Acta Psychologica 149 (2014) 129–133

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/ locate/actpsy

Time perception, attention, and memory: A selective review

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ARTICLE INFO

Article history:
Received 13 January 2013
Received in revised form 24 October 2013
Accepted 13 November 2013
Available online 21 December 2013

PsycINFO classification:
2300

Keywords:
Time perception
Time estimation
Attention
Memory

ABSTRACT

This article provides a selective review of time perception research, mainly focusing on the authors' research. Aspects of psychological time include simultaneity, successiveness, temporal order, and duration judgments. In contrast to findings at interstimulus intervals or durations less than 3.0–5.0 s, there is little evidence for an "across-senses" effect of perceptual modality (visual vs. auditory) at longer intervals or durations. In addition, the flow of time (events) is a pervasive perceptual illusion, and we review evidence on that. Some temporal information is encoded All rights reserved. relatively automatically into memory: People can judge time-related attributes such as recency, frequency, temporal order, and duration of events. Duration judgments in prospective and retrospective paradigms reveal differences between them, as well as variables that moderate the processes involved. An attentional-gate model is needed to account for prospective judgments, and a contextual-change model is needed to account for retrospective judgments.

1. Introduction

Scientific research on time perception is multifaceted. Time perception involves the study of diverse perceptual, cognitive, and brain processes. Research on psychological time dates to Vierordt (1868). He is usually cited for his research using himself and a student as the only subjects in a very large and data-rich repeated-measures design (Lejeune & Wearden, 2009). Vierordt is best-known for what researchers now call *Vierordt's Law*, a basic finding. He found that from seconds to years, the same law holds: Judgments of relatively short intervals are lengthened, and judgments of relatively long intervals are shortened. However, this finding is more general. This finding might reflect a central-tendency effect in judgment. For example, when people judge the likelihood of causes of death or when they judge the duration of typical autobiographical or naturalistic experiences (Yarmey, 2000; see later), they also tend greatly to overestimate short magnitudes and slightly to underestimate longer magnitudes.

Many processes are involved in psychological timing, whether by non-human animals or by humans. It is now apparent that many brain areas subserve the experiencing and remembering of various aspects of time. In this review of older and more recent evidence, we discuss these aspects, and we provide a view on psychological time, both within and across senses. We focus especially on perceptual and cognitive processes within perceptual modalities, but we also review evidence on processes between them. Thus, based on recent meta-analytic findings, we also focus on time perception within and across senses, or perceptual modalities.

Shifting to physics, Einstein (1955/1979) said that "people like us, who believe in physics, know that the distinction between past, present, and future is only a stubbornly persistent illusion." Pirsig (1974) wrote: "We want to make good time [on a motorcycle trip], but for us now this is measured with emphasis on 'good' rather than 'time' and when you make that kind of shift in emphasis the whole approach changes" (p. 5). To us, what is especially "good" is the resurgence of studies of psychological time during the past decade or two (Hancock & Block, 2012). What is the past, present, and future except for a stubborn perceptual and cognitive illusion? What is psychological time? The answers to these questions depend on evidence and theories. We selectively review these questions, among others. Various aspects of psychological time involve dissociable perceptual and cognitive processes (Block, 1996; Block & Zakay, 2001; Pöppel, 1997). We also review these processes and the evidence for them, as well as some applications (Block & Hancock, in press). We mainly focus on our past and present research findings, but of course we include other findings.

2. Simultaneity, successiveness, and temporal order

Researchers in the tradition of time psychophysics have examined questions, especially about very short duration experiences, for many decades. Although methods have been refined over the years (Grondin, 2008; Pöppel, 1988; Zakay, 1990), many basic findings are now clear (Eisler, Eisler, & Hellström, 2008).

