects. *Vis Cogn* 2005; **12**:395–404.
6. Scholl B, Nakayama K. Causal capture: contextual effects on the perception of collision events. *Psychol Sci* 2002; **13**:493–498.
7. Squires N, Squires K, Hillyard S. Two varieties of long-latency positive waves evoked by unpredictable auditory stimuli in man. *Electroencephalogr Clin Neurophysiol* 1975; **38**:387–401.
8. Donchin E. Surprise!…Surprise? *Psychophysiology* 1981; **18**:493–513.
9. Donchin E, Spencer K, Dien J. The varieties of deviant experience: ERP manifestations of deviance processors. In: van Boxtel G, Bocker K, editors. *Brain and behavior: past, present, and future*. Tilburg: Tilburg University Press; 1997. pp. 67–91.
10. Fabiani M, Donchin E. Encoding processes and memory organization: a model of the Von Restorff effect. *J Exp Psychol Learn Mem Cogn* 1995; **21**:224–240.
11. Hansen J, Hillyard S. Selective attention to multidimensional auditory stimuli in man. *J Exp Psychol Hum Percept Perform* 1983; **9**:1–19.
12. Polich J. Overview of P3a and P3b. In: Polich J, editor. *Detection of change: event-related potential and fMRI findings*. Boston, MA: Kluwer Academic Press; 2003. pp. 83–98.
13. Gray H, Ambady N, Lowenthal W, Deldin P. P300 as an index of attention to self-relevant stimuli. *J Exp Soc Psychol* 2004; **40**:216–224.
14. Johnston V, Miller D, Burleson M. Multiple P300s to emotional stimuli and their theoretical significance. *Psychophysiology* 1986; **23**:684–694.
15. Klein M, Coles M, Donchin E. People with absolute pitch process tones without producing a P300. *Science* 1984; **233**:1306–1309.
16. Michotte A. *The perception of causality*. New York, NY: Basic Books; 1963.
17. Jonides J, Nee D. Brain mechanisms of proactive interference in working memory. *Neuroscience* 2006; **139**:181–193.
18. Donchin E, Coles M. Is the P300 component a manifestation of context updating? *Behav Brain Sci* 1988; **11**:357–374.
19. Looren de Jong H, Kok A, van Rooy J. Early and late selection in young and old adults: An ERP study. *Psychophysiology* 1988; **25**:657–671.