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How cognitive load affects duration judgments: A meta-analytic review

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ABSTRACT

A meta-analysis of 117 experiments evaluated the effects of cognitive load on duration judgments. Cognitive load refers to information-processing (attentional or working-memory) demands. Six types of cognitive load were analyzed to resolve ongoing controversies and to test current duration judgment theories. Duration judgments depend on whether or not participants are informed in advance that they are needed: prospective paradigm (informed) versus retrospective paradigm (not informed). With higher cognitive load, the prospective duration judgment ratio (subjective duration to objective duration) decreases but the retrospective ratio increases. Thus, the duration judgment ratio differs depending on the paradigm and the specific type of cognitive load. As assessed by the coefficient of variation, relative variability of prospective, but not retrospective, judgments increases with cognitive load. The prospective findings support models emphasizing attentional resources, especially executive control. The retrospective findings support models emphasizing memory changes. Alternative theories do not fit with the meta-analytic findings and are rejected.

1. Introduction

People are experiencing increasing perceptual, attentional, and performance load: automobile drivers experience cognitive load attributable to the use of cell phones and in-vehicle devices and to increased traffic. Airplane pilots and air-traffic controllers experience cognitive load attributable to complicated instrumentation and to increased air traffic. The increasing complexity of technology makes high cognitive load ubiquitous (Hancock & Szalma, 2008). Ways to reduce errors in human performance under conditions of cognitive load depend on methods to measure load. Those measurements are derived from and have an impact on basic theories of human attention, perception, and performance and how they are best assessed. As information processing increasingly became the focus of modern work, there arose a need to identify methods to evaluate cognitive load. To resolve this problem, researchers looked to previous methods of physical work assessment for solutions. One approach, first developed in time-and-motion studies at the turn of the last century (e.g., Taylor, 1913), is primary task performance. This takes the form of online measurement of output in relation to the task that people perform. If a task involves industrial processing, the number of units of a product per unit of time reflects the level of load experienced. Unfortunately, for many tasks, the output rate is difficult to specify.

However, secondary task performance is the one most rooted in psychological theory. Largely founded on the notion of limited attentional capacity, this methodology argues that as the cognitive load demanded by performance of a primary task increases, the performance on a secondary task decreases. Ways to measure cognitive load include physiological measures, primary task performance, secondary task performance, and opinion surveys. Attentional resource theories (Kahneman, 1973; Navon & Gopher, 1979; Wickens & Kessel, 1980) focused on secondary task methodology, using tasks that presumably required the same attentional resources as the primary task. The undifferentiated attentional resource model, first proposed by Kahneman, rendered this assessment process simple because all cognitive tasks were assumed to compete for a single limited pool of attentional resources. However, when subsequent theorists proposed multiple resource pools, the choice of a specific secondary task became problematic. Questions arose as to which secondary tasks tapped which respective resource pools, and evidence began to accumulate of dissociations between increasing task difficulty and primary and secondary task performance (Hancock, 1996). Although cognitive load measures usually agree, instances of dissociation reveal the lack of theoretical guidelines as to when they might occur (but see Yeh & Wickens, 1988).

1.1. Duration judgments as a cognitive load measure

Time (duration) estimation, a measure of secondary task performance, has been shown in several experiments to be a reliable and valid measure of cognitive load. For this reason, applied researchers, beginning with Hart (1975) and Casali and Wierwille (1983, 1984),

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have increasingly focused on duration estimation. It is thought that when a person is working on a difficult or attention-demanding task, time seems to pass quickly, but if a person is working on an easy or less attentional-demanding task, time seems to pass slowly (Block, George, & Reed, 1980; Block & Zakay, 2008; Brown, 2008). Although the past century of research contains findings that support these intuitive observations, researchers have failed to reveal the reasons for these kinds of temporal distortion. Our meta-analytic review focuses on the first century of research on this issue, which dates from the seminal study of Yerkes and Urban (1906). It establishes the relative size and direction of these effects, and it also tests various models that have been proposed to explain the underlying phenomena.

Reasons to investigate the effects of cognitive load on human duration judgments are motivated by both basic and applied concerns. Understanding the effects of cognitive load on duration judgments can help develop and refine theories of human duration judgment and, more generally, human information processing. For example, one current hypothesis is that cognitive load is “a function of the proportion of time during which a given activity captures attention, thus impeding other central processes” (Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007, p. 570). Along these lines, several researchers (e.g., Rammsayer & Brandler, 2007; Zakay, Block, & Tsal, 1999) have suggested that duration judgments may be a reliable and valid index of cognitive load to the extent that they involve time-shared central processes, especially attentional, executive, or working-memory resources. Recent research on duration judgment processes has increasingly focused on issues concerning the division of attentional resources between nontemporal and temporal information processing (for recent reviews, see Block, 2003; Grondin, 2001, 2008; Zakay & Block, 1997).