Simultaneity is experienced if two auditory stimuli occur less than about 2–3 ms (longer for visual stimuli). Successiveness is only experienced at slightly longer durations. However, temporal-order judgments cannot be made until the interstimulus interval is about 20–30 ms

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http://dx.doi.org/10.1016/j.actpsy.2013.11.003

(Block, 1979; Hirsh & Sherrick, 1961). These judgments rely mainly on automatic processing of stimulus information in sensory systems of the brain, as well as on neuronal networks that subserve these kinds of experiences and judgments. There is an extensive literature on these issues, but it is not a major focus in this article.

Earlier and more recent evidence clearly supports some general conclusions. The auditory system is more sensitive to short interstimulus-interval information than is the visual system. This fine-tuning (i.e., the very short interaural time difference) of the auditory system is important in localizing sound sources. The visual system relies on well-known parietal-lobe systems in localizing stimulus locations, and these do not have to be very fine-tuned in the temporal domain. In this regard, here is where sensory ("across-senses") differences are typically large and significant. However, with durations longer than about 3.0–5.0 s, perceptual and memorial differences are typically small and not significant (see later).

2.1. Flow of time (flow of events)

The transition from past to present and future involves a changing present. In this view, time flows like a river. It is a basic perception of the flow of time. Perhaps it was best said as "you cannot step twice into the same river," or "everything flows, nothing stands still" (Heraclitus, c. 450 BCE, cited in Kahn, 1981). We now turn to examine recent evidence on specific durations.

The perceptual flow of events, occurring at 3.0–5.0 s, involves all perceptual modalities. One can easily show this in the auditory modality by playing the first four notes of Beethoven's famous Fifth Symphony at an interstimulus interval of 3.0–5.0 s; most people do not recognize it, and those four notes do not sound much like music (Gruber & Block, 2013). In the visual modality, consider similar interstimulus intervals (ISIs) of 0.5, 3.0, and 7.0 s, Gruber and Block used ten frames (snapshots) captured from a man-walking scene to be representative of the walk from its beginning to its end (spatial change). In other conditions, similar frames depicted stationary bread-products being toasted (color change). Each frame was presented for 100 ms. The ISI between frames (stimuli) was 0.5, 3.0 or 7.0 s. As the ISI was increased, subjects reported that the event did not *happen*, only that they *knew* that some changes had occurred.

In this review, we elaborate on these findings. The percept of *flow* was more frequently reported for the walking-man videos than for the toasting-bread videos. The mean (and standard error of the mean) proportion of *happening* responses for both *walking* and *toasting* stimuli

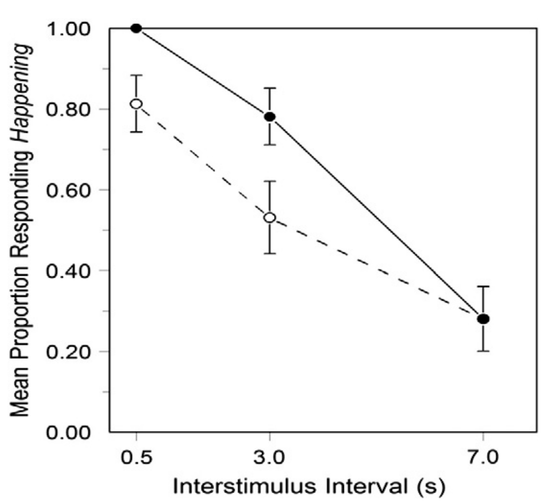

Fig. 1. Proportion of subjects reporting that they saw happening in the walking (solid line: spatial change) and toasting (dashed line: color change) conditions as a function of interstimulus interval. Original figure based on data from the authors. Gruber and Block (2013).

are shown in Fig. 1. The experience of *happening* (change) for both walking (spatial change) and toasting (color change) depended on the ISI. At an ISI of 0.5 s, most participants in the walking and toasting conditions responded experiencing *happening*. At an ISI of 7.0 s, many fewer participants in both conditions responded experiencing *happening*. These data suggest that *happening* is a time (frequency) dependent phenomenon. The flow of time (events) begins to be lost at about 3.0 s, and this percept is almost completely lost at an ISI of 7.0 s.[1]

Thus, time perception (of motion, in particular) takes place in discrete processing epochs, frames, or "snapshots" (Crick & Koch, 2003, 2007). The *flow of events* is a time percept, a property of the frequency at which its percept occurs. People experience a flow of time, or flow of events, and it is a *perceptual illusion*. It is an illusion partly because, in modern physics, time does not "flow." Our brains are, of course, part of the physical universe. However, modern physics does not explain our brains. Instead, it restricts equations to those that apply to the universe as a whole. In modern physics, each moment ("event") is separate from the next. In equations, time (t) a static slice of spacetime (Davies, 2002).

