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The role of verbal behavior on human timing

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By

Carolyn A. Brayko

Dr. Ramona Houmanfar / Dissertation Advisor

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We recommend that the dissertation
prepared under our supervision by

CAROLYN A. BRAYKO

Entitled

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Ramona A. Houmanfar, Ph.D., Advisor

Steven C. Hayes, Ph.D., Committee Member

Matthew Locey, Ph.D., Committee Member

Sushil Louis, Ph.D., Committee Member

Yvonne Stedham, Ph.D., Graduate School Representative

David W. Zeh, Ph. D., Dean, Graduate School

December, 2017

Abstract

The predominant literature on time takes a decisively mentalistic view of timing which involves the modeling of internal timing devices. While the popular vein of timing research has produced large quantities of data on timing, still relatively little is known about tracking time for minutes at a time, over a period of time. Taking a behavior analytic approach, time is defined based on environmental change, and the act of tracking time is attending to relevant changing environmental change. This dissertation investigated the extensive philosophical and empirical literature regarding psychological timing. Focusing particularly on verbal humans, the discussion explores the opportunities for a more pragmatic approach to studying time, increasing the chances for future applied research. More specifically, the aim for the conducted studies were twofold: investigate the general patterns of timing responses in humans for longer durations (i.e., three minutes) over a sustained period (i.e., 30 minutes) and explore the conditions under which different verbal stimuli establish stimulus control over timing behavior. Results indicated that sampled groups tended to underestimate time when providing time estimates and overestimate time when producing intervals. Providing verbal antecedents successfully prompted the self-generation of timing rules, however, timing methods only appeared to effectively reduce timing error when participants' timing responses were also verbal (i.e., time estimate). Significant interference effects were found between the two tasks required of the participants, particularly when the non-timing task presented as more challenging to the participant. The final discussion connects the dissertation findings to the existing literature and proposes promising avenues for future research.

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I. Introduction

The topic of time has intrigued humans for millennia. Scholars believe that many ancient structures, such as the Egyptian time stick (c. 10^{th} century B.C.) and Stonehenge in England (c. 2000-1500 B.C.), served as ways to understand hours and periods of the year (Priestly, 1964). Although humans have been creating devices to track time for thousands of years, there is still much to be learned about how we organize our behavior with respect to time. Time and timing interest many, particularly those who value, study, or otherwise are constrained by time. Although not universal, the concept of time has become an essential element in many cultures. Whether its viewed as linear, cyclical, or based on some other pattern, humans track events based on external environmental change (Scaglion, 1999).

More specifically to the field of behavior analysis, many behavioral principles rely on temporal relations. Most notably, the latency between behavior and consequence has been studied in a variety of forms, from the early animal labs, delay discounting work, and feedback studies. Nevertheless, there is little cohesion between the researcher groups engaged in basic timing research, and most of the literature that has been produced, does not translate easily into practical application.

There are a range of issues that arise from parallel programs of research developing in isolation. Matthews and Meck (2014) name three problems in the timing research: (1) the extreme susceptibility of temporal judgments to be manipulated by extraneous variables, (2) major findings are only robust at the group level and are washed out by idiosyncratic differences at the individual level, and (3) the external validity of many time studies are suspect on the basis that most research is focused on activity and contexts that are highly contrived. These three concerns, along with those specific to behavior analysis, are the basis for the dissertation research discussed below. As a pragmatic science, behavior analysis has a history of focusing on behavior change that brings meaningful impact (Baer, Wolf, & Risley, 1968; Houmanfar, Alavosius, Morford, Herbst, & Reimer, 2015; Skinner, 1971). The issues with timing in our current society are countless: prioritization, writing effective "to do" lists, saving for retirement, punctuality, respecting deadlines, etc. By expanding our basic knowledge of time tracking for longer periods of time, and how that level of awareness is developed, applied researchers and practitioners could use these findings to create procedures that would enhance efficacy and efficiency of time-related tasks in people's daily lives.

Many scientists, have taken note of similar weaknesses within the timing literature, particularly when considering the potential impact of verbal behavior. Wearden (2008) commented on the citation gaps between disciplines covering the same phenomena. He mentioned that in articles discussing the role of language in timing repertoires there is very little mention of "the names of the researchers who have made major contributions to time perception research in recent years" (p. 163). As the field expands, it becomes more likely that parallel research programs will develop without much awareness of one another. From the other perspective of applied scientists and practitioners, Berman Brown and Herring (1998) mentioned how they failed to see any relevant and helpful information in the basic timing literature that would work well in the workplace. In this case, little or no overlap could indicate that the foundational group is not serving the needs of the consumer group. Either way, as isolation increases within this subject matter, redundancies and missing opportunities to develop a coherent and cohesive basis for understanding timing issues also increases.

The following sections provide an overview of various philosophical assumptions and how the differing assumptions about time affect the types of research conducted. Mainly, the discussion focuses on the ontology of time, whether it is stimulus or event, and the interactions between physiology and behavior acquisition as mechanisms for responding to time. The timing theories introduced are evaluated based on the values of coherence and pragmatism. The discussion then turns to a literature review of the representative basic studies highlighting the major findings in timing research.

The overarching goal of this dissertation is to explicitly discuss verbal behavior as an important, but widely neglected, factor in human timing research. Further advances in timing research could be made by incorporating a functional account of language as a major factor for developing and maintaining timing repertoires. The primary aims of the tested methodologies were to provide a preliminary framework for investigating verbal stimuli as it interacts with various timing responses. The series of studies investigated factors for both increasing timing accuracy and reducing timing variability using verbal antecedents prompting attention to environmental change. The challenges of investigating timing repertoires at the individual and group level as well as manipulating verbal stimuli as an experimental variable are discussed, along with the implications and value of pursuing this line of research in the future.

