# A Class of Temporal Boundaries Derived by Quantifying the Sense of Separation

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# A PSYCHOPHYSICAL APPROACH TO EVENT SEGMENTATION

## Abstract

The perception of moment-to-moment environmental flux as being composed of meaningful events requires that memory processes coordinate with cues that signify beginnings and endings. We have constructed a technique that allows this coordination to be monitored indirectly. This technique works by embedding a sequential priming task into the event under study. Memory and perception must be coordinated to resolve temporal flux into scenes. The implicit memory processes inherent in sequential priming are able to effectively shadow then mirror scene-forming processes. Certain temporal boundaries are found to weaken the strength of irrelevant feature priming, a signal which can then be used in more ambiguous cases to infer how people segment time. Over the course of 13 independent studies we were able to calibrate the technique and then to use it to measure the strength of event segmentation in several instructive contexts that involved both visual and auditory modalities. The signal generated by sequential priming may permit the sense of separation between events to be measured as an extensive psychophysical quantity.

KEYWORDS: event perception, sequential priming, perceptual organization

The sensory surfaces of an animal are subjected to a continuous flow of energy. This flow is not what the animal experiences, however, but rather a series of meaningful events, which are comprised of information. The transformation of energy into meaningful information is achieved through perceptual organization. In this article we are interested in the particular aspects of perceptual organization that govern how we partition temporal flux into discrete events that have beginnings and endings. We introduce a psychophysical technique to determine when beginnings and endings are perceived. This technique depends upon the novel discovery that certain types of sequential priming manifest with reduced strength when prime and probe straddle temporal boundaries.

The study of perceptual organization dates back to the early twentieth century. Gestalt psychologists identified perceptual organization as an important problem (e.g., Wertheimer, 1912; 1923/1938), and the questions they studied remain relevant even in modern psychology (e.g., Palmer & Rock, 1994). Historically, the major focus of this work has been identifying grouping principles, such as similarity, proximity, and common fate, which foster a sense of association among elements. Many of these principles (e.g., continuity) appear to be amodal, seemingly applying across multiple modalities. Wertheimer, for instance, was of the opinion that many of his visual grouping principles applied within the auditory domain as well. Yet despite this general recognition that perceptual organization is not purely a visual problem, research on grouping in other modalities began relatively late and is still relatively undeveloped.

### Methods for Studying Event Segmentation

What work has been done on temporal grouping comes largely from the tradition of event perception, emerging not from Gestalt but from social psychology. This field has been primarily interested in determining how people segment meaningful actions and consequently has focused upon temporal grouping at a semantic level--for instance, grouping as defined by articulable long-range goals (Newtson, 1973). A common technique for studying boundaries between temporal units (i.e., "events") in event perception utilizes a simple explicit labeling procedure, in which participants view videos and report in real time when they perceive boundaries by pushing a button (Newtson). The events studied tend to be complex, emerging from videos of people completing everyday tasks, such as building a campfire, or even from cinematic films (e.g., Zacks, Speer, & Reynolds, 2009). Such studies conclude that people do exhibit an awareness of boundaries in these contexts, and that these boundaries remain fairly consistent for individuals over time (Speer, Swallow, & Zacks, 2003).

Newtson's video unitization technique has been validated using a number of convergent measures. Neuroimaging has found increased neural activity at explicitly labeled event boundaries even during passive viewing of videos (Zacks et al., 2001; Zacks, Swallow, Vettel, & McAvoy, 2006). Neural signatures have also been observed at boundaries in the realm of music perception using fMRI (Sridharan, Levitin, Chafe, Berger, & Menon, 2007) and EEG (van Zuijen, Sussman, Winkler, Näätänen, & Tervaniemi, 2004). Additionally, infants as young as 9 months old have been found to respond to points in temporal sequences that would be explicitly labeled as boundaries (Saylor, Baldwin, Baird, & LaBounty, 2007). Combined, these findings offer evidence that subjectively reported boundaries do correspond to objectively measurable, automatic neural processes. Other studies have shown relationships between event boundaries and performance on implicit behavioral measures, such as visual dwell time (Hard, Recchia, & Tversky, 2011), reading rate (Zacks, Speer, & Reynolds, 2009) and memory (Huff, Schwan, & Garsoffky, 2011; Swallow et al., 2010; Swallow, Zacks, & Abrams, 2009). Boundaries also appear to influence how people describe events (Zacks, Tversky, & Iyer, 2001).

What these studies demonstrate is that people are able to find and report temporal boundaries, and that these explicitly reported boundaries are accompanied by various neural and behavioral changes. However, it is equally clear that the elicitation of boundaries reported in typical event segmentation studies represents only part of the perceptual experience of event structure. Events are hierarchically structured (Zacks, Tversky, & Iyer, 2001). When speaking of human events, this hierarchy encompasses the long-range setting and completion of goals, occurring at one level; the individual actions to complete those goals, at another; and the accelerations of body parts in the normal course of motoric activity, at still another. The boundaries typically reported in event segmentation tasks inevitably arise from the way in which the study is contextualized for participants. Participants generally do not report every acceleration as a boundary (except perhaps in cases of very simple stimuli; Zacks, 2004), nor do they report only the beginning and ending of an entire video session as boundaries. The set of understandings that participants possess when entering the task, coupled with the instructions that they receive, implicitly determine what they construe as the appropriate level of boundary to report, and to some extent this has been studied (Cohen & Ebbeson, 1979; Zacks; Zacks, Tversky, & Iyer). Every explicit segmentation scenario involves a tacit agreement concerning the appropriate level of boundary. This is the nature of any self-report method.

For this reason, it is essential to develop implicit methods that provide indirect measurement of perceived boundaries, methods that do not rely on self-report. The techniques described in this article allow boundary percepts to be inferred through data signatures arising from a secondary task, a task that is unrelated to event structure and positioning of boundaries. In this way, we are able to minimize the demand characteristics that permeate self-report. Indeed, participants tell us where they perceive boundaries without our ever asking. If these implicitly detected boundaries occasionally differ from those elicited using self-report, we can take this as an indication that there is a class of natural boundaries that may have proven difficult to differentiate from other types of change that people report as boundaries when asked to segment videos.

## A New Tool

Several theories have been advanced in an attempt to explain how people segment their perceptual experiences of time. The study of beginnings and endings grows out of the work of Newtson (1973). Newtson's theory of event perception suggests that observers segment action on the basis of “noticeable” changes in features (1976). The major prediction of this theory is that boundaries are more likely to occur at moments of great perceptual change. However, a more thoroughly specified theory has since been proposed by Zacks et al. (2007). Event Segmentation Theory (EST) is prediction driven, proposing that event segmentation is guided by the active maintenance of event models in memory. These models remain active until the predictions generated by that model begin to diverge from what is actually experienced. At this point, an event boundary occurs, and the model is reset, allowing a new model to be constructed. A notable feature of EST is the clearing of active memory that occurs at event boundaries, a notion which is pivotal in our development of a new behavioral technique to identify boundaries in event perception.

Temporal scenes cannot be formed without the active participation of memory. Because scenes unfold over time, whatever relations are perceived among temporally distributed elements cannot exist without memory mechanisms that create associations. Our technique is based on an idea similar to EST’s clearing of active memory at event boundaries (Zacks et al, 2007). The idea is that associations in memory will be coordinated with the formation of groups in perceptual organization. Because memory and perception must be coordinated, it may be possible to study the boundaries that are formed in event perception using psychophysical measures of memory. While some studies have shown indications of reduced working memory across boundaries (Carroll & Bever, 1976; Gernsbacher, 1985; Radvansky & Copeland, 2006; Swallow et al., 2010), we propose to refine and extend these approaches by linking event structure to particular signatures in working memory. To this end we have developed a method that grafts a secondary implicit memory structure onto the principal scene formation mechanisms.

The crux of this method is the use of sequential priming as a signal that probes the instantaneous state of scene-forming memory, as detailed in Figure 1. At the top of this figure we show the temporal flux that exists in the world ($S_1$-$S_6$), which is packaged into meaningful events (Group 1 and Group 2). Our technique is to embed markers ($s_1$-$s_6$) within this higher-level flux and to study how these markers are associated in implicit working memory (i.e., priming), with the hope that the relationships between markers will be reflective of, and coordinated with, the event formation process. By creating a one-to-one pairing between each marker ($s_i$) and an element in the temporal flux of real-world events ($S_i$), we hope to shadow the processes of event formation through signatures that are manifested at the level of sequential priming.

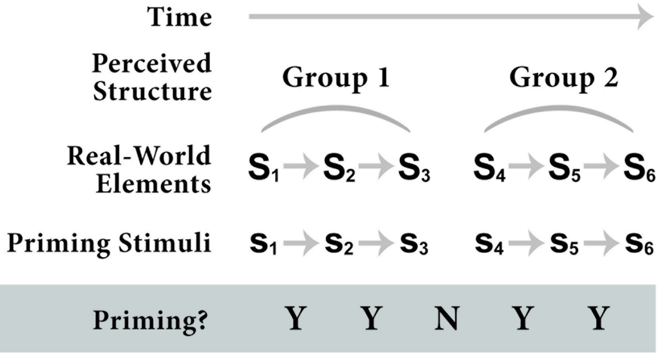

*Figure 1.* Illustration of study logic. Figure illustrates the manner in which priming stimuli ($s_i$) are grafted onto real-world elements ($S_i$) in order to assess the state of memory processes in scene formation. Priming effects act as a signal that reflects higher-level grouping. “Real-world” arrows indicate locations in sequence where temporal integration is strong; “priming stimuli” arrows indicate locations where priming is strong.

In the present technique, sequential prime and probe stimuli ($s_i$) are strategically placed so that they occur either interior to the same temporal group (e.g., $S_2$ and $S_3$) or on either side of a temporal group boundary ($S_3$ and $S_4$). If the associative memory operations involved in priming are synchronized with those of scene formation, then we would expect to see priming effects change depending upon the location of primes and probes relative to higher-level boundary cues. Prime and probe stimuli placed interior to the same temporal group should be strongly associated--that is, priming should appear as it typically does during a trial block. However, if associative memory operations are weaker crossing temporal group boundaries, then probes placed after boundaries should show a diminished effect of the primes that preceded them. In this way, the state of priming might reflect where boundaries occur between temporal groups.

The empirical effort in this article is largely concerned with showing that boundary formation can indeed be studied using priming, and with considerable experimental control. Our technique both allows and requires rigorous control over the temporal construction of events. Because of the difficulty of grafting psychophysical stimuli onto a real-life scene, it is not particularly well suited for studying videos of real-world events. The events studied using our technique are simpler and can be completely characterized, allowing us to understand the psychophysics that underlie their perception. In this sense our technique is not much different from those normally used in psychophysics, where impoverished stimuli are substituted for real-world elements in order to bring experimental control and rigor to bear on the problem under study.

## Irrelevant Feature Priming

The form of priming used in the present work, sometimes known as irrelevant feature priming, extends the simple repetition priming relationship (i.e., a speeding of response when the same stimulus is encountered multiple times; e.g. Hyman, 1953) by adding an additional irrelevant feature[1]. What we and others have found is that people bind up the irrelevant and relevant features in terms of congruence of change. Studies in a variety of experiments involving multiple features and modalities have produced similar patterns of results (e.g., Feinstein, 2006; Hommel, 1998; Huang, Holcombe, and Pashler, 2004; Huettel & Lockhead, 1999; Notebaert & Soetens, 2003). The basic data pattern is an interaction illustrated in Figure 2. Specifically, people are fastest in their responses if both features change from trial $i$ to trial $i$+1 or if both features remain constant (Figure 2, points 1 and 4). If one feature changes and one

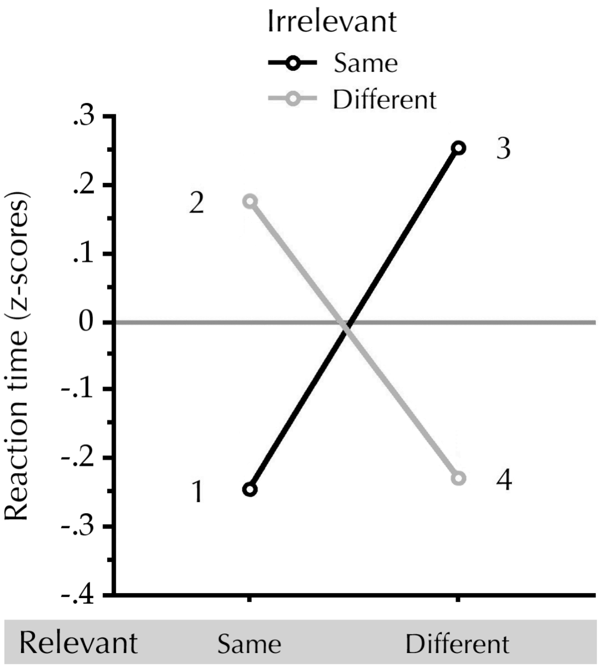

*Figure 2.* Illustration of an irrelevant feature priming interaction. Changes in irrelevant features affect the manner in which participants respond to relevant features. When the relevant feature and the irrelevant feature both repeat from trial n to trial n+1, or when they both change, participants respond quickly (points 1 and 4). When only one of these features changes, participants respond more slowly (points 2 and 3).

remains constant there is a substantial reaction time (RT) cost (points 2 and 3).