2.2. Specious present

James (1890) wrote that "the practically cognized present is no knife-edge, but a saddle-back, with a certain breadth of its own on which we sit perched, and from which we look into two directions into time" (p. 609). He added that people "are constantly conscious of a certain duration—the specious present—varying in length from a few seconds to probably not more than a minute" (p. 642). Research now reveals that this time interval is about 3 s to, arguably, about 7 s, during which the brain can compare and analyze very recent high density memories in working memory. For example, Pöppel (1997) convincingly reviewed evidence showing that there is a break in the perception of time at about 3.0 s. It is that interval during which the closed mind opens up for new information from the environment—an interval during which the brain can differentiate future from past (e.g., to have one uttered phrase separate from the prior one). As noted earlier, Gruber and Block (2013) used ISIs of 0.5–7.0 s and found that the perception of the flow of time (events) was lost after more than 3.0 s. Meta-analytic reviewers (e.g., Block, Hancock, & Zakay, 2010) realized this distinction and excluded data at durations less than 5 s. This is in agreement with the conclusion that different perceptual and cognitive processes are implicated in durations below about 3.0 s or 5.0 s as compared to longer durations.

This 3.0- to 5.0-s range does not mean that the rest of psychological time is continuous. Some psychophysicists have discovered that other distinctive "breaks" in durations may occur at about 1.3 s (see Grondin, 2012, for evidence). There may be several such "breaks" in even longer duration judgments (Eisler et al., 2008).

3. Experienced versus remembered duration

Consider durations longer than about 3.0–5.0 s. Present-time, or *experienced duration*, judgments are theoretically and empirically different from past-time, or *remembered duration*, judgments (Block, 1990). These two paradigms are typically called *prospective* and *retrospective*, respectively. This is highlighted by the meta-analytic findings of differences between prospective and retrospective estimates in the two judgment paradigms (Block & Zakay, 1997). In experiments conducted using

[1] A Cochran Q test, conducted separately for the *walking* and *toasting* conditions, revealed these findings: For the *walking* condition, $Q = 36.3$, $p < .001$, shows a significant difference between the three ISIs. For the *toasting* condition, $Q = 24.1$, $p < .001$, also shows a significant difference between the three ISIs. The *walking* and *toasting* conditions differed at each of the three ISIs. At the 0.5-s ISI, $Q = 6.0$, $p = .01$. At the 3.0-s ISI, $Q = 4.6$, $p = .03$. At the 7.0-s ISI, there is no significant difference between the *walking* and *toasting* conditions, $Q = 0.0$, $p = 1.0$. Finally, all participants of all groups (whether they experienced *happening* or not) recognized the chronological order of stimuli and approximate duration of intervals between stimuli.

the prospective paradigm, a person knows in advance that a duration judgment is required. In experiments conducted using the retrospective paradigm, a person does not have this prior knowledge. These two kinds of judgment are often in opposite directions, revealing different time-estimation processes for each; namely, attention to time in the prospective paradigm and memory for events and contextual changes in the retrospective paradigm. They are also affected by different variables (Block & Zakay, 1997). For example, different cognitive load variables (e.g., degree of task difficulty), affect (moderate) the two kinds of judgment (Block et al., 2010).

Under some conditions, judgments in these paradigms may involve somewhat overlapping processes. If a prospective judgment is delayed, memory may be involved, as in the retrospective paradigm. If an interval experienced under the retrospective paradigm contains monotonous or boring events, attention to time may be involved, as in the prospective paradigm.