II. Philosophy of Timing Research

To begin, the difficulties in studying time is greatly linked to its challenging philosophical history. Better understanding of the underlying philosophical differences in approaching time, leads to making better research decisions , thus the following section discusses the primary challenges and philosophical disagreements regarding time within psychology. Next the manuscript addresses the values within the natural sciences and discuss timing philosophy with respect to those values. Finally, the discussion shifts to focus on behavior analysis as a suitable field for adding to the already substantive discussion on time.

A. Unique problems with conceptualizing time

Tracking time has been a major source of human ingenuity and creativity for thousands of years (Killeen, 2014; Priestley, 1964). There remains, however, a disparate treatment of time, largely based on differing foundational assumptions about what time "is." Furthermore, there is disagreement as to how organisms respond to time. Outside of the natural sciences, there are scholars who speculate whether it is possible to be objective in analyzing time (Priestly, 1964; p. 12), and who internalize time and timing within the individual (see Kant's *Critique of Pure Reason*, "On time").

Part of the variability and diversity of timing research could be from different views on how to treat time. The two major topics creating opposition are (1) whether time possesses stimulus qualities, and (2) whether organisms process time through an internal timing mechanism. Taking a stance on these topics builds a case for the larger timing issues of whether time is perceivable. Being clear about one's assumptions regarding time "perception" is important in defining the relevant behaviors. Differing assumptions about relevant behavioral origins has a significant impact on how timing research is conducted and analyzed. The following sections unpack the primary positions to determine a philosophical foundation on time that is consistent with behavior analysis.

1. Defining time

Many definitions of time share similar qualities but differ on important foundational issues. For example, few people would disagree that time is a constructed metric. A minute is always a minute no matter what country or universe one may be in. A minute is a constant and a standard, because humans have made it so. What is unusual about time as a metric, however, is that psychologists have historically internalized a process for detecting it. Whether organisms process time through an internal timing device (i.e., internal clock), or track environmental change, or senses time *a priori,* depends on the scientists' perspectives on the causality of behavior. A sample of time definitions is listed in Table 1.

Some of the difficulty of defining time philosophically is that historically, philosophers have analyzed time without the added empirical data available to inform them. Furthermore, philosophers questioned whether time was subject to empirical testing at all. Immanuel Kant's (1724-1804) *Critique of Pure Reason*, a highly influential work in the Western world, described time in the following way:

> Time is not an empirical concept that is somehow drawn from an experience. For simultaneity or succession would not themselves come into perception if the representation of time did not ground them *a priori* (Kant, 1998, p. 162).

Kant's analyses were advancements in a sense, in that he built off the positions of Newtonians and Leibniz (Kant, 1998; p. 7). At the time, there were debates as to whether time was absolute and independent of physical beings and events (i.e., the Newtonian position) or relative to the coexistence of objects and succession of events (i.e., Leibniz's position; Alexander, 1956; p. *xxv*). Studying under Leibniz, Kant adopted similar positions, emphasizing the empirical physical over the metaphysical. For Kant, scientific analysis was important and having a philosophically sound description of time would be helpful for analyses. Kant sympathized with the relative nature of time by stating "time cannot be a determination of outer appearances; it belongs neither to a shape or a position, etc." (Kant, 1998, p. 163). With respect to space and time outside of the organism, his views fit the values of natural science. Within the organism, however, Kant begins to appeal to "intuition" and an "inner state" which aligns with his notion of *a priori* knowledge, or what some could consider the evolutionary history of the organism, that predisposes an individual to respond appropriately without being directly taught.

Today one might say that humans have evolved in such a way to where we can organize and sequence events, both verbally and nonverbally. Most humans orient to environmental changes and develop verbal repertoires for predicting and planning. Nevertheless, by defining time as a stimulus to be perceived, the corresponding research based on that definition begins to investigate internal mechanisms for sensing time rather than identifying the overt behaviors involved when someone is described as "tracking time" by responding to relevant events.

J.J. Gibson's (1975) pivotal chapter "Events are perceivable but time is not" has generated much discussion from timing researchers. At the time of this manuscript's development, Google Scholar reports that Gibson's article has been cited 210 times, with 18 citations occurring in the last year (*i.e*., 2017), demonstrating its continued relevance. Beyond Gibson's ecological background or his information-based theory of perception, most of the citations come from various disciplines discussing the matter of time. Gibson's position was that time is "not perceived, and [it is] not prerequisite to perceiving" (p. 299). Although much timing literature does not include an explicit definition of time, much can be learned about the researchers' assumptions by how they conducted their studies. The type of research that develops from Gibson's definition looks distinct from research based on definitions implying internal clocks, or some form of temporal perception. The former sets the context for observing the environmental manipulations and corresponding behavior, whereas the latter place the emphasis on comparing behavior to formulae inferring mechanisms occurring within the organism.

2. The perils of metaphor in time science

At this point, it must be emphasized that this manuscript only considers philosophical assumptions and definitions that fit a natural scientific perspective. According to Marr (2009) "No object or phenomenon of study in any natural science is considered to be an agent unto itself, never mind endowed with some quality deemed 'free will'" (p. 106). Furthermore, an adequately scientific analysis of time should only include objective measures of the phenomena, in as directly a manner as possible. Until the last few centuries, many psychological events were thought to be inaccessible to empirical study and were either described as pertaining to a soul, intuition, or other internal force that prohibited measurable observation. Oftentimes, describing psychological events involved metaphors to make visible the invisible. Time and timing are no different here.