Theoretical attempts to explain irrelevant feature priming distinguish between decisional and perceptual recency effects (Jones, Love, & Maddox, 2006; Kleinsorge, 1999; Huang, et al.; Huettel & Lockhead, 1999; Notebaert & Soetens, 2003; Stewart, Brown, & Chater, 2002). Decisional recency effects are often framed in terms of stimulus predictability, and as such may be thought to resemble the predictive event models proposed by EST. Typically, when asked to predict the next stimulus in a series, people show a greater-than-chance likelihood of predicting that the new stimulus will repeat the preceding one (Bertelson, 1965; Hyman, 1953; although this does not hold true during runs where the same stimulus is repeated several times, Jarvik, 1951--this is the Gambler's fallacy). However, decisional biases appear to be modulated by the perceptual similarity between current and previous stimuli (Bertelson). When perceptual similarity is high, decisional recency effects remain potent, with people showing biases in favor of the previous response. However, when perceptual similarity is low, this bias weakens or is even replaced by a bias in favor of the alternate response. These two tendencies essentially account for the crossed interaction that we observe in irrelevant feature priming.

The present work uses the magnitude of the irrelevant feature priming interaction to indicate the strength of moment-to-moment temporal integration. Strong irrelevant feature priming, manifested as a strong interaction, demonstrates the active functioning of temporal integration and would be expected to occur when stimuli occur within the same temporal group (e.g., $S_1$ to $S_2$ and $s_1$ to $s_2$). Weaker priming is manifested as a reduction of the strength of the interaction and would be expected to occur when stimuli straddle temporal group boundaries (e.g., $S_3$ to $S_4$ and $s_3$ to $s_4$). At present, the work is developed only so far as to use the technique as a dichotomous meter, showing temporal organization to be in one of two states, "grouped" or "not grouped." However, the data offer preliminary indications that the strength of priming effects may be correlated with grouping strength.

## Summary of Experiments

In the experiments presented below, we had two primary goals. First, we evaluated the utility of the proposed method by examining priming interaction strength in a case of overt temporal grouping with high face validity: rhythmic meter. Then, after having justified the use of the technique to measure temporal grouping, we deployed the technique more broadly to determine what structure people impose upon other types of temporally spaced stimuli, focusing on parametric manipulations of rhythm, spatial transformations in visual and auditory modalities, and culminating in a more abstract instance of temporal grouping involving shape identity and boundary ownership. The experiments serve to validate the technique, to reveal new insights into the cues governing temporal grouping, and to provide evidence for the refinement of existing theories of event segmentation.

## Experiments: Rhythm

Our initial study served as a proof of concept. Rhythmic grouping was selected as the test bed for our priming method because it represents a potent example of temporal grouping with strong face validity. Rhythmic proximity creates a clear sense of what goes with what that often cannot be overturned even with great effort (which is why musical and also spoken phrases are frequently separated by pauses). Although we are most accustomed to considering rhythm as an auditory phenomenon, a sense of rhythm can be created in the visual modality as well. In the present study, we embedded a standard priming task within an overarching rhythmic experience by systematically altering the rate of presentation. Trials were presented in pairs, followed by long pauses, giving the impression of a type of pulse (trial-trial-*rest*...), where each pair creates its own temporal group.

## General Method

**Participants.** Participants (ages 18 to 25) were recruited from a pool of introductory psychology students. They received course credit for their participation. All participants reported having normal vision and/or hearing, as required for each task. Participants did not overlap across experiments.

**Design.** All experiments were continuous-responding two-alternative forced-choice reaction time tasks. Stimuli varied on two features, each of which had two possible levels. Participants responded to a single relevant feature by key press. The other feature was irrelevant. This produced a 2 × 2 matrix of stimulus features, for a total of four possible irrelevant feature priming stimuli. All stimuli appeared the same total number of times during any block of the experiment; however, the order in which they appeared was randomized. There was no overt cueing; rather, each stimulus served as both prime (for the following stimulus) and probe (for the one that preceded it).

When not otherwise specified, priming stimuli were circles that varied on the dimensions of color and position. Colors were red and blue. Positions were high and low. With the exception of rhythm experiments (Experiments 1-3b), color-position stimuli were presented in either the top or bottom portion of a divided vertical rectangle frame. Unless otherwise noted, ITIs were 250 ms.

**Procedure.** Participants responded to the relevant feature by key press (1 or 2 on a standard keyboard number pad with the first and second fingers of the right hand). Sounds were presented via headphones. Participants in these experiments were given the opportunity to review auditory stimuli prior to practice sessions when categories involved relative relationships (e.g., “soft” and “loud”). They were instructed to respond as quickly as possible while maintaining a reasonable level of accuracy (85%-95%). In all experiments participants demonstrated an ability to achieve the desired accuracy level in one to two practice blocks before completing the test block. Participants who were not able to respond within the desired level of accuracy were not included in analyses.

**Analysis.** Individual participant data were inspected, and trials were removed if reaction times exceeded three standard deviations from the mean, or if they were shorter than 200 ms, as these trials typically represent outliers. Additionally, since we were only interested in sequential dependencies--that is, the agreement or disagreement of features across trials--nonsequential effects for the relevant and irrelevant feature (e.g., faster responses to blue stimuli) were not of interest and were also removed.

Participants showed differences in their mean reaction times as well as in their variability. Each participant’s reaction times were thus converted to z-scores in order to reduce the effect size to the overall level of variability. Each participant’s data were divided into cells based on relevant feature repetition (i.e., repetition versus alternation), irrelevant feature repetition, and temporal grouping condition. In the experiments reported here, there were four possible transition combinations for the relevant and irrelevant features: both features could repeat, both features could alternate, or one feature could repeat and the other could alternate. Grouping conditions varied across experiments, but in most cases there were two: within-group and across-boundary. This resulted in a total of eight cells ($4 \times j$, where $j$ is the number of grouping conditions). Participants’ cell means were then compiled and tested for main effects and interactions using repeated-measures ANOVAs.

## Experiment 1: Rhythmic Pairs Proof of Concept

In Experiment 1, participants responded to the color of a circle presented with a simple visual rhythm. Trials were presented as pairs separated from other pairs by a long pause. This was achieved by alternating intertrial intervals (ITIs) between short and long, so that trials had a pulsed rhythmic feel. We expected that trials separated by a short ITI would be experienced as belonging to a single pulse group, and that long ITIs would feel like rhythmic rests separating each pair of trials from the next. Thus, trials separated by short ITIs represented the within-group condition, and those separated by long ITIs represented the across-boundary condition. The goal of this experiment was to observe whether there was any difference in sequential priming between within-group and across-boundary conditions.

It should be noted that the across-boundary condition in Experiment 1 differed from the within-group condition in several ways. The ITI in the across-boundary condition was longer. In addition, across-boundary trials contained a “rest” screen that was not seen in within-group trials, and across-boundary trials were separated by three intertrial stimuli (dot-rest-dot) rather than by one (dot only). The influence of these differences is tested separately in Experiment 2.

**Method.** Seven participants completed one block of 400 trials. In addition to color-position stimuli, intervening stimuli included small black dots and the word “rest” (see Figure 3). This experiment used short and long ITIs of 250 ms and 1500 ms, respectively. Short and long ITIs alternated every trial. Both short and long ITIs were brief enough to result in a crossed interaction pattern of priming in a standard irrelevant feature priming experiment with constant ITI.

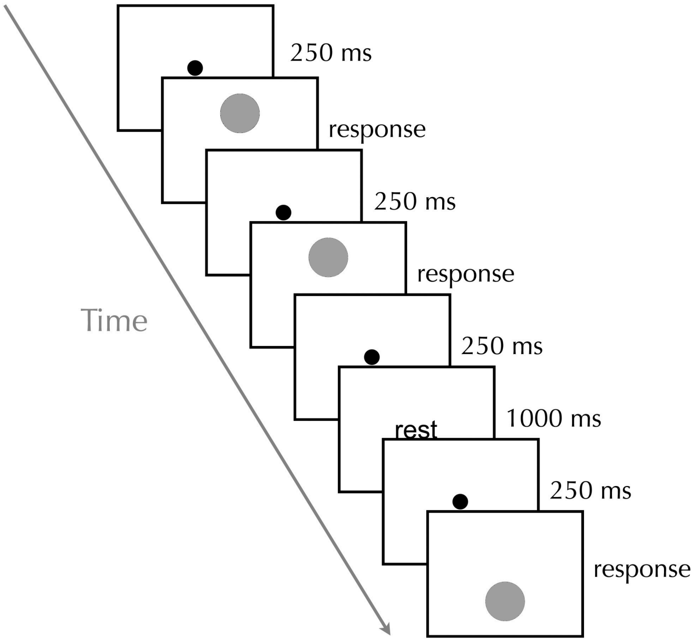

*Figure 3.* Trial sequence for rhythmic pairs experiment. Participants respond to red and blue circles appearing in top or bottom positions. Trials are bounded by alternating short and long ITIs. Short ITIs consist of a single 250-ms dot, while long ITIs consist of a 250-ms dot followed by a 1000-ms “rest” screen and another 250-ms dot.

Event grouping status was determined based on the location of a trial within the rhythmic presentation sequence by noting whether adjacent trials straddled a short (within-group) or a long (across-boundary) ITI. In order to draw attention to the timing of the experiment, fixation dots and "rest" screens appeared during ITIs. During short ITIs only the fixation dot appeared onscreen, and during long ITIs the word "rest" appeared for 1000 ms, with the fixation dot appearing for 250 ms both before and after the word.

**Results and Discussion.** In this experiment, the major question was whether participants’ response latencies would be affected by the temporal structure of the task. This was clearly the case, with across-boundary and within-group conditions showing markedly different patterns of results (Figure 4). Although several differences emerged, the most critical was a highly significant three-way interaction between color repetition, position repetition, and grouping condition, $F(1,6) = 66.22$, $p = .0002$, $\eta_p^2 = .92$. As expected, irrelevant feature priming did occur as an interaction between color repetition and position repetition, $F(1,6) = 16.93$, $p = .006$, $\eta_p^2 = .74$. Yet this interaction, which we have proposed to use as a marker of temporal integration, showed a nearly complete decoupling of the relevant and irrelevant features at the proposed boundary. This suggests that memory for the preceding stimulus was drastically reduced when trials occurred after rest boundaries (consistent with EST). What is most remarkable about this result is the simultaneity of the higher-level temporal boundary cue (rests) and the disruption of the lower-level signal (priming). This result supports the proposal that there is a connection between sequential priming and temporal grouping as we experience it in the real world. What's more, it appears that we are able to effectively use the state of sequential priming to infer the state of the higher-level system.