3.1. Prospective duration (present time)

Present time (prospective judgments of time in passing) involves a situation in which person knows that duration is relevant and important (Zakay, 1992). They lengthen as cognitive load increases. Block et al. (2010) conducted a meta-analysis of 117 experiments. Prospective judgments are moderated by: (a) cognitive load type (response demands, attentional demands, processing difficulty, and so on), (b) duration-judgment method (time productions show the largest effect size), and (c) judgment immediacy (i.e., immediate judgments show the larger effect size). Of importance for this special issue, stimulus modality (auditory vs. visual) did not moderate duration judgments. One additional variable that was not coded—absorption, or immersion—is probably important, as in the adage, “Time flies when you are having fun,” because then a person is not attending to time.

The attentional-gate model is a leading model of prospective time judgments (Zakay & Block, 1995). It is similar to earlier models from scalar expectancy theory, except that the attentional-gate model explicitly takes into account the role of attention to time in prospective situations. In this model, attention to time mediates the flow of pulses from a pacemaker to an accumulator.

Several areas of applications of prospective timing include these (see Block & Hancock, in press, for details and references):

1. Sports timing. In football (soccer), the players must prospectively estimate the time remaining in the game, which is uncertain. Although estimation of time-to-contact is not an example of prospective timing per se, it might also involve similar processes. In baseball, for example, the pitcher suggests an illusion in time about the speed of the ball, and the batter must accurately estimate time-to-contact (cf. Hancock & Manser, 1998).
2. Airplane piloting. Physical, or perceptual-motor, load (e.g., complexity of maneuvers in flight simulators) reveals that prospective time judgments are a reliable and valid measure of attentional demands (Block, Hancock, & Zakay, 2013).
3. Automobile driving and pedestrian accidents. Attentional distraction caused by cell phone use leads to increased accidents. Although this is mainly an attentional issue, this perhaps leads to time-to-contact misjudgments (e.g., Recarte et al., 1998). This is the case even if a cell phone is not hand-held or if the person is not texting. It also results in increased pedestrian accidents.

3.2. Retrospective duration (past time)

Past time (retrospective judgments of time in memory) involves a situation in which a person does not know in advance that duration is relevant and important. These estimates, which are extremely variable when subjects are asked to give numerical estimates (seconds and minutes) lengthen as contextual changes increase (Block & Reed, 1978; Block et al., 2010). Importantly, Boltz (1998) found that if events have a regular and predictable tempo, duration judgments might be more accurate. Of particular interest to this special issue, she also found that whether subjects retrospectively or prospectively judge durations of naturalistic events in an auditory, visual, or audiovisual modality, no differences in either accuracy or bias were found (Boltz, 2005).

In addition, retrospective judgments of relatively longer durations show a positive time-order effect—the first of two equal durations seems longer in retrospect—which is probably attributable to greater contextual changes during the first duration (Block, 1985). In this explanation, there are greater changes in environmental, mood, and other contextual elements at the start of a new experience, such as participating in an experiment. One moderator of this effect is segmentation of the duration, which might lead to increased contextual changes.

Several areas of applications of retrospective timing include (see Block & Hancock, in press, for elaboration and references):

1. Eyewitness remembering. Vierordt's Law is usually supported: In unusual or stressful situations, longer durations are usually overestimated, although shorter durations (seconds-to-minutes) may not be underestimated in verbal (numerical) testimony.
2. Everyday activities. Vierordt's Law is also supported with so-called *variant* and *invariant* everyday, naturalistic activities ranging from 4.0 s to 4008 s (Yarmey, 2000; see also Block & Zakay, 2008). As shown in Fig. 2, shorter episodes were overestimated and longer events were slightly underestimated—more so for variant events (e.g., waiting to use an ATM), than invariant events (e.g., taking a one-stop subway ride).
3. Affective experiences. The most intense moments and the most recent moments dominate duration judgments (Ariely & Zakay, 2001).