We conducted a meta-analysis focusing broadly on the effects of cognitive load on human duration judgments. A critical feature of it is the specification of the meaning of the term *cognitive load* and how it is used in the literature. We define *cognitive load* as the amount of information-processing (especially attentional or working-memory) demands during a specified time period; that is, the amount of mental effort demanded by a primary task. These demands may also include some heavily cognitively driven perceptual-motor processes. We use the term *cognitive load*, or more simply *load* (e.g., Barrouillet et al., 2007) instead of various near-synonymous terms that other researchers use, such as *mental workload* (e.g., Hancock & Meshkati, 1988; Proctor & Van Zandt, 1994; Wierwille, Rahimi, & Casali, 1985), *cognitive workload* (e.g., Patten, Östlund, Joakim, Nilsson, & Svenson, 2006), or simply *workload* (e.g., Gopher & Donchin, 1986).

1.2. Theoretical focus

In most experiments on duration estimation, researchers have obtained duration judgments as a function of nontemporal stimulus information or information-processing demands, not merely as a judgment of an *empty* duration (one devoid of externally presented stimulus content). In one early study, Swift and McGeoch (1925) asked college students to judge the duration of a time period during which they either listened to an interesting passage (a low-load condition) or wrote down the passage while they were listening to it (a high-load condition). Many early researchers (e.g., Gulliksen, 1927) used several qualitatively different kinds of tasks, with the type of activity apparently selected in an atheoretical way. One critical issue is that there has been little if any theoretical coherence in the choice of tasks used to manipulate cognitive load. Our meta-analysis remedies this failure by classifying different kinds of cognitive load and assessing each type separately, then relating the findings to theoretical accounts.

One of the earliest reviews of the literature on time perception and estimation was written by Weber (1933). His review was essentially a narrative summary of wide-ranging articles (49 of them) on the psychology of time. For present purposes, he distinguished between the amount of mental content and its complexity, which others have mentioned more recently (e.g., Ornstein, 1969). Even more recent duration judgment literature contains reports of some experiments in which participants passively viewed different numbers or complexities of stimuli, or in which they only estimated time or estimated time while performing a task, without any manipulation of the load of that task. Although it might be argued that passively viewing fewer or less complex stimuli requires lower load demands, whether participants increase their cognitive load if they passively view more stimuli or more complex stimuli is unclear. In these experiments (e.g., Ornstein, 1969), sensory or perceptual factors could influence any observed differences in duration judgments, not cognitive load per se. Therefore, we have not included those kinds of studies in the present meta-analysis. As much as possible, we included only comparisons of experimental conditions in which the number of presented stimuli were comparable in high and low load conditions, and in which the main manipulation involved cognitive load per se, not merely a single-task (timing only) condition compared to a dual-task (timing plus a secondary task) condition. In some studies that made that comparison, in the dual-task conditions participants were instructed to make verbal responses that created a sensory–perceptual “filling” of the interval. According to the well-known *filled-duration illusion* (see, for example, Poynter, 1989), duration estimates lengthen if a duration is filled, as opposed to unfilled. In order to determine whether cognitive load per se affects duration estimates, we needed to rule out the possibility of an artifactual change in duration judgments attributable to the filled-duration illusion.

1.3. Duration judgment paradigm: models and predictions

Some studies have revealed that the duration judgment paradigm affects duration estimates. In the *prospective* paradigm, a person is aware prior to or immediately upon the onset of a duration that a duration judgment is necessary and important. In contrast, in the *retrospective* paradigm, a person becomes aware only after the duration has passed that a duration judgment is needed. The current duration judgment literature reveals several major theoretical controversies: (a) Do the processes underlying prospective and retrospective duration judgments differ and, if so, in what ways? (b) Are prospective duration judgments affected by attentional processes, or can they be explained by other kinds of processes? (c) Are retrospective duration judgments affected by memory processes, or can they be explained by other kinds of processes?

Prospective and retrospective paradigms sometimes show opposite effects on duration judgments (e.g., Block, 1992; Block & Zakay, 1997), but this is by no means an invariable finding. For example, Brown and Stubbs (1992) concluded that “similar timing processes operate under prospective and retrospective conditions” (p. 545). One way to resolve this issue is to determine whether various kinds of cognitive load differentially affect duration judgments under the two paradigms. If cognitive load affects duration judgments in different ways, this finding will finally resolve important theoretical arguments about whether prospective and retrospective duration judgment processes are similar or different.

We first investigated duration judgment paradigm as a potential moderator variable. Because it was, we conducted separate analyses to investigate the specific cognitive load and other moderator variables that affect judgments in each paradigm. Consider the broad context of models of prospective and retrospective time estimation and how they do or do not make predictions about effects of cognitive load.

1.3.1. Prospective paradigm

Treisman (1963) proposed one of the first formal models of an internal clock, which included a pacemaker, a counter, and a comparator mechanism. At present, the most influential pacemaker-accumulator model of prospective timing is scalar expectancy theory (SET). It was proposed to explain the timing behavior of animals such as pigeons and rats, and it remains influential (e.g., Church, 2006; Gibbon, Church, & Meck, 1984). According to SET, animal timing relies on an internal clock