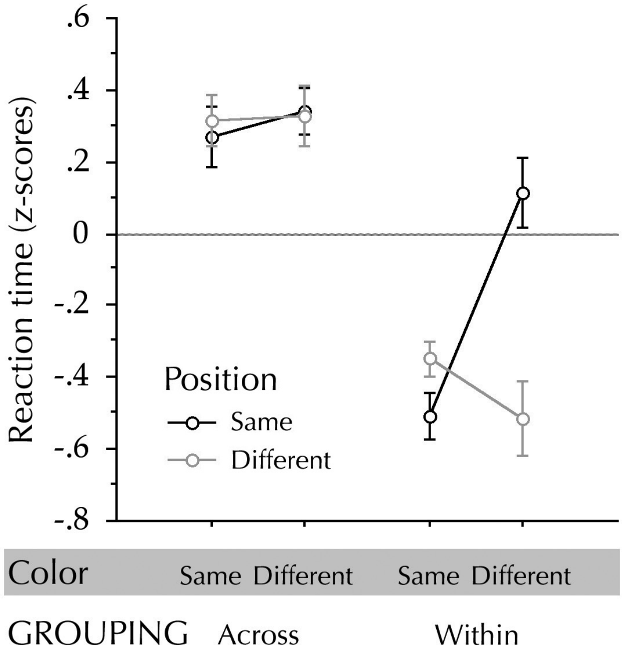

*Figure 4.* Color-position interaction as a function of rhythmic grouping (Experiment 1). Error bars represent standard error. The reduction of the irrelevant feature priming interaction in the across-boundary condition offers evidence that the perception of rhythmic grouping is accompanied by a reduction of temporal integration at boundaries.

In addition to the collapse of the interaction in the across-boundary condition, there were a few other notable effects of temporal grouping. Response latencies in the across-boundary condition were generally slower, $F(1,6) = 37.96$, $p = .0008$, $\eta_p^2 = .86$. It is not immediately evident from this experiment whether this is a general property of people's response to new temporal groups, or whether this slowing might have resulted from some other aspect of this experiment. Similar main effects arise as costs in task switching (see Monsell, 2003, for a review), although in the present study, participants' explicit task of responding to color did not change. Nevertheless, similar mechanisms may be involved in both phenomena (for instance, attention shifting or some type of reconfiguration process, Monsell). There was also an interaction between position repetition and grouping, $F(1,6) = 10.40$, $p = .02$, $\eta_p^2 = .63$. Participants showed a general tendency to respond more quickly when position alternated, $F(1,6) = 13.39$, $p = .01$, $\eta_p^2 = .69$, which was stronger on within-group trials. However, this effect appears to be largely driven by a single point (within-group trials where color changed but position did not).

### Experiment 2: Random Presentation of ITIs

Experiment 1 demonstrated that irrelevant feature priming appears to be disrupted by rhythmic boundaries. However, as noted previously, rhythmic grouping was confounded with differences in timing and intertrial stimuli. In Experiment 2, we sought to verify that the reductions in irrelevant feature priming in Experiment 1 were due to temporal grouping and not due to one of these other factors. To address this concern, Experiment 2 examined the effects of ITI duration and the intertrial stimuli used in Experiment 1 independent of rhythm.

Experiment 2 was identical to Experiment 1 in every respect except for the placement of short and long ITIs. In Experiment 2, the short- and long-ITI sequences from Experiment 1 were shuffled so that they occurred in a random order throughout the experiment. The experiment thus included long rests and the same intertrial stimuli as did Experiment 1, but it possessed no predictability or rhythmic feel. If rhythmic grouping was the driving force behind the disruption of irrelevant feature priming observed in Experiment 1, then Experiment 2, which had no rhythmic feel, should display no reduction of the irrelevant feature priming interaction.

**Method.** Nine participants completed the task. Experiment 2 was identical to Experiment 1 except for the order in which short and long ITIs occurred. Although the total number of short and long ITIs was held constant, they were shuffled to appear at random times within the experiment. Trials were categorized into two conditions according to whether they were preceded by a short or long ITI (analogous to the "within-group" and "across-boundary" conditions in Experiment 1).

**Results and Discussion.** It is obvious at a glance that Experiment 2 did not produce the same pattern of results observed in Experiment 1 (Figure 5). While Experiment 1 showed a strong three-way interaction between color repetition, position repetition, and grouping, Experiment 2 did not. Though there was clear evidence of a color-position interaction, $F(1,8) = 35.03$, $p = .0004$, $\eta_p^2 = .81$, there was no evidence that this interaction was weakened by the intertrial "rest" sequence from Experiment 1 in the absence of rhythmic presentation. The event partitioning that occurs in rhythmic structure appears to be required in order for people to show reductions in irrelevant feature priming. This further suggests that the sequential priming signal used in the present technique is an effective means of indicating the state of higher-level temporal grouping.

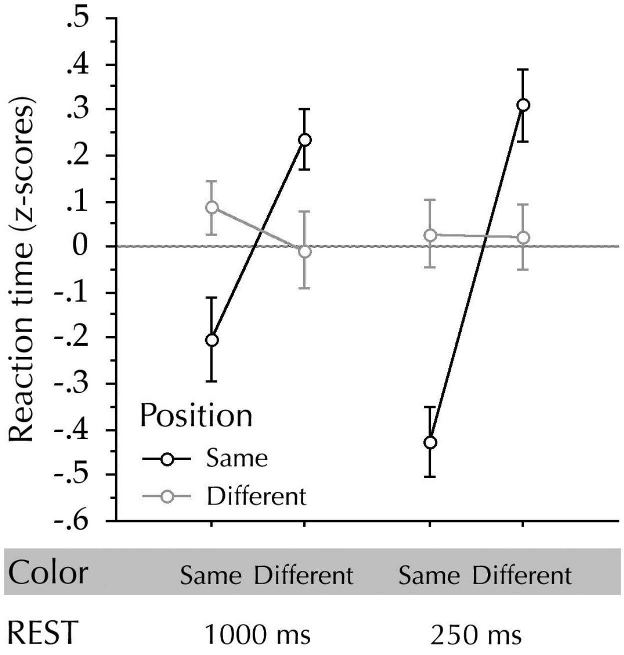

*Figure 5.* Color-position interaction as a function of preceding delay (Experiment 2). Error bars represent standard error. There was no reduction of irrelevant feature priming in the 1000-ms ITI condition, suggesting that priming will modulate only when there is grouping.

### Experiments 3a & b: Rest Duration

Having demonstrated that irrelevant feature priming does respond to boundaries in a case of overt temporal grouping, we were then able to apply the technique toward our goal of revealing how people group more ambiguous stimuli. We began by continuing to test rhythmic grouping but systematically manipulating the timing of the rhythm in order to explore the limits of what is rhythmically groupable. Experiment 1 contained 1000-ms " rest" screens which were utilized to separate pairs of trials. In Experiments 3a and 3b, we manipulated the duration of this screen in an attempt to determine how brief a "rest" is required in order to create a sense of rhythmic grouping.

It is worth noting, however, that rhythm is formed on the basis of timing ratios. A whole note is not defined as a precise unit of time but as it relates to the beat of the music. It is important to acknowledge, then, that what we are testing is not a lower threshold on rhythmic feel generally, but rather the lower threshold of rhythmic feel in an experiment with this exact sequence, and where intertrial dots appear for 250 ms and where an average reaction time is about 400 ms.

**Experiment 3a: Rest duration–400 ms.** In Experiment 3a, rest duration was more than halved from the 1000 ms used in Experiment 1 to 400 ms. This duration was selected because it was roughly equal to the average reaction time of participants in Experiment 1. In this series of experiments, the “beat” of the rhythm may be thought to be set by the participant’s response time, so using a rest that lasts for one such beat is a rational starting place. Experiment 3a is identical to the original pulsed rhythm experiment, but with rest screens appearing for 400 ms rather than 1000 ms.

***Method.*** Eight participants completed the task. This experiment was identical to Experiment 1 except for the fact that “rest” screens appeared for 400 ms rather than 1000 ms. Total ITI was 900 ms.

***Results and Discussion.*** Experiment 3a produced results remarkably similar to those of Experiment 1 (Figure 6). Participants showed color-position interactions, $F(1,7) = 15.24$, $p = .006$, $\eta_p^2 = .69$, that were strong in the within-group condition and significantly reduced in the across-boundary condition, $F(1,7) = 21.17$, $p = .003$, $\eta_p^2 = .75$. They also showed the same overall slowing in the across-boundary condition that was observed in Experiment 1, $F(1,7) = 6.17$, $p =.04$, $\eta_p^2 = .47$. This suggests that participants in Experiment 3a experienced temporal grouping much the same as did participants in Experiment 1. It seems that rest duration does not have a great deal of impact on temporal grouping beyond establishing one group as separate from another. Once a sufficient interval for grouping has been achieved, the specific rest duration does not notably affect the pattern of results.

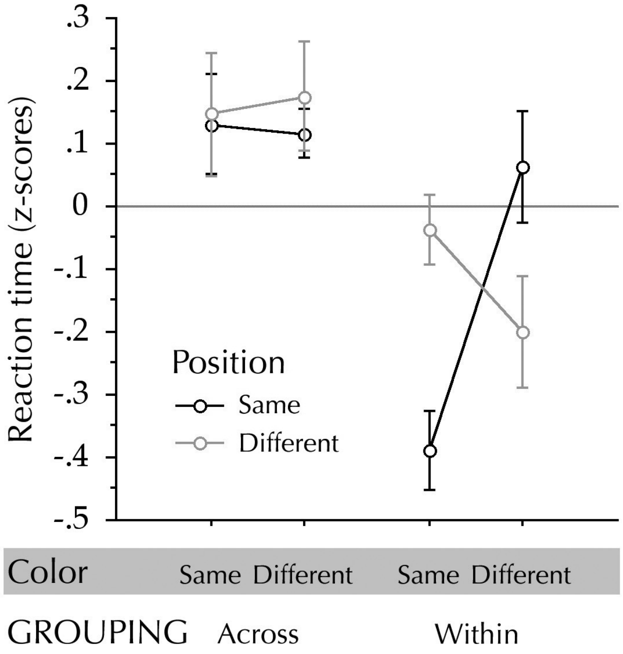

*Figure 6.* Color-position interaction as a function of rhythmic grouping (with 400-ms rest; Experiment 3a). Error bars represent standard error. There was a reduction of irrelevant feature priming in the across-boundary condition, suggesting that the relatively short 400-ms rest succeeded in giving rise to the perception of grouping.

That being said, the results of Experiments 1 and 3a are by no means identical. For instance, the color-position interaction appears stronger in Experiment 3a. These differences may reveal other sensitivities of the irrelevant feature priming interaction, but they are not the focus of the present work.

**Experiment 3b: Rest Duration–250 ms.** Experiment 3a showed strong reductions of irrelevant feature priming when rest duration was shortened to 400 ms. In Experiment 3b the duration was shortened even further from 400 ms to 250 ms, the same as the duration of one of the interstimulus dots. This duration is equivalent to little more than half of an average reaction time.

***Method.*** Eight participants completed the task. This experiment was identical to Experiment 1 except for the fact that “rest” screens appeared for 250 ms rather than 1000 ms. Total ITI was 750 ms.

***Results and Discussion.*** Experiment 3b showed none of the effects associated with temporal group boundaries observed in Experiments 1 and 3a (Figure 7). Participants did demonstrate irrelevant feature priming, $F(1,7) = 15.33$, $p = .006$, $\eta_p^2 = .69$, but these did not appear to be reduced at any point in the sequence. Nor were responses slowed in the across-boundary condition. This evidence suggests that people did not experience a sense of temporal grouping when rest duration was shortened to 250 ms. Participants' response latencies in Experiment 3b showed greater variability as well, perhaps because long ITIs lost their coherence as boundary cues and caused trial presentation to instead appear inconsistent and unpredictable.