The likelihood of reification is particularly likely when the concept is invisible and abstract, like time. Gibson (1975) critiques Newton's (1643-1727) treatment of time as absolute in "that events are what 'fill' time, as if time were a container into which events can be put. […] Time is not a receptacle for events" (p. 299). A more contemporary position on the metaphor of time as a container was made in Hayes, Barnes-Holmes, and Roche (2001): "Arranging a past, present, and future along a single so-called dimension is not the same as ordering a small, medium, and large box into a sequence of increasingly larger physical objects" (p. 37). As these authors and others have noted, the risk of applying metaphors for analyzing time is potentially leaving one's assessment at the level of the metaphor as if it were real.

Thinking of time as a container was helpful for mathematicians and physicists, but less so for psychologists. When one's scholastic goal is to generate models that predict natural events, one is creating a modeled metaphor. For example, Killeen (2014) describes time as "based on motion. Sometimes the motion is linear, as sand or water through apertures. But most often time is abstracted from periodic motion, from oscillations" (p. 155). The distinction Killeen makes is an important one because it differentiates two views: one where time is treated like a thing, and one where time is treated like an event.

Whether it is a sundial or a model, we are attempting to make predictions based on previously observed patterns of events. They reveal our assumptions and shape the way research is built on those assumptions. Killeen's metaphor emphasizes the Gibsonian perspective that timing is responding to events, whereas some cognitive models have viewed time and attention as containers for activity**.** These subtle initial differences may seem insubstantial until one examines the larger trends of research and their future opportunities for cohering with other scientific work.

The next section explores the research outcomes and scientific trends for the two major views on time: time as stimulus and time as event.

B. Time as stimulus

Much of the mainstream timing literature proposes time as something to be perceived. Perception requires the body to sense through stimulation, which requires time to be a stimulus. If time is a stimulus, then temporality should be detectable through stimulation, much like pupils dilating in the presence of light or cochlear activity in the presence of sound. In the case of considering time as a stimulus, the assumption is that organisms perceive duration. Methodologically speaking, timing perception refers to the individual's detection of a feature of a physical stimulus (e.g., light or sound durations). Many have also acknowledged that time does not fit with other physical stimuli (e.g., light, sound) which typically can be sensed on two different dimensions: quality and quantity, where quality is evaluated based on the type or form of the stimulus (e.g., middle C versus low B flat, in music) and quantity describes the stimulus magnitude (e.g., the volume of the note played). It may be easy enough to think of duration as quantitative, but it is difficult to picture what the spectrum of temporal quality would look like.

There are several timing theories that either promote or align with a "time as stimulus" assumption. Among the most well-known theories is the Scalar Expectancy Theory, or SET (Gibbon & Church, 1981). SET originated in the cognitive domain which views time as the "interaction of internal clock, memory, and decision processes" (Lejeune & Wearden, 2006). SET postulates that "time appreciate[s] in a linear fashion" (Gibbon & Church, 1981; p. 88), and proposes that cognitive processing devices (e.g., pacemaker, accumulator, long-term memory) "explain the temporal regularities of learned behavior" (Machado, 1997; p. 241). In another cognitive model, Treisman and colleagues use an oscillatory-based approach, which is similar to SET except that the former's internal mechanism consists of multiple parts (i.e., the temporal oscillator and the calibration unit) instead of a single pacemaker (Treisman & Brogan, 1992). The existence of an internal timing mechanism is needed for these theories to work. Starting from the assumption that time is perceivable leads to the notion that organisms capable of responding to temporal constraints must possess some anatomy that processes time.

In a variety of fields, the notion of an internal clock is readily accepted. As such, there are also many terms for this mechanism: biological clock, central timing device, information-processing device, oscillator, pacemaker, etc. There are also copious articles focusing on the neuroanatomy which may be responsible for time, such as the suprachiasmatic nucleus (Damiola et al., 2000), or the fronto-polar and lateral parietal cortex (Peters & Büchel, 2009). For the sake of clarity and concision, the remainder of the paper will refer to any hypothetical construct or putative neuroanatomic process referring to perceiving time as an “internal clock.” It would be unfair, however, to claim that these models are entirely reliant upon an internal timing device, however. As Wearden (2008) points out, “The operation of the internal clock is just the first stage of the process that leads to time judgments, and the clock is embodied in a more complex cognitive mechanism involving both memories of duration” (p. 155).

There are advantages to structuring research around an internal clock and its functions. Organisms tend to organize their behavior in a way that fits with standardized time and timing patterns. As such, there is some face validity to the notion that organisms are equipped with a physiology to detect time. Speaking directly to empirical productivity, a wealth of knowledge has accumulated regarding how organisms respond based on different temporal arrangements and contingencies, all in the name of determining how these internal clocks work. For example, in Grondin’s (2001) comprehensive review “Timing and time perception: A review of recent behavioral and neuroscience findings and theoretical directions,” he notes that those who subscribe to internal clocks are more likely to be interested in testing the capacities of organisms for short intervals (p. 567). Those tests have created a vast basis for understanding temporal discrimination for verbal and nonverbal organisms.