4. Episodic and autobiographical memory

People remember less recent events as relatively more recent. They also base past-time estimates on two main kinds of processes—called *distance-based* and *location-based* (e.g., Friedman, 1993, 2004). In distance-based processes, a memory trace is retrieved and experienced in terms of apparent recency (Hintzman, 2005). In location-based processes, an event is retrieved along with contextual associations (e.g., other events that occurred at about the same time). Forgetting of many time-based (episodic and autobiographical) details is the norm.

In contrast, cases of superior autobiographical memory have recently been revealed (Leport et al., 2012). So far, about 20 subjects have been

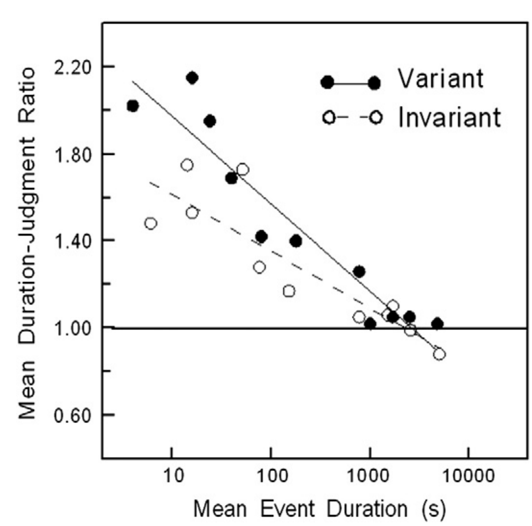

Fig. 2. Duration judgments of variant and invariant episodes ranging from 4.0 s to 5008 s. Data from Yarmey (2000), plotted from his table.

discovered and studied. They show hardly any forgetting of what they experienced on any randomly selected date in their past. The connections between these remarkable findings and more general theories on the psychology of time and memory may be a fruitful source of investigation. The main question concerns the ways otherwise fairly routine and ordinary events are remembered in such detail, retrieved simply by asking what happened at a random date in the remote past, for these individuals.

5. Time-based prospective memory (future time)

Time-based prospective memory involves remembering an intention to perform an action at a specific future time. Researchers have become increasingly interested in time-based prospective memory, and they have conducted many recent studies (see Block & Zakay, 2006, for a review and models). In contrast, many more studies have been conducted on event-based prospective memory, which involves remembering to perform an action when a specific event occurs. Time-based prospective memory requires timing processes similar to those in prospective timing: attending to time (and concurrently also to events), and also remembering an intention and when to perform it. In other words, explanations of time-based prospective memory require an attentional-gate model, or some similar model. Event-based prospective memory may involve some processes similar to those involved in time-based prospective memory, as well as others. Models of these processes might include a focus on contextual-changes.

6. Summary and conclusions

We selectively reviewed evidence on time perception. Psychological time relies on sensory, perceptual, attentional, and memory processes at different time scales. These range from milliseconds to seconds, minutes, hours, and a lifetime. Psychological time is influenced by many different factors, such as attentional processes and contextual changes. Actual duration has important effects, and there is a difference between processes implicated at durations less than about 3.0–5.0 s and processes implicated at longer durations. There an "across-senses" (across-modalities) effect of perceptual modality (visual vs. auditory) at shorter durations, but not at longer durations. New evidence on the flow of time (flow of events, or *happening*) seems to approximate a 3.0–5.0 s rule. There are differences between the experiencing and remembering of time at differing durations across perceptual modalities. We also discussed duration judgments under prospective and retrospective conditions, which are mainly influenced by attentional and memory processes, respectively. Time-based prospective remembering relates importantly to prospective estimates, along with other factors.

In modern physics, time is simply a slice of non-flowing spacetime. In animals' varied experiences of time, it is not: Time flows, with an ever-changing present, and present time and future time are easily distinguished. For humans and other animals, times past, present, and future are remembered, experienced, and anticipated in ways other than those dictated by physicists.

Acknowledgments

We thank Dr. Rolf Ulrich and several anonymous reviewers for very helpful suggestions on drafts of this article.

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