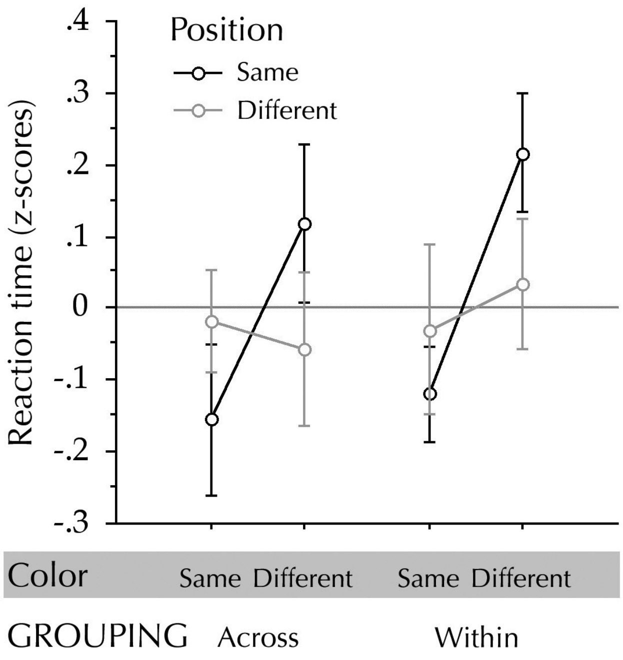

*Figure 7.* Color-position interaction as a function of rhythmic grouping (with 250-ms rest; Experiment 3b). Error bars represent standard error. There was no reduction of irrelevant feature priming in the across-boundary condition, suggesting that the 250-ms rest did not give rise to the perception of grouping.

These results would appear to indicate that the lower threshold of rest duration for rhythmic grouping (in experiments with this particular sequence and element timing) is somewhere between 250 and 400 ms, which roughly corresponds to the average reaction time of participants in color-position tasks. This experiment demonstrates that it is not sufficient for a rest to merely last longer than a non-rest in order to give rise to temporal grouping. It must meet or exceed a certain duration, possibly that of the "beat" established by a participant's own reaction times.

## Experiments: Spatial Transformations

The preceding experiments demonstrate that strong rhythmic group boundaries appear to be accompanied by a weakening of temporal integration, and that this can be used to reveal how people experience grouping as physical parameters are manipulated. This weakening is consistent with a resetting of memory at boundaries, as proposed by EST. It also justifies the extension of the technique to other instances of temporal grouping. While there exist an indefinite number of potential temporal grouping cues, we chose to begin with those derived from kinematics and spatial displacement, which have been studied by a number of other event researchers (Hard, Tversky, & Lang, 2006; Maguire, Brumberg, Ennis, & Shipley, 2011; Newtson, Engquist, & Bois, 1977; Zacks, 2004). Previous research has found that explicitly labeled boundaries often correspond to movement bursts in visual scenes, consistent with the predictions of both Newtson's theory and EST. Using spatial transformations as temporal grouping cues offered an opportunity to compare implicitly identified boundaries with these previous explicit results. An additional benefit of using these cues was that they afforded a great deal of modal flexibility, allowing us to test similar cues in multiple dimensions and using both visual and auditory stimuli.

### i. Motion Change: Experiments 4a & 4b

Experiments 4a and 4b examined whether changes in the direction of motion would be perceived as strong temporal group boundaries. Experiment 4a explored the effects of consistent, predictable direction changes upon sequential priming, while Experiment 4b involved more dramatic, unpredictable changes in direction as well as speed. One challenge of this series of experiments is that spatial position served two roles, both as a grouping cue (i.e., overall stimulus motion) and as an irrelevant feature (i.e., position of the colored circle). In order to disambiguate overall stimulus motion from position as an irrelevant feature, we presented motion at two distinct scales. The colored circles used for irrelevant feature priming were presented on a small scale, appearing either in the top or bottom portions of a rectangular frame roughly twice their size. These positions were separated by only a few degrees (see, e.g., Figure 8). The frame served to preserve a clearly defined sense of relative "top" and "bottom" regardless of how the frame itself moved. The motion of the frame, by contrast, occurred on a larger scale, in most cases covering distances many times the size of the frame. It was on this larger scale that temporal groups were defined.

**Experiment 4a: Predictable Direction Change.** Experiment 4a tested whether predictable, repeated changes in motion direction give rise to the perception of temporal grouping. In this experiment, the frame moved along a diamond-shaped path in a smooth, continuous manner (see Figure 8). Trial onsets occurred either where the frame was moving in a straight line down one of the sides of the diamond, or where the direction of motion was about to change at the vertices. This allowed us to compare a potential within-group condition (where motion direction did not change) with a potential across-boundary condition (where it did). The principal question was whether participants would experience the diamond as four distinct paths, or as a single unified path.

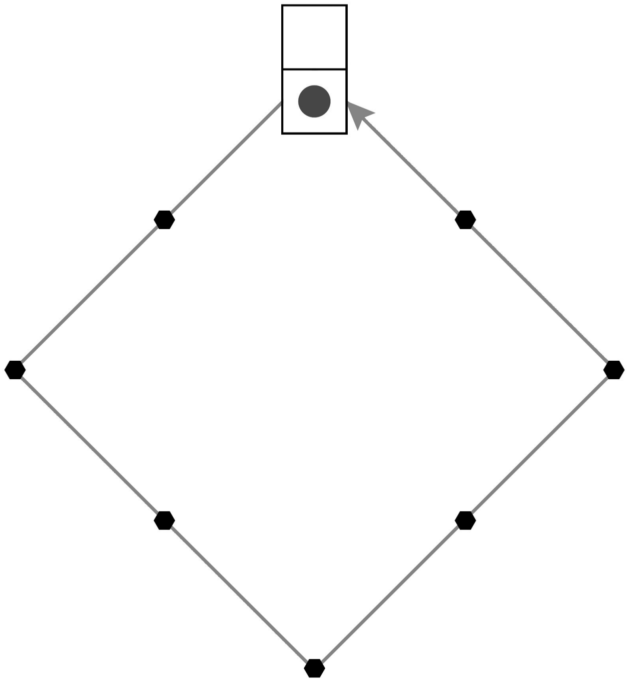

*Figure 8.* Trial sequence for predictable direction change experiment. Participants responded to stimuli as stimulus frame moved continuously in a diamond pattern. Black hexagons indicate trial onset points.

***Method.*** Eight participants completed a 400-trial block. The stimlus frame moved in a continuous counterclockwise diamond pattern around the center of the screen. A trial onset occurred when a prime/probe appeared inside the moving frame. Trials could occur either at the midpoint of one of the diamond's sides (when the frame was moving in the same direction as on the previous trial), or at a vertex (when the frame was about to move in a different direction from the previous trial). Because the direction of motion on the previous trial was the same, midpoint-onset trials were expected to act as within-group trials. Vertex-onset trials were expected to act as across-boundary trials because the direction of motion changed across trials.

Priming stimuli appeared inside the rectangle at trial onset positions and remained onscreen until either the subject responded, or the rectangle reached the next trial onset point. 1700 ms was allotted between these points, and participants hardly ever missed a response. Once a response was registered, the priming stimulus would disappear and the empty rectangle would continue to slide in the same direction until reaching the next onset point.

***Results and Discussion.*** There was no evidence in this experiment that changes in the direction of motion caused people to perceive trials as belonging to different temporal groups (Figure 9), which runs counter to Newtson's predictions that boundaries will occur at points of noticeable change (although boundaries still may have occurred that were too weak to be detected using our technique). The color-position priming interaction was strong throughout, $F(1,7) = 48.10$, $p = .0002$, $\eta_p^2 = .87$, and there was no significant reduction of its strength in across-boundary conditions. We also failed to observe any slowing in the across-boundary condition. These results suggest that what participants perceived was the overall path of motion, rather than four temporal groups consisting of different directions of motion. However, it is possible that this perception of the path as unified may have been strengthened by the fact that the frame outlined a geometric figure, with the diamond shape of the path providing an artificial sense of unity across path segments that normally would have been perceived as distinct. This possibility was explored in Experiment 4b.

**Experiment 4b: Unpredictable speed and direction change.** Experiment 4b again explored direction change as a potential temporal boundary cue. However, in response to concerns that the unified diamond shape of the path in Experiment 4a may have diluted the potency of direction changes, the motion in Experiment 4b was determined randomly. The stimulus frame thus glided unpredictably in various directions across the screen. Like Experiment 4a, Experiment 4b contained two types of trials: those in which the frame continued the same speed and direction of motion as in the preceding trial, and those in which the direction of motion (and also the speed) changed. The latter trial type was also accompanied by a percussive sound in order to draw attention to the change and to enhance the sense of ricochet (as in Watanabe & Shimojo, 2001[2]). If the failure to interrupt irrelevant feature priming observed in Experiment 4a was mediated purely by path shape or predictability, Experiment 4b should show greater disruption at direction-change boundaries.

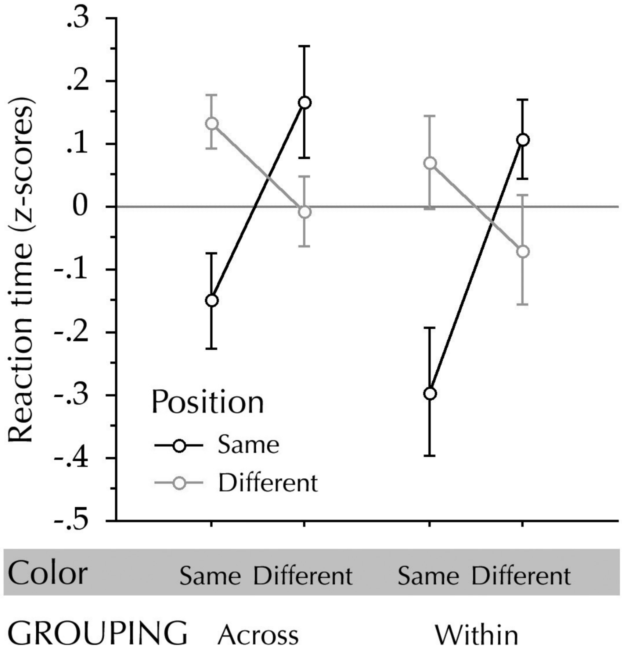

*Figure 9.* Color-position interaction as a function of predictable motion-based grouping (Experiment 4a. Error bars represent standard error. There was no reduction of irrelevant feature priming in the across-boundary condition, suggesting that predictable direction change did not give rise to the perception of grouping.

***Method.*** Ten participants completed a 400-trial block. The stimulus frame followed a continuous path of motion that changed every two trials. On these trials, a new speed and direction was chosen randomly every two trials by drawing from a set of X and Y incrementation values. Changes were dramatic and noticeable. In addition, every change in speed and direction was accompanied by a brief percussive sound. A new trial was presented every 1500 ms. This was ample time for participants to make a response, and hardly any misses occurred. Once a response was registered, the priming stimulus would disappear and the empty frame would continue to slide in the same direction until the time limit was reached.

***Results and Discussion.*** The results of Experiment 4b are presented in Figure 10. While these results are not identical to those obtained in Experiment 4a, they do show considerable similarity on one key feature--namely, that the shape of the interaction does not significantly change from the within-group condition to the across-boundary condition. This shows that participants do not appear to have perceived the random motion change in Experiment 4b as creating temporal groups. It may be that the present method was unable to resolve weak grouping that would be detected using other techniques such as explicit labeling; nevertheless, this experiment offers compelling evidence that observers' primary perceptual experience is of the path itself.

There were differences in the pattern of the color-position interaction in both grouping conditions. While an irrelevant feature priming interaction was present, $F(1,9) = 26.33$, $p = .0006$, $\eta_p^2 = .75$, its overall shape was less cross-like than in previous experiments. In this experiment, position repetition did not appear to have much of an effect when color alternated. There was also a general benefit for position repetition, $F(1,9) = 10.05$, $p = .01$, $\eta_p^2 = .53$. Although it is difficult to absolutely determine what caused these differences, they may have resulted from participants' inability to predict the motion of the frame.

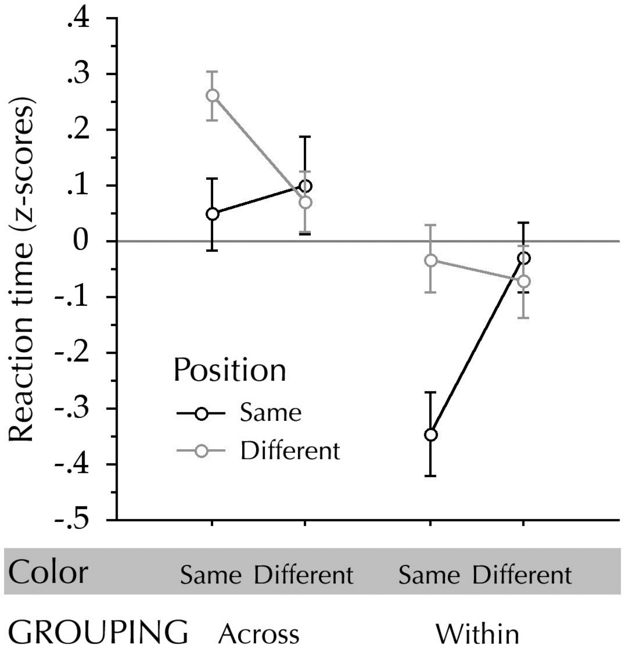

*Figure 10.* Color-position interaction as a function of unpredictable motion-based grouping (Experiment 4b). Error bars represent standard error. There was no reduction of irrelevant feature priming in the across-boundary condition, suggesting that unpredictable direction change did not give rise to the perception of grouping.