Two significant critiques weaken the initial assumption of the internal clock. First, the limitations of looking for an internal clock are similar to the perils of using metaphor in science: over simplification and reification. Much in the same way that cognitive psychology has adopted the metaphor of the computer as an explanation for how the brain "computes" sensory information, scientists have inferred a clock in our brains. Consistent with Skinner's radical behaviorist view, L.J. Hayes (1992) states "there is little reason to assume that the workings of organic matter will ultimately be found to have the character of machine operations" (p. 140). Creating a specific and visual metaphor to a debatably invisible (or insubstantial) process like time is helpful for thinking about the complex subject matter; however, it is fallacious to assume that organisms function in the same way as the product constructed by those organisms.

Secondly, the internal clock emerged from the original assumption that time is perceivable. From looking at how the history of our assessment of time and time processing has developed philosophically and then scientifically, the original presupposition of the internal clock is not founded upon observable, objective evidence. As Poynter (1989) highlights "the perception of time passage does not involve an obvious transduction of physical energy by a sensory organ" (p. 305). He continues to mention that even though there are physiological systems in our brains (e.g., suprachiasmatic nuclei) they are only considered to be clocks "because their biochemical functioning follows a cyclical pattern of change with a predictable period" (p. 305). To go the step farther to say that these cyclical patterns "cause" timing is still unknown.

Even one of the more prolific time perception scholars, Simon Grondin, has expressed that time is not necessarily a stimulus, thus requiring no exteroceptor (2001). Even in the 21st century, inconclusive behavioral issues become a matter of the brain. Still needing an explanation for timing perception, Grondin stated that time perception is "simply an inner activity in the nervous system" (p. 23). Acknowledging the importance of neural activity in human functioning is not problematic as long as the model fits the phenomenon. An example of a problem that arises based on assuming time perception by internal clock is that individuals are not skilled at reliably telling time without aid. Psychophysicists, and other scientists subscribing to the perception of time via central timing devices, create models to predict timing behavior, and also have to account for when the participant "errs." It is not yet clear whether the participant's timing is flawed or the researchers underlying assumptions.

Despite these admitted issues, studying time in a similar manner to the perception of other physical stimuli provides a rich psychophysical framework and modeling to base a career's worth of work. The literature on time perception is expansive, in no small part to its easily conducted procedures, relative rapidity of acquiring data, and the alignment with the mechanistic models that break phenomena down into smaller parts. Many scientists are content to look at time as a stimulus that can be perceived and collected by a physiological mechanism, not yet convincingly identified. It could also be the case that new researchers coming into the timing literature finds a vast array of timing articles that discuss time as a stimulus and learn to treat time similarly. Zakay (2016)**,** seems to share a similar perspective with Grondin. While he considers the phrase "time perception" to be more metaphorical, "the overall perspective which sees time perception as part of the overall human perceptual system is justified" (p. 55). Whether the phrase is meant to be taken literally, clearly some ambiguity is created when scientists use scientific terms to explain scientific phenomena in a metaphorical sense.

C. Time as events

Returning to Gibson's poignant 1975 chapter "Events are perceivable time is not," we can now review the alternative position on time: time as an event. From his ecological framework, J.J. Gibson's views on time capture the naturalistic perspective aligned with behavior analysis in that the primary source of behavioral influence is in the physical environment. Not all psychologists have accepted the Gibsonian view such as the notable time researcher Wearden (2008) who refers to the 1975 chapter title as "mischievous" and later states "Gibson may be alluding to the fact that no established 'organ' for the perception of time has been identified, although, as noted earlier, the proposition that an internal clock exists has been useful for time psychologists" (p. 164). Unfortunately, Wearden's only counterargument to Gibson's position is to point out the research productivity in this subject area rather than providing an alternative theoretical stance.

Rather than detecting "time," a more parsimonious answer could be that the individual detects patterns of events, either in the environment or their own behavior, which allow for temporal points of reference. Establishing time as perceivable has proven difficult. On multiple levels, time does not fit in with the concepts of stimulus and the resulting stimulation of an organism. Lejeune, Richelle, and Wearden (2006) doubted that different durations of physical stimulus presentations should be considered to fall along the same stimulus continuum in the way that red and green stimuli do (p. 126). Fortunately, time does not have to be considered a stimulus to allow for empirical analysis. The accumulation of research on time suggests that "in spite of the absence of specific receptor channels, duration is a type of information in its own right" (Lejeune, 1998).

Thinking about time as a measure of environmental events, is not a new concept. Over a century ago, William James commented in his section of *Principles of Psychology* (1890) "We have no sense for empty time" that "Awareness of change is thus the condition on which our perception of time's flow depends" (p. 620). He further clarified that: "there exists no reason to suppose that empty time's own changes are sufficient for the awareness of change to be aroused" (p. 620). James means that the environment is constantly changing regardless of whether an individual acknowledges those changes. Furthermore, one could interpret his words to mean that the passage of events in time is not sufficient for an individual to "perceive" time; thus, it is more the activating of attending to change that results in time perception.

It is sometimes helpful to distinguish between time as a measure of event sequences versus time as past, present, and future. However, in terms of the theoretical assumption of how organisms track time, we can look at both processes in the same way. L.J. Hayes (1992) stated that the past and future "express a realization that although there is only now, now is a condition of continuous change" (p. 144). In her article about the psychological present, Hayes emphasizes that the only reality is the present and that the present is constantly evolving. Even though verbal humans can construct statements about the past or future, they will only ever be doing so in the present. Nine years later, S.C. Hayes, Barnes-Holmes, and Roche (2001) support this view:

> In a nonarbitrary sense what underlies 'time' is merely change. Change is always unidirectional, from now to a new now, or from this to a new this, never from a new this to an old this. Nonverbal organisms are exquisitely sensitive to sequences of change […] but abstracting the physical dimension along which temporal / causal comparatives are arranged is a highly verbal action" (p. 34).

Not only does viewing time as a measurement of change remove the difficulties of inferring an internal clock, but it also serves to answer other questions about time. For example, if time is the transpiring of events in the present moment, it is a simple way to further explain why things can never revert to the way things were. An event remembered is never the same as the event itself when it happened. An organism on an extinction protocol does not return to an unlearned state. Nevertheless, nostalgic statements about making a nation "great again" or dreaming about a future where equality exists are arbitrary verbal statements, about a past and future, taking place in the present.

Speaking less abstractly, Gibson (1975) spells out how he supposes that the biological organism tracks time as events rather than perceiving time itself. He states that contacting the present moment "comes from proprioception, that is, from the perception of the body of the observer himself as distinguished from his environment. […] What is experienced is a moving self in a stationary environment" (p. 300). Noticing relative change all contributes to how individuals learn and develop in time.

Just as the time perception labs have developed models, other psychologists have developed their own framework for tracking time based on changing contextual events. Less well-known but theoretically viable, is the change/segmentation approach developed by Poynter (1989). Sometimes referred to as the contextual change model, Poynter's framework aligns with the assumption that time is no more than the interpretation of change. Although Poynter was also sympathetic to a cognitive position, he denied the need for an internal clock, or “a single method for judging duration for all individuals and all contexts” (p. 309). Poynter states that the change/segmentation model relies on several variables such as “the duration of the interval to be judged, whether the judgment is ‘prospective’ or retrospective’, and the temporal pattern of subintervals (regular vs. irregular)” (p. 310). Using these points, the change/segmentation model maps on well with behavioral theory.

Learning how one operates within an environment based on the context of standardized time is a helpful skillset when planning activities, making deadlines, or judging whether to drive through a yellow light. Yet, there are some legitimate barriers to studying the behavioral phenomenon of attending. Empirically, measuring a level of awareness is illusive. Contacting something either by touch or sight may imply that we have become “aware” of something; however, research on priming demonstrates that subtle cues may be presented and even looked at by an individual, but not “remembered.” Simply measuring eye-tracking, which would answer the question “Did this person see stimulus X?” does not resolve our issue of whether the individual was aware. The position of this manuscript and the following studies suggest that awareness can be discussed as the behavior of “orienting” and that it is extremely important on the basis for understanding how an individual learns about time based on change. Not only would this level of understanding aid the timing literature, but would also provide another foundational layer to operant theory.

Recent empirical work has supported Poynter's model (Brown, 1995; Kladopoulos, Hemmes, & Brown, 2004). The advantages of adopting the contextual change model is that it relies on observable stimulus changes which can be objectively measured and strategically manipulated to produce findings that replicate data procured from cognitive psychologists. The theoretical advantage is that it is more parsimonious in that it does not assume hypothetical, mental entities intervening with the psychological process.

Attending to time has been widely acknowledged to be pivotal to time judgments, regardless of how one explains the nature of time and timing. Grondin (2001) himself has posed the question "In what way does attention influence the time perception process?" (p. 34). By looking at time as change, using procedures based in a behavior analytic tradition, a fruitful program of research could develop on the interrelation of attending repertoires and timing.

Although he articulates the importance of observable events in the environment as the mechanism for tracking time, Poynter's "change/segmentation" model is also rife with hypothetical constructs that may not be useful to a behavior analyst. Some points of derision may arise when a behaviorist reads about how Poytner (1989) explains that timing behavior, "is based on the ability to remember the sequence of events experienced during an interval, and to infer inter-event duration on the basis of the 'intrinsic characteristic of that which endures' in memory" (p. 309). For example, as he describes factors influencing timing accuracy, shorter time estimates are produced because the events "are poorly organized, yet have priority access to attentional capacity" (p. 317).

Attentional capacity is unclear, not to mention the conditions under which access to it is prioritized. Further, he explains “Events that are hard-to-remember, or dispersed in a way that does not lead to efficient storage of temporal segments, have little value as temporal markers” (p. 317). These assumptions begin a cycle of self-referential logic which has limited value for identifying the relevant features (topographical or functional) of the event.

For behavior analysts, we may have to be willing to suspend judgment about the mentalistic philosophical assumptions in service of noticing the influential factors. As Poynter suggests, attending to salient changes in the environment is key. Tracking all changes in the environment is neither possible nor likely to be functional for the individual; thus noting that attention to relevant stimulus change is important for identifying the behavioral repertoire involved in timing responses. It’s not just attending to all change, but change that is meaningful for the organism.

D. A behavior analyst’s theoretically consistent account of time

Behavior analysts have a special kinship with time on multiple levels. For one, the strength of the within subject design with repeated measures are often tracked over time. Skinner’s cumulative record demonstrates orderly behavioral events under various conditions in real time, some of them even being time-related (e.g., fixed and variable schedules; Ferster & Skinner, 1957). Yet, behavior analysts have been careful not to overvalue time. Unlike traditional developmental psychology, time is never treated like a cause for behavior. Focus has remained on what individuals achieve within a time constraint or temporal context.

Some theoretical discussion about time has emerged in behavior analysis. Perhaps it is in response to one of the major assumptions that learning requires some involvement with one's "learning history." As mentioned previously, L.J. Hayes's (1992) article on "The psychological present" discusses the problematic nature of one's learning history as an explanation for events. She says "when the past to which we refer in saying 'there *was* a past' prevailed, it too was a present event: an earlier present" (p. 141) and later emphasizes, "From this perspective, a learning history may be conceptualized as a succession of present events, wherein each new present entails all previous presents" (p. 143). Time as a context and a basis for philosophical discussion is no stranger in the behavioral field.