Despite the lack of evidence for temporal boundaries mediated by direction change cues, participants were not altogether oblivious to the change. There was a general slowing after the frame changed direction, $F(1,9) = 10.92$, $p = .009$, $\eta_p^2 = .55$, a pattern we have previously associated with temporal group boundaries. It is possible that participants were faster on within-group trials because they were able to predict where the stimulus would appear (as in cueing tasks; Posner, Snyder, & Davidson, 1980). There was also an interaction between color repetition and grouping, $F(1,9) = 12.00$, $p = .007$, $\eta_p^2 = .57$. Color repetition benefits were greater when direction did not change.

**Discussion of direction-change experiments.** The results of Experiments 4a and 4b suggest that people did not perceive strong temporal grouping on the basis of changes in direction; that is, each segment does not constitute a new event. Participants perceived a unified path regardless of motion predictability. This finding appears inconsistent with explicit labeling studies that have shown boundaries at points of acceleration and requires some explanation. We believe that acceleration boundaries in explicit studies may have resulted from the tacit understanding of what constituted a boundary in those studies. A participant in a Newtson task must trust that in most cases videos will contain boundaries of some sort. If the most natural level of boundary is not present within a video, then the participant may resort to reporting a weaker temporal change signal because that is his task. Yet because the implicit priming technique presented here does not involve any conscious demand to produce segmentation, we are able to use it to reveal the natural temporal groups that people form as they experience temporal flux. In this case, there are no boundaries--the path remains unified.

However, an alternate explanation is that differences in the results of explicit techniques and the current implicit technique may emerge from differences in the regularity of stimulus motion. Although Experiment 4b involved random changes of speed and direction, these changes did occur at regular intervals. It is possible that this regularity may have biased perceivers toward viewing the motion of the stimulus as a sort of process, whereas objects with intermittent changes in motion (as in Zacks, 2004) may evoke a greater sense of agency. This sense of an intervening force acting on objects may drive users to label changes as boundaries.

## ii. Spatial Displacements

We next turned our attention to boundaries formed by spatial displacement. Physical location is a potent static grouping cue, but here we were concerned with discovering whether its grouping qualities would extend to the temporal domain. Experiments 5-7 shared the same basic structure. In each case, prime/probe stimuli appeared twice in one location, and then twice in a second location. We tested three types of locations: lateral displacements, perceived displacements in depth, and auditory displacements. We expected to see groups defined by these changes in location, with spatial displacements causing reductions in irrelevant feature priming.

**Experiment 5a: Lateral displacement, small distance.** One of the simplest possible spatial relationships is juxtaposition in the same plane. In Experiment 5a, stimuli appeared on either the left or right side of the screen a small distance apart.

***Method.*** Seven participants completed a 400-trial block. Stimuli could appear in either left or right locations on the screen, separated by a distance of 2 cm (the approximate width of the stimulus). Stimuli appeared twice in the first location, then twice in the second location.

***Results and Discussion.*** Experiment 5a showed the signature data patterns associated with temporal grouping (Figure 11), suggesting that trials were grouped by location and that spatial displacement does act as a temporal grouping cue. There was a significant reduction of the irrelevant feature priming interaction in the across-boundary condition, $F(1,6) = 7.20$, $p = .04$, $\eta_p^2 = .55$, and, as in Experiments 1 and 3a, participants responded more slowly on trials following boundary cues, $F(1,6) = 55.62$, $p = .0003$, $\eta_p^2 = .90$. In addition, participants showed weaker color repetition priming in the across-boundary condition, $F(1,6) = 41.16$, $p = .0007$, $\eta_p^2 = .87$.

Despite this evidence of temporal grouping, irrelevant feature priming also showed an unexpected main effect of color repetition. Unlike previous experiments, there was a large color repetition benefit both in across-boundary and in within-group conditions, $F(1,6) = 23.72$, $p = .003$,

$\eta_p^2$ = .80. Although the expected color-position interaction was present, $F(1,6) = 10.42$, $p$ =.02, $\eta_p^2$ = .64, it appeared weaker due to the pronounced color repetition effect. Strong repetition effects have previously been associated with experiments that involve high information content (such as an overabundance of alternatives; Hyman, 1953), and the existence of such an effect in the present experiment may indicate that participants perceived stimuli as ambiguous in some way.

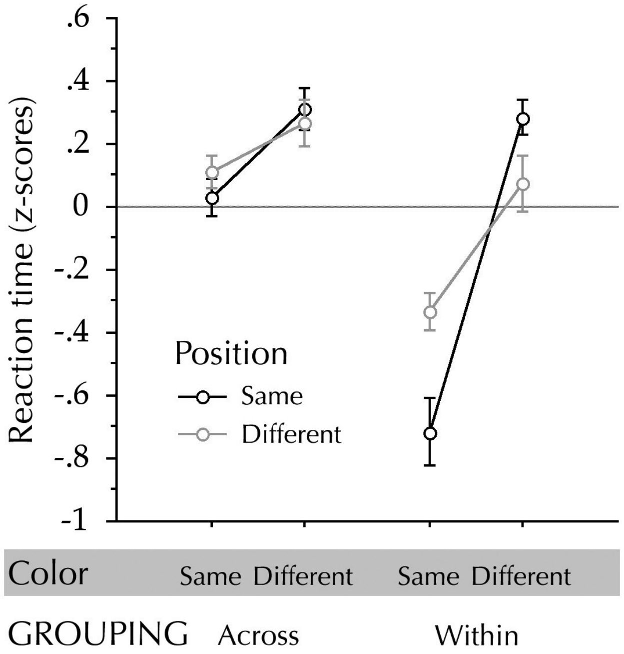

*Figure 11.* Color-position interaction as a function of grouping by small lateral spatial displacement (Experiment 5a). Error bars represent standard error. There was a slight reduction of irrelevant feature priming in the across-boundary condition, suggesting that spatial displacement did give rise to the perception of grouping. However, this effect is obscured by a strong color repetition benefit.

A potential culprit is the double use of position. In this experiment, relative position within the frame served as a prime/probe stimulus feature (top versus bottom), while the location of the frame itself served as a grouping variable (left versus right). The close proximity of the two frame locations might have caused them to appear to participants as four possible alternatives. If positional ambiguity was the driving force behind the large main effect observed in the within-group condition in Experiment 5a, it may be possible to reduce this main effect by reducing the perceived ambiguity in the experiment. This was the goal of Experiment 5b.

In addition to the effects discussed previously, there were also two effects relating to the side of the screen on which the frame and prime/probe stimuli appeared. Responses were faster for stimuli that appeared in the right location of the screen, $F(1,6) = 5.98$, $p$ =.05, $\eta_p^2$ = .50 (rightward biases are reviewed in Robertson, 2004, pp. 69-71). There was also an interaction between grouping and location, $F(1,6) = 12.92$, $p$ = .01, $\eta_p^2$ = .68. Within-group latencies were reduced when stimuli appeared in the left screen location.

**Experiment 5b: Lateral displacement, large distance.** Experiment 5a provided evidence that spatial displacements are perceived as temporal group boundaries, but it also showed an unexpected main effect for color repetition which may have resulted from positional ambiguity. In Experiment 5b we sought to reduce this ambiguity by increasing the physical distance between stimulus locations.

***Method.*** Seven participants completed the task. This experiment was identical to Experiment 5a except for the fact that locations were separated by a distance of 9.5 cm (roughly five stimulus widths).

***Results and Discussion.*** In the previous experiment (Experiment 5a), we observed a three-way interaction between color repetition, position repetition, and location-defined grouping that was somewhat obscured by a strong main effect for color repetition. In Experiment 5b, we attempted to generate a cleaner pattern of results by more clearly distinguishing relative prime/probe position from global frame location. As Figure 12 shows, the manipulation appears to have been successful.

Despite a lingering main effect for color repetition, $F(1,6) = 9.53$, $p = .02$, $\eta_p^2 = .61$, there was a highly significant effect of grouping upon the color-position interaction, $F(1,6) = 15.72$, $p = .007$, $\eta_p^2 = .72$. Participants also showed the overall slowing in the across-boundary condition that has been observed in previous experiments, $F(1,6) = 29.18$, $p = .002$, $\eta_p^2 = .83$, as well as reduced color repetition priming in the across-group condition, $F(1,6) = 9.06$, $p = .02$, $\eta_p^2 = .60$. The overall color-position irrelevant feature priming interaction was present as well, $F(1,6) = 7.59$, $p = .03$, $\eta_p^2 = .56$. These results confirm the effectiveness of spatial displacement as a temporal grouping cue.

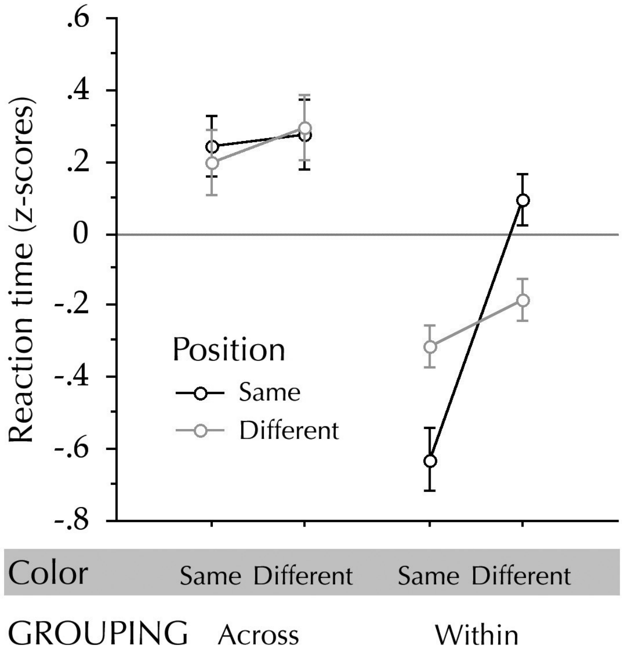

*Figure 12.* Color-position interaction as a function of grouping by large lateral spatial displacement (Experiment 5b). Error bars represent standard error. Increasing interstimulus distance appears to have resulted in a stronger reduction of irrelevant feature priming in the across-boundary condition and clear evidence of a grouping percept.

This result also further illustrates the sensitivity of the irrelevant feature priming technique. By increasing physical distance between stimuli, we were able to show a corresponding change in the strength of the decoupling of relevant and irrelevant features. This result leads us to believe that the technique may ultimately be employed to render boundary formation as existing on a continuum, rather than as either existing or not existing. This extension would further differentiate the present technique from previous techniques that rely upon binary outcomes (for instance, button presses). In addition, this result is consistent with a stimulus position ambiguity explanation for the large color repetition effects observed in Experiment 5a. By increasing the distance between stimuli, it appears that global location (as a grouping variable) was more clearly distinguished from relative position (as an irrelevant feature).

**Experiment 6a: Displacements in depth–Occlusion.** Experiments 5a and 5b showed that abrupt lateral displacements appear to give rise to the perception of temporal grouping. In Experiments 6a and 6b, we attempted to extend those results to the dimension of depth. These experiments involved the illusion of depth created using the monocular depth cues of occlusion and shading. Because no actual stimulus movement is required, these cues emphasize the role the viewer's interpretation of visual space plays in temporal grouping.

The first depth experiment relied entirely upon occlusion to indicate changes in depth. It featured a large rectangle which slid from off-screen to occlude the previous stimulus in the background plane. This rectangle would remain onscreen for two trials (with trials now ostensibly occurring in the foreground plane), then slide back down to allow the next two trials to occur in the background plane. Our prediction was that if the displacement was perceived (and it formed a boundary), the experiment should show results similar to those using lateral displacements (5a and 5b).

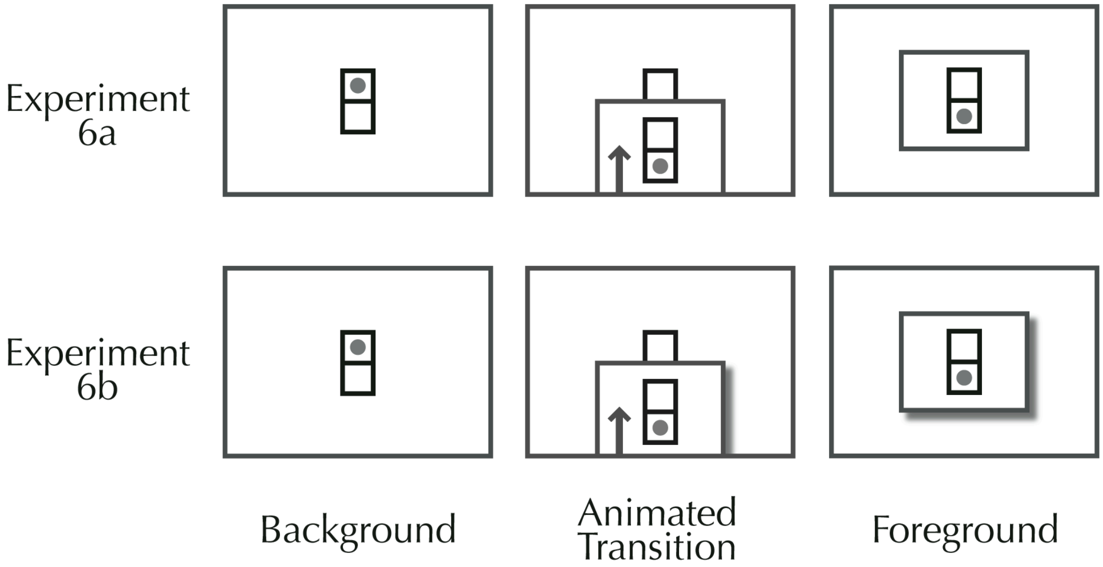

*Figure 13.* Sample "background" and "foreground" stimuli for experiments involving spatial displacement in depth (Experiments 6a and 6b). Experiment 6a (top) involved only occlusion cues, which occurred during trial transitions, whereas Experiment 6b (bottom) also included a drop shadow to enhance the sense of depth, which remained onscreen during trials. A sequence comprised four trials. Between the second and third trials, a larger rectangle carrying the next stimulus would slide up from offscreen to occlude the empty stimulus frame from the preceding trial. After two trials, the rectangle would slide back offscreen revealing the "original" stimulus frame.

***Method.*** Six participants completed a block of 400 trials. A full experiment sequence spanned four trials. Two trials occurred before the appearance of the occluding rectangle (Figure 13, top). After the second trial, a large, blank occluding rectangle carrying an empty frame (that is, the divided rectangle containing no priming stimulus), slid quickly upward from the bottom of the screen, occluding the previous frame. The occluding rectangle remained onscreen for the next two trials, after which it (and its empty frame) slid downward to reveal the "original" frame. This sequence repeated throughout the course of the experiment. Animations had the same duration as within-group ITIs (400 ms). This was longer than the standard ITI used in other visual experiments because 250-ms animations were too fast to be easily comprehended.

***Results and Discussion.*** The present experiment failed to produce compelling evidence of temporal grouping (Figure 14). Although there was an overall slowing in the across-boundary condition (possibly due to distraction or by the occlusion animation), $F(1,5) = 28.74$, $p = .003$, $\eta_p^2 = .85$, irrelevant feature priming remained strong throughout, $F(1,5) = 25.16$, $p = .004$, $\eta_p^2 = .83$, with no significant reductions. This may indicate that displacements in depth serve as weaker group boundaries than do lateral displacements. However, it may also be that the sense of depth was not sufficiently established. Depth cues only appeared in the animated transitions between trials. If participants were able to ignore the moment of occlusion, there was little evidence that one stimulus should be perceived as belonging to a different plane from another. Additional cues to magnify the sense of displacement between the two planes might produce stronger grouping. This was explored in Experiment 6b.

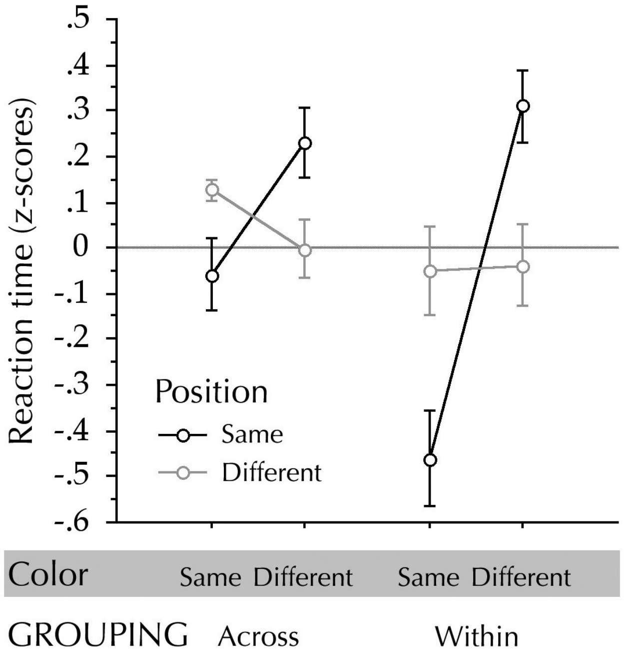

*Figure 14.* Color-position interaction as a function of grouping by spatial displacement in depth when depth was illustrated only by occlusion cues (Experiment 6a). Error bars represent standard error. There was not a statistically significant reduction of irrelevant feature priming in the across-boundary condition, suggesting that this experiment did not produce a strong grouping percept. This may have been due to low discriminability between foreground and background depths.

Finally, there was also a slight benefit for color repetition, $F(1,5) = 7.14$, $p = .04$, $\eta_p^2 = .59$. However, it was much less pronounced than that observed in Experiments 5a and 5b.

**Experiment 6b: Occlusion with shading.** The present experiment sought to create a more compelling sense of depth between the two locations by introducing a drop shadow behind the occluding foreground rectangle. Unlike the preceding experiment, depth cues remained onscreen during trials (in the form of shading). Experiment 6b remained otherwise identical to Experiment 6a.

***Method.*** Six participants completed the task. The design was identical to that used in Experiment 6a except for the occluding rectangle, which was a large, unfilled horizontal rectangle with a drop shadow displayed to the lower right side (Figure 13, bottom).

***Results and Discussion.*** The results of the present experiment (Figure 15) were dramatically different from those of the preceding unshaded version. The irrelevant feature priming interaction, $F(1,6) = 17.76$, $p = .006$, $\eta_p^2 = .75$, appears to have been greatly reduced after participants viewed shaded occlusion animations, $F(1,6) = 27.37$, $p = .002$, $\eta_p^2 = .82$. There was also a significant slowing of reaction times, $F(1,6) = 31.23$, $p = .001$, $\eta_p^2 = .84$. This demonstrates that the ability of visual spatial displacements to serve as temporal group boundary cues is not restricted to lateral displacement, but also operates in depth. However, this result is all the more remarkable when considering that Experiment 6a, which did not disrupt the priming interaction, was identical in every respect except that its occluding rectangle lacked shading. This experiment is a persuasive demonstration of the importance of people's interpretation of stimuli in temporal grouping. Although all priming stimuli occurred at the same physical location on the screen, the addition of the shadow was sufficient to bring about a major change in perceived grouping. This experiment suggests that it is viewers' sense of distance between stimuli rather than physical distance that drives the reduction of temporal integration.

Finally, there was once again a benefit for color repetition, $F(1,6) = 13.12$, $p = .01$, $\eta_p^2 = .69$, indicating that there may still exist some source of ambiguity in the experiment.

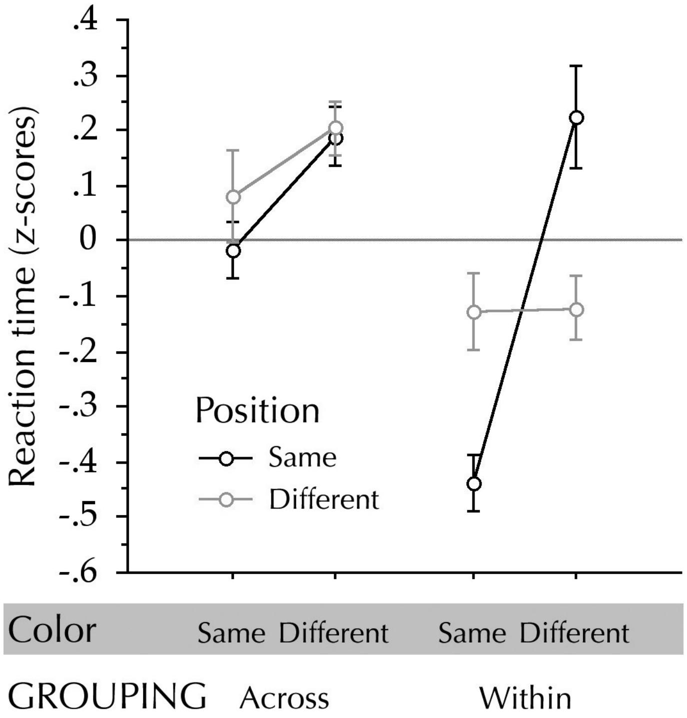

*Figure 15.* Color-position interaction as a function of grouping by spatial displacement in depth when depth was illustrated by occlusion and drop shadow cues (Experiment 6b). Error bars represent standard error. Strong disruption of irrelevant feature priming in the across-boundary condition suggests that increasing the perception of depth between foreground and background positions succeeded in enhancing the perception of grouping.

**Experiment 7a: Auditory spatial displacements.** One of the goals of the present work was to demonstrate that temporal grouping effects in priming occur at a general level, rather than being specific to any single type of grouping or sensory modality. One of the ways we attempted to do this was by using a grouping cue that was known to be effective in one perceptual modality and observing whether it produced similar results in a different modality. In the following experiment, spatial displacement, an effective temporal grouping cue in the visual domain, was explored as a potential auditory grouping cue. Although the perception of spatial displacement was created through the use of auditory localization cues rather than visual cues, the logic of the experiment was identical to that of the preceding experiments on spatial displacement.

The irrelevant feature priming stimuli used in this experiment were adapted from Huettel and Lockhead's (1999) study on interactions between tone loudness and pitch. Examining a loudness-pitch interaction rather than a color-position interaction allows spatial location to play only one role in the experiment as the temporal grouping cue. This should remove the spatial confound which occurred in Experiments 5a and 5b, and which may have contributed to their pronounced color repetition effects. We also sought to reduce any potential localization ambiguity by simulating sounds a full 180° apart on either side of the head. There should be little potential for spatial ambiguity in this experiment, and for this reason, we expected to see a strong crossed interaction without the strong main effects for relevant feature repetition observed in visual spatial displacement experiments.

***Method.*** Eleven participants completed a block of 400 trials. Priming stimuli were 250-ms tones that varied in frequency and intensity. The relevant feature was loudness (70 and 72 dB, labeled "soft" and "loud" for participants). Pitch was irrelevant (1000 and 1015 Hz). Spatial grouping was achieved by presenting stimuli to either the left or right ear, which switched every two trials. Participants required more time to respond to these stimuli, so the ITI was increased to 600 ms.

***Results and Discussion.*** This first experiment on auditory grouping demonstrated that the patterns observed in visual temporal grouping generalize well to the auditory modality (Figure 16). As in previous experiments, irrelevant feature priming was reduced across boundaries, $F(1,10) = 9.56$, $p = .01$, $\eta_p^2 = .49$. There was also a highly significant slowing when stimuli crossed spatial displacement boundaries, $F(1,10) = 27.33$, $p = .0004$, $\eta_p^2 = .73$. The data also suggest that simple loudness repetition priming may have started to reverse in the across-boundary condition, although this was not significant. It appears that spatial displacement is as effective a grouping variable in the auditory modality as in the visual modality. This suggests that the irrelevant feature priming technique developed here draws upon general qualities of temporal perception and may be used to examine temporal grouping in any perceptual modality that exhibits irrelevant feature priming.

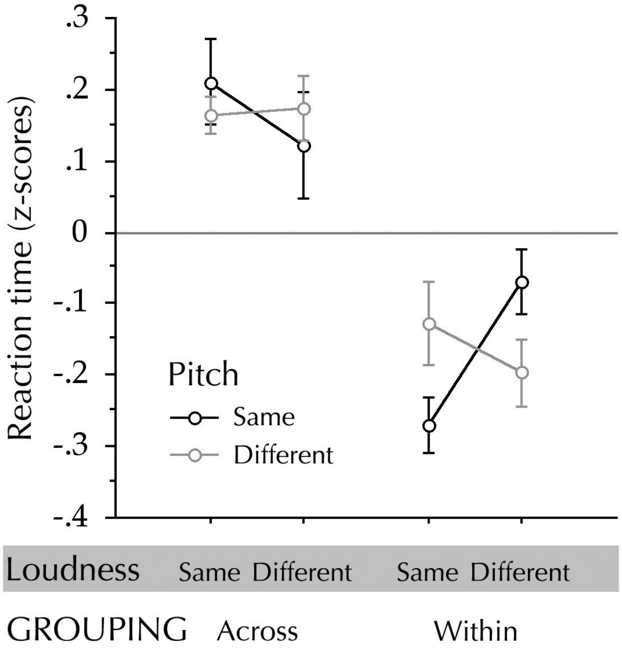

*Figure 16.* Loudness-pitch interaction as a function of grouping by ear (Experiment 7a). Error bars represent standard error. There was a statistically significant reduction of irrelevant feature priming in the across-boundary condition, suggesting that changes in ear did give rise to the perception of grouping.

**Experiment 7b: Pitch.** A second question was whether other sound features may also guide the perception of temporal groups. Auditory scene analysis offers an abundance of potential grouping cues such as spatial location, pitch, and timbre (Bregman, 1990). Indeed, it has been suggested that spatial location is actually a relatively weak auditory grouping cue (pp. 82-83). In Experiment 7b, we tested the grouping qualities of displacements in pitch. There exists a natural synesthesia between pitch and spatial position which has been studied in psychology since 1930 (Pratt), wherein higher pitches are found to be associated with higher spatial positions. In Experiment 7b, we tested whether pitch would also serve as an effective temporal grouping variable.

Experiments 7a and 7b were highly similar. Both experiments involved the use of changes in pitch, ear (i.e., location), and loudness. In the previous Experiment 7a, ear served as the temporal grouping variable, while loudness and pitch served as the relevant and irrelevant features (respectively) for irrelevant feature priming. In Experiment 7b, pitch and ear switched roles, so that pitch acted as the temporal grouping variable and ear acted as the irrelevant feature. In this experiment, participants responded to loudness while ear changed in the background. Pitch, as the grouping variable, alternated every two trials. Loudness and ear were found to demonstrate irrelevant feature priming much like that observed for loudness and pitch, which constituted an effective grouping signal for Experiment 7b.

***Method.*** Nine participants completed a block of 400 trials. Stimuli were 250-ms tones that varied in frequency (the grouping variable), intensity, and ear. The relevant feature was loudness (again 70 and 72 dB). Ear was irrelevant. Grouping was determined according to whether pitch alternated (across-boundary) or repeated (within-group). Pitches included musical notes C5 (523.25 Hz) and C6 (1046.50 Hz). Pitch switched every two trials, and ITI was 600 ms.

***Results and Discussion.*** Experiment 7b produced strong evidence of grouping. As in previous cases, the crossed interaction associated with irrelevant feature priming, $F(1,8) = 46.33$, $p = .0001$, $\eta_p^2 = .85$, appeared to weaken in the across-boundary condition, $F(1,8) = 7.75$, $p = .02$, $\eta_p^2 = .49$ (Figure 17). A slowing also occurred on across-boundary trials, $F(1,8) = 20.11$, $p = .002$,

$\eta_p^2 = .72$, a trend we have often observed alongside weakened priming interactions. These results reveal that people do appear to group tones on the basis of pitch, much as they grouped tones on the basis of ear in Experiment 7a. Both location and pitch are identified as auditory stream segmentation cues (Bregman, 1990), offering preliminary evidence of overlap between the present work and that of auditory scene analysis.

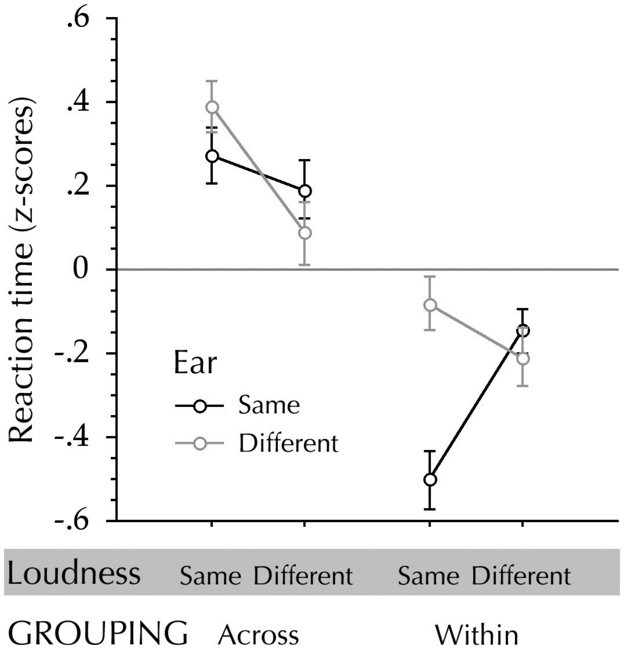

*Figure 17.* Loudness-ear interaction as a function of grouping by pitch (Experiment 7b). Error bars represent standard error. There was a statistically significant reduction of irrelevant feature priming in the across-boundary condition, suggesting that changes in pitch also give rise to the perception of grouping.

Perhaps the most interesting result of this experiment, however, is the demonstration that certain perceptual features may switch roles. Experiments 7a and 7b possessed an identical logical structure and the same three auditory features. In Experiment 7a, participants grouped tones on the basis of ear, while loudness and pitch served as sequential priming features. Yet in Experiment 7b, pitch acted as the grouping feature. In these experiments, grouping features were distinguished from the irrelevant features only because they were not random. With one feature alternating regularly, the other appears to have been released to act as an irrelevant feature for sequential priming. This pair of experiments demonstrates that either feature can act as a grouping cue, and either feature can be released to act in a sequential priming role.[3]

## The Sense of Separation

We have now presented twelve experiments, all of which involved different ways of potentially evoking the perception of boundaries. Yet despite the similar logical structure of these experiments, only some of them succeeded in generating patterns of data that indicate strong boundary perception. These differences are not accounted for by theories of event perception that rely upon informal notions of “noticeable” change, as all experiments were designed to include changes that were noticeable. While priming signals for event segmentation were observed for select experiments (Experiments 1, 3a, 5a, 5b, 6b, 7a, and 7b), several large, noticeable changes (nonrhythmic pauses and changes in direction, for instance; Experiments 2, 4a, and 4b) failed to produce any such signal.

It is difficult to evaluate EST using the present data because EST is based on predictability, yet most of the experiments presented here are highly predictable. In cases where sequences are not predictable (Experiment 2, involving nonrhythmic presentation of rests, and Experiment 4a, involving unpredictable direction change), their unpredictability is to a degree that would appear to preclude formation of the mental models necessary to determine that a prediction has been violated. Thus, on the question of boundary placement in EST, the present results remain neutral (although there is support for EST’s proposed reduction of memory at boundaries).

Nevertheless, more is needed to explain the behavior observed in the preceding experiments.

We suggest that the priming behavior we have managed to isolate is governed by three criteria. First, grouping states must be distinct and discriminable. In other words, the physical variable upon which group membership is assigned should have high contrast. Experiment 6a on occlusion-guided displacements in depth failed to produce a grouping signal in sequential priming, which we have theorized was due to a failure of group discriminability; that is, viewers could not discriminate foreground stimuli from those that were intended to be perceived as occurring in the background. Stimuli appeared highly similar in A and B states; there was no clear sense of "near" and "far." It required the addition of a drop shadow to enhance the sense of distance between foreground and background in order for a clear grouping signal to be generated (Experiment 6b).

A similar result was observed in Experiments 5a and 5b on lateral visual spatial displacements. Although both experiments did generate grouping signals in sequential priming, the signal became stronger when the physical distance between A and B positions was increased in Experiment 5b. Experiment 3b involving brief rhythmic rests may have failed to produce grouping for the same reason. Whereas Experiments 1 and 3a created a clear sense of temporal grouping by placing relatively long rests between pairs, the rests in Experiment 3b appear to have been too similar to other timing intervals in the experiment to have been perceived as pauses. Instead of a stream of unique pulses, participants seem to have experienced Experiment 3b as a single stream (even if this stream was somewhat halting).

The second criterion is that temporal structure must be transparent. An undifferentiated stream of identical stimuli contains no features that would influence perceivers to group stimuli in one way or another. By the same token, if features are inconsistent or fail to correspond with reasonable categories, they will not give rise to grouping. This was likely the case in Experiment 2 involving random presentation of short and long ITIs. By presenting stimuli at randomly determined short or long intervals, the rhythmic structure created in Experiment 1 was destroyed. It was the regular presentation of ITIs in Experiments 1 and 3a that caused long ITIs to be perceived as pauses between rhythmic pairs. Without this structure, long ITIs were perceived only in terms of temporal intermittency, rather than as separating groups of stimuli. However, it should be noted that this criterion may at least in part reflect the limitations of the highly repetitive priming task.

The final criterion is that grouping states must not be readily subsumed into the same temporal unit. It is always possible to conceptualize an event that is higher in the temporal hierarchy (an epoch, for instance); likewise, people are able to detect and label minute changes as boundaries. Nevertheless, the boundaries to which our meter responds appear to represent a distinct, unit-based level of perception, a level which is superordinate to kinematic change. We would argue that this is why Experiments 4a and 4b, which examined changes in the direction of stimulus motion, failed to produce any evidence of boundaries. The most available and compelling interpretation of the scene was not many discrete line segments, but rather a unified path.

We suggest, then, that what we have achieved with this technique is a psychophysics of separation. Separation represents more than change--rather it is an amodal experience that signifies a break, a gap, or a discontinuity. While more obvious in space, separation also applies in the realm of time (in the form of musical rests) as well as object identity. Understanding what causes separation turns out to be a highly abstract and complex problem that is bound up in notions of identity and difference. For this reason, that we can perform a psychophysics of separation, albeit in the context of a continuous stimulus stream, is notable.

Based on the present work, we propose two theoretical advances. First, we believe that theories of event segmentation must acknowledge the existence of a discernable level of temporal structure that can be tracked by irrelevant feature priming and for which boundaries are formed on the basis of the salience of separation. Second, we believe that separation must be identified as a temporal segmentation cue that is distinct from other types of temporal change. In our final experiment, we sought to validate this separation hypothesis by testing a highly abstract form of temporal separation based on object identity.

## Experiment 8: Object-Based Separation

In previous experiments we have tested rhythmic separation, spatial separation, and separation in pitch, but now we seek to probe a sense of separation that is more abstract. In addition to separation in physical space, objects also possess a separateness of identity. An object, as we perceive it, has its own clear bounds and characteristics, each of which belongs uniquely to that object. We perceive even a perfect replica as being a different object from the original. By the same token, an object may be painted or broken, and yet that object's fundamental identity is not altered--it has undergone a transformation, but it has not become a different object. Object identity exists in a way that is not easily explained on the basis of purely physical rules, and it is for precisely this reason that it serves as an ideal test for our separation hypothesis.

In Experiment 8, object identity was incorporated into a shape-tracing animation. As in Experiments 4a and 4b, we once again used frames that predictably changed direction after a set number of trials. In previous experiments, this change in direction did not produce evidence of grouping. However, in the present experiment we created a sense of belonging by allowing frames to outline two different geometric shapes, a triangle and a square, one after the other. The motion itself was continuous and should have produced no sense of temporal grouping, and yet by outlining a shape, the priming stimulus gained a sense of belonging to that shape. This sense underwent a major change when the priming stimulus began to outline the alternate shape. We were interested in discovering whether by allowing the stimulus to become strongly associated with two separate shapes, we might be able to transfer the sense of separateness between those two objects to the (normally unified) trajectory of a moving priming stimulus.

### Method

Seventeen participants completed a block of 420 trials. The experiment had a 2 × 2 × 7 design, with two across-boundary conditions (trials where the traced shape alternated) and five within-group conditions (trials where the traced shape remained the same). The experiment featured two large geometric shapes, an equilateral triangle and a square, which were traced by the smaller frame (Figure 18). These shapes were shown in gray onscreen while they were actively being traced and disappeared when not in use. Trial onsets occurred at each vertex of the two large shapes; thus there were three onsets for the triangle and four for the square, for a total of seven in each sequence. The frame remained in constant motion around the two large shapes. At each trial onset point, the prime/probe stimulus would be presented within the moving frame. After a response was registered, the prime/probe would disappear, and the empty frame would continue its motion toward the next trial onset point (i.e., the next vertex). The frame moved in a counterclockwise direction around the triangle, then in a clockwise direction around the square. This sequence repeated throughout the course of the experiment. Across-boundary conditions occurred on Trials 1 (square to triangle) and 4 (triangle to square). Timing between stimuli was fixed at 1500 ms, and participants hardly ever missed a response deadline.

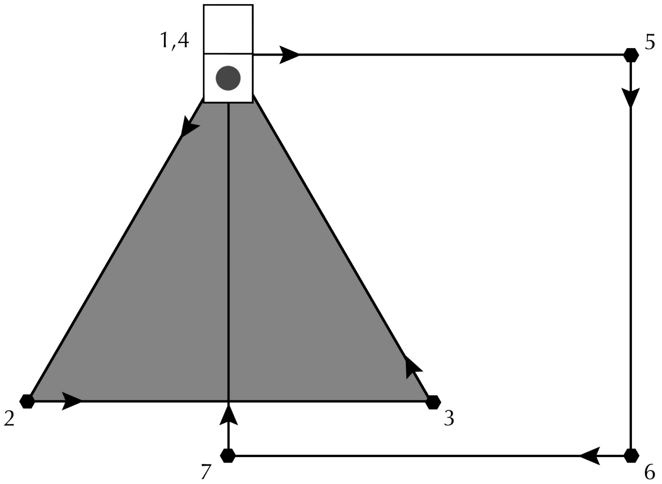

*Figure 18.* Trial sequence for shape-tracing experiment. Stimulus frame moved continuously through seven locations. Black hexagons indicate trial onset points. Gray triangle was visible for trials 1-3 of full sequence, then disappeared and was replaced by a gray square (in the position outlined) for trials 4-7.

## Results and Discussion

By this point, we were able to make several predictions about the results of Experiment 8. First, we predicted that the data would be structured in patterns of three (for the triangle) and four (for the square). We also predicted, most importantly, that the irrelevant feature priming interaction would be uniquely reduced at points where shape transitions occurred (points 1 and 4). We also expected these points to be slower overall. The remaining five points should be faster and have more strongly crossed interactions. Experiment 8 also incorporated a large change at shape transitions, where one large shape disappears from the screen and another takes its place. We may then predict, on the basis of auditory Experiments 7a and 7b, that we might observe an inhibition of responding to relevant feature repetitions on these transitions.

Our predictions were confirmed on every count. The two across-boundary conditions in Experiment 8 showed the patterns that we have come to associate with strong temporal group boundaries. There was an overall slowing in these conditions, $F(6,96) = 9.82$, $p < .0001$, $\eta_p^2 = .38$, and more importantly, there was evidence that irrelevant feature priming ($F(1,16) = 8.21$, $p = .01$, $\eta_p^2 = .34$) was significantly reduced as well, $F(6,96) = 2.18$, $p = .05$, $\eta_p^2 = .12$ (Figure 19).

Once again, it is the simultaneity of effects at the higher level of real-world events and of the lower level of sequential priming that yields the strongest support for our hypothesis. Out of seven possible points, only two showed strong boundary signatures, both of which coincided with object transitions. This indicates that the two major groups perceived were a "triangle path" and a "square path." We also managed to transform an unsuccessful boundary cue (changes in direction of motion, Experiments 4a and 4b) into one with strong, predictable disruptions in priming by the simple addition of shapes. By allowing the stimulus frame to trace the two shapes, we were able to impart a sense of object separation to the frame's trajectory. This result yields considerable evidence for our separation hypothesis. The clear identification of boundaries is also offers further validation for the precision of the priming technique presented here.

There was also an apparent reversal of color repetition priming on the across-boundary trials, although it did not produce a statistically significant interaction. This is similar to patterns observed in the two experiments on auditory grouping (Experiments 7a and 7b), although the effect appears even stronger in Experiment 8. This is again consistent with a change-monitoring explanation. Additional effects in Experiment 8 included a speeding of response when position repeated, $F(1,16) = 12.16$, $p = .003$, $\eta_p^2 = .43$,

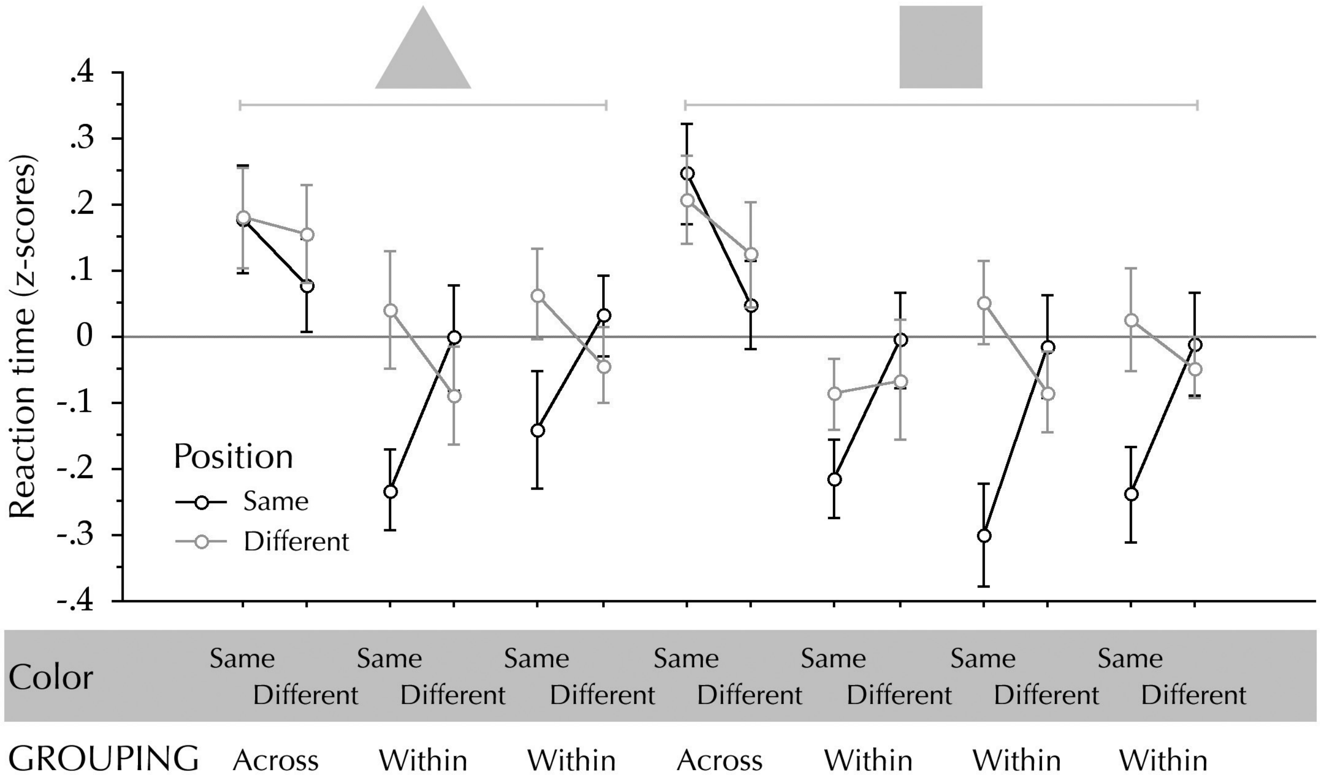

*Figure 19.* Color-position interaction as a function of point in shape-tracing sequence (Experiment 8). Error bars represent standard error. Shape changes occurred at first and fourth sequence points. Disruption of irrelevant feature priming only at first and fourth sequence points offers strong evidence that stimulus pathways were grouped on the basis of shape.

which was also observed in other experiments involving moving frames (4a and 4b).

## General Discussion

In this paper we introduced a technique that produces an objective signature which marks when people experience strong boundaries between temporal groups. This technique is based on the idea that the integrative memory processes involved in forming scenes may be coordinated with sequential priming. We proposed that memory would be disrupted at temporal group boundaries, and that this disruption would be mirrored in sequential priming. Disruption of active memory at event boundaries is also a key feature of EST and is in fact validated using this technique.

Like several previous measures of event perception, the technique produces boundaries that possess a certain degree of face validity. However, some boundaries we observed using this technique do differ from previous results. These differences may be related to boundary strength or possibly to implicit task demands that exist in button press methodologies. We have suggested that the boundaries that the present technique identifies may correspond to a sense of separation, which may be evoked through temporal disruption (i.e., pauses), but also more abstractly when there is some feature that modulates over time. A sense of separation will grow in a temporal stream "A1-A2-B1-B2-…" to the extent that events in one group (A1 and A2) have a feature that discriminates them from elements in the other group (B1 and B2), to the extent that the sets {A1, A2} and {B1, B2} form sensible categories, and finally to the extent that there is not some available and compelling interpretation of the stream that would lead elements of both sets to be grouped into one super-ordinate event.

The present work deepens our theoretical understanding of events in three ways. First, it shows that memorial processes can be used to infer the perception of temporal structure. Second, it demonstrates that there is a definable class of temporal disruptions that produces a sense of separation, and that these disruptions generate strong grouping. Finally, it indicates that the sense of separation is not identical to temporal change or kinematic features, but operates on more subtle interpretations of what is taking place within a sequence.

Yet perhaps the most promising aspect of the technique we have developed here is the potential to move beyond the binary alternatives of "grouped" or "not grouped." In reality it is likely that the sense of boundary is graded much like any other sense. Our results (for instance, Experiments 5a and 5b involving small and large spatial displacements) have shown that the meter developed here appears to distinguish between weaker and stronger instances of grouping. A future avenue of research will be to use the present technique to generate continuous curves of priming strength as the underlying sequence is parametrically manipulated. In this way the sense of separation may be brought under experimental control, offering the promise of bringing the field of event segmentation within the purview of psychophysics.

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# Footnotes

[1] Our experience is that some of the more common forms of priming lack the sensitivity needed to show any effects of temporal grouping. Simple repetition priming is one such example (color priming, for instance, does not significantly change across boundaries in several experiments reported in this paper; see, e.g., Experiments 1, 3a, and 6b).

[2] Watanabe and Shimojo (2001) presented ambiguous animations of circles moving toward one another, which could be perceived as depicting either ricochet motion or passing motion. By presenting sounds at the moment of convergence, they produced a higher likelihood of ricochet percepts.

[3] An unexpected effect of Experiment 7b was that people responded more quickly when the relevant feature changed in the across-boundary condition (interaction between loudness repetition and grouping, $F(1,8) = 32.48$, $p = .0005$. It was unexpected because people usually respond more quickly to repeated features, where the same keypress occurs on two subsequent trials. It appears that pitch change inhibits use of the same response key as on the preceding trial. Changes in ear also showed a similar, albeit weaker, effect in Experiment 7a. However, this pattern was not observed for the visual stimuli we have examined. We suggest that the difference lies in the fact that the auditory differences in Experiments 7a and 7b were more categorical in nature. Sounds occurred at distinct pitches, or in one ear or another. Visual space, by contrast, is more continuous.