Yet, there is even some distance between the more mainstream behavior analysis and the behavioral psychologists who study time. Few articles in the flagship journals of behavior analysis, particularly in the applied journals like *Journal of Applied Behavior Analysis* (*JABA*) and *Journal of Organizational Behavior Management* (*JOBM*) have discussed the relevant repertoires related to time. Even greater distances lay between behavioral scientists who have studied time and psychologists in other domains. Reading papers from various sources on a topic, there seems to be little overlap in cited sources. If groups of researchers read only the work of their familiar peers, the possibility of creating redundancy (or worse, unknown discord) greatly increases.

One of the goals of this dissertation research is to begin bridging the gaps between labs and disciplines to work toward a more cohesive and coherent portrayal of time. Natural sciences studying phenomena with integrity should produce findings that cohere with the findings in other scientific domains. Thus, behavior analysis as a natural science should approach the work of others with different assumptions eagerly, rather than defensively. The following review and research will attempt to embrace a wide range of work to ensure that the proposed empirical work is productively using the consistent findings across the timing spectrum. The section below will provide the specific values and framework from which the dissertation will unfold.

1. Behavior analysis as a natural science

From a philosophical point of view, we need to be clear about to what we refer when talking about time. For example, William James makes this point multiple times in his 1890 textbook *Principles of Psychology* (James, 1890). At one point, James analyzes the thought "the pack of cards is on the table" and how one may be tempted to deconstruct the sentence into smaller parts, such as the part of the thought about the cards and the part of the thought that is about the table to assemble the parts into knowing the whole. He states "What a thought *is*, and what it may be developed into, or explained to stand for, and be equivalent to, are two different things, not one" (p. 279). This differentiation becomes important when investigating the concept of time and an organism's interaction with it, in that "To be conscious of a time interval at all is one thing; to tell whether it be shorter or longer than another interval is a different thing" (James, 1890; p. 614). James' account of timing and separating a behavior from what is said about that behavior, is consistent with philosophical texts within behavior analysis. J.R. Kantor's interbehavioral texts heavily emphasize this point as well**.** Kantor (1953) makes the distinction between "pristine data" and "transformed data" to separate the thing or event itself from what is said about or constructed upon that thing or event (p. 31).

Lejeune, Richelle, and Wearden (2006) mention Skinner's resistance to treating time as a stimulus and refer to his discussion of temporal matters in *The Behavior of Organisms*: "the problem is how time as a dimension of nature enters into discriminative behavior," (p. 132). The key phrase Skinner uses to describe time is "dimension of nature"; he does not describe it as a thing, neither necessarily a perceived event. He appeals to some feature of the natural environment to which an organism can orient and respond.

A common misconception of behavior analysis is that because there is no appeal to the "hypothetical interior" that behaviorists deny the importance of the interior. As Thompson (2007) succinctly summarizes in his article on relating functional systems: "There is nothing inherent in a functional analysis of behavior that requires all of the variables to be located external to the skin" and elaborates upon multiple examples about how operant behavior co-occurs with "endogenous physiological and biochemical events" (p. 436). The behavioral perspective, upon which this dissertation is based, holds that the brain is not to treated as a mysterious black box of causality, rather as an organ necessary but insufficient to explain the behavioral event. More importantly, the inductive approach commonly adopted by behavior analysts allows to make steady, cumulative progress based on the evidence without making assumptions about hypothetical entities. Behavioral theory "insist[s] that behavior presents a primary datum for psychology which is not to be treated as a mere symptom of underlying structures of either the cognitive or physiological kind" (Costall, 1984). Rather than acknowledging that the organism possesses an internal clock to correctly or incorrectly tell time, it may be more parsimonious to accept that there is another behavioral process at work.

No one scientific discipline bears the responsibility of explaining natural phenomena from all levels of analysis. Neuroscientists, biologists, and psychophysicists, have produced work on time that is consistent with their targeted level of analysis (i.e., neural networks, cellular processes of living organisms, predictive models of animal behavior). Maintaining focus on the behavioral level of analysis creates the space needed to investigate time from a behavior science perspective, without requiring inference of physiological and mental mechanisms. Lejeune, Richelle, and Wearden (2006) cite the importance of Skinner's early work on operant methodology and externally-focused, naturalistic theory on the development of animal timing research. As they put it, Skinner's theory is useful for explaining "how it happens that animals and humans can show sensitivity to temporal properties of events" without requiring direct perception of time as a stimulus (p. 125). So long as the work of science is done in a naturalistic, parsimonious way, in theory all disciplines' findings on time should coalesce.

2. Comprehensive is not eclectic

The value in thinking about developing scientific investigations systemically is in the quality of the outcome: a productive and progressive knowledge base that stimulates both basic research and application. Building a program of research that is both philosophically grounded but transcendent of disciplinary boundaries promotes two important qualities in research: comprehensiveness and parsimony. Heuristically, the two may seem diametrically opposed in that to be comprehensive you might consider all possible factors responsible for a phenomenon, making for a complex analysis; whereas, to achieve parsimony, one may think about the 'silver bullet' explanation that accounts for the studied phenomenon. Upon further reflection, the beauty in science is that truly parsimonious explanations also function comprehensively.

Building more systemic research agendas that demonstrate coherence across areas of interest related to a construct like "time" would be valuable. That is not the same as saying that one's scientific study should meet the needs for all researchers. As previously discussed, part of the difficulty in studying time and time-related issues is that time has been conceptualized differently in different disciplines. Most fundamentally, there are disagreements about what time "is," let alone to what matters time applies, and in what capacity. Thus enters the potential problems of eclecticism. Colleagues at Yale University, Sternberg and Grigorenko (2001) differentiated between what they called "unified psychology" and eclecticism. From their views on how research institutions categorized subdomains of psychology, they illustrate how the organizational system creates contingencies for siloed work rather than unified study. They have also highlighted the problems with eclectic collection of ideas or techniques "but they may not sufficiently synthesize them to truly be unified psychologists" (p. 1078).

Being able to draw relations among scientific findings across disciplines may create a more robust analysis but is rarely sought. For example, in timing research, domain labels (i.e., behavioral, cognitive) are ignored which seems to embrace an interdisciplinary, systemic research agenda. Problems may arise, however, if the underlying philosophical tenets are also ignored, creating conceptual confusion in the literature. Part of this could be due to what Costall (1984) noted about the theoretical levity some scientists have taken with time: "cognitive psychologists have felt free to disregard [Skinner's] metaphysical criticisms and insist that choice of means and ends in sciences is merely a matter of taste" (p. 110). Successful comprehensive analyses should also be unified, or synthesized in a way that does not conflate opposing philosophies into an uninterpretable black hole. Such voids exist in the timing literature, which could be a reason why the precision and depth of timing investigations are expanding but the scope is narrowing.

Promoting experimental work that fills in the gaps between isolated research areas can more effectively point the scientist into more constructive and progressive directions. Scientific activity is cumulative and progressive, which according to Kantor (1958), "constitutes an enterprise for ascertaining the structure, operation, and interrelation of things and events," (p. 98). Reese (1989) cited the various categories by which theories may be evaluated, focusing on "progress." He stated "A theory or an approach is progressing if its scope is being widened and/or if its precision is being increased" (p. 22). Arguably, the precision of timing models are increasing; but it is difficult to assess the external validity or generalization of some of these findings. For example, some models successfully predict timing judgments for only short durations (i.e., 2 to 4 seconds) or only for static behavior patterns (Machado, 1997). The volume of timing research swells, but for most, it appears the aim is to increase precision of the previously established timing conditions and procedures. It is debatable whether the scope of timing research has expanded in a way to call it progressive.

While progress should not be the only point of evaluation, strong theories produce progressive research which sets the occasion for greater applicability. In timing research one can see there are certain areas at risk for losing their progressive edge. Not to be confused with productivity, progress leads to the exploration of phenomena at greater scope, breadth, and depth (S.C. Hayes, Barlow, & Nelson-Gray, 1999). When a scientific domain has invalid assumptions, and is inconsistent with the goals of natural science, progress is inherently limited. S.C. Hayes and Berens (2004) present an additional perspective which posits that "a bottom-up strategy only makes sense if it actually leads to analytic-abstractive theories of complex behavioral events. Behavioral principles are not ends in themselves" (p. 343). Put in another way, science should produce increasingly comprehensive conclusions from the accumulation and extension of theoretically consistent findings. The timing literature has developed solid frameworks of increasingly complex findings about particular timing conditions, but there has been little forward movement to understanding how these findings generalize to larger, naturalistic temporal repertoires.

3. Parsimony is not restrictive

Building a coherent foundation of knowledge around any phenomenon will result in an increasingly complex analysis of it. That does not require, however, that the theoretical assumptions must also be complex. Parsimony, or valuing the simplest reasonable explanation for an event, can help as a guide for choosing among multiple theoretical approaches. For example, Poynter (1989) who advocated for a contextual change model of time mentioned that accuracy in Poynter and Homa's (1983) study was greater in empty intervals which could be explained in change/segmentation terms, accuracy resulted from “freedom to mentally generate individual- and duration-specific markers for efficient storage and retrieval of temporal information” (p. 318). These assumptions are problematic because it adds a layer of hypothetical mechanisms which cannot be (or at least have not yet been) observed. Even though the change model holds considerable value in orienting the scientist to the manipulable environment, basing its validity upon a mentalistic framework jeopardizes the whole enterprise.

Overall, the goal of the current investigation is to construct research that is systemically integrated with the existing literature. One may look at a parsimonious conclusion as being merely simple, or overly restrictive in a way that is too general or isolated to do much good (Shimp, 1999). Although topographically simple, the function of parsimony should afford multiple avenues of research across disciplines. In some ways, adding layers of unnecessary complexity adds rigidity to the process that distracts the researcher from contributing to the overall goal of increasing precision, scope, and depth.

Evidence that may not support the Poynter’s tenets of “mental freedom” and “efficient storage” could also lead to scientists rejecting contextual change as a promising avenue of research. Just as eclecticism sets the occasion for disorganized and confusing research programs, excessively complex explanations beyond what the scientific evidence demonstrates introduce unnecessarily restrictive, and potentially invalid investigations. If we have evidence indicating that orienting to relevant environmental change leads to improved timing, there may be greater risk than benefit in pursuing additional hypothetical mechanism. Ironically, Poynter (1989) cites “parsimony” as a distinct advantage of his change/segmentation model over the other cognitive timing models. Relative to the models he was examining, he was right to reject the notion of the internal clock "by accounting for the 'nontemporal' change between delimiting events" (p. 329); however, from a behavior analytic perspective, further simplicity can be achieved by avoiding notions of temporal perception via internal clocks altogether.

4. Comprehensive parsimony in functional contextualism

In reviewing the extensive literature on time, particularly when crossing into other psychological domains, it becomes necessary to firmly establish the philosophical core of the arguments one plans to make in defense of their empirical work. In the past several decades, more behavior analysts have discussed the explicit declaration of a philosophical worldview and the merits therein. Starting principally with S.C. Hayes, L.J. Hayes, and Reese in 1988, they reviewed Steven Pepper's (1942) philosophical text *World Hypotheses* as a vehicle for introducing the clarity that is gained by adhering to a particular worldview (c.f. Marr, 2009). Pepper posited that all philosophical positions can be reduced to four core philosophies, each with its own root metaphor: formism, mechanism, organicism, and contextualism. Most behavior analysts are most familiar with mechanism and contextualism, based on the historical development of behaviorally theory and research.

The primary goal in mechanism is to break the phenomena of interest into increasingly smaller parts to understand the larger whole. Although rarely explicitly stated, much of timing research fits within the mechanistic worldview. To better understand timing repertoires, researchers have taken specific aspects of timing (e.g., discrimination between stimuli presented at different intervals). Whether with humans, pigeons, or mice, research is conducted in a laboratory setting with tightly controlled conditions where the only changes occurring are the pre-programmed tasks. It is rarely stated, but the implicit assumption of this accumulation of timing research is that it will cohere into a larger knowledge-base for how organisms interact with time. Mechanism is a traditional and lauded form of scientific research. It can be predictable and conservative in service of its success criterion; however, a critique of mechanism is that it can lead to "science for science sake." This, of course, is only a problem if one's perspective is that science should bear impact on a larger level.

S.C. Hayes, L.J. Hayes, and Reese (1988) identified contextualism as the framework that fits best for behavior analysts for whom producing research with pragmatic and applicable effects is their analytical goal. Later articles building off this seminal piece (S.C. Hayes, Barnes-Holmes, & Wilson, 2012; Vilardaga, S.C. Hayes, Levin, & Muto, 2009) introduced "functional contextualism" which aims "to predict-and-influence, with precision, scope, and depth, whole organisms interacting in and with a context considered historically and situationally" (S. C. Hayes et al., 2012; p.4). Successful research questions advocate for "successful working" which is a pragmatic goal, recognizing the "truth" of findings based on how well it works in its relevant context (S.C. Hayes, 2004). Adopting successful working places a different contingency on researchers studying natural phenomena. Although experimental control is highly valued by all scientists, those subscribing to a contextual worldview focus on research with high external validity.

Those applying functional contextualism to timing would be more interested in investigating a timing repertoire as a holistic, observable event under conditions supporting externally valid findings. They would support stating their scientific goal “a priori in order to serve as a guide to pragmatic truth” (Vilardaga et al., 2009; p. 110) wherein this “ultimate goal” is the prediction and influence of behavioral events as manipulated by the environment (i.e., context; (S. C. Hayes, 2004; p. 647). There is little to no timing research that adopts this perspective. Machado (1997) specifically mentioned that neither SET nor BeT, two of the most common timing models, speak to the acquisition of timing repertoires. Furthermore, very little research to date has explored the functional contribution of verbal behavior on timing.

The current literature review attempts to expand upon the existing time literature such that the work done outside of behavior analysis is addressed to provide a roadmap for functional contextualist goals. Additionally, the bulk of the timing research has mechanistic elements and should not only be appreciated for their contribution to science but also evaluated based on mechanistic goals. It is not constructive to critique psychophysics literature on the just-noticeable-difference of short intervals based on the fact that it does not readily apply to ‘real life’ (Shimp, 1999). Thus, for the following review of the literature, summaries and conclusions will be based on the assumed intent with which the research was conducted. The conducted research for the dissertation project, however, attempts to bring what we know about mechanistic timing so we can apply it to more generalized, externally valid settings for verbal humans.

III. Timing Research

Moving away from a philosophical discussion, we will present a representative sample of findings from basic timing research. Understanding the commonly used approaches to investigating timing has helped with the development of the studies conducted. Regardless of the mechanism(s) responsible for timing repertoires, there is a vast array of data that paint a comprehensive picture regarding the relative capacity of individuals to time and sequence their activities and environment with some degree of accuracy.

A. Timing research from different perspectives

To begin reviewing the timing literature, the discussion will acknowledge the value of the work done in psychological domains outside of behavior analysis. The problem of scientific silos is not a new issue. Over 100 years ago, Edwin Holt, J.J. Gibson's mentor, stated, "Will it not be a source of strength for all if [psychologists] can manage to keep a sympathetic eye on the methods and discoveries of one another?" (from Holt, 1915, as quoted by Costall, 1984). One could argue that the current discord observed within the timing research is the accumulation of empirical isolation over several generations. A review of the representative literature in different domains will help orient the conversation to a more inclusive, comprehensive analysis going forward.

1. Psychophysics of time

Whenever the research question may be construed in terms of perception, there are likely to be psychophysicists studying it. According to Merriam Webster psychophysics is "the branch of psychology concerned with the effect of physical processes (as intensity of stimulation) on the mental processes of an organism." As the name implies, this work is highly mathematical and measures psychological responses as a function of stimulus quality and quantity. Regardless of differing philosophical perspectives on defining time, "Since the nineteenth century, psychophysics has explored time perception in humans by using classical procedures, involving the discrimination, production, reproduction, or comparison of durations" (Lejeune, Richelle, & Wearden, 2006; p. 129). Time has been a fruitful subject matter for psychophysicists and has produced increasingly complex models for how individuals interact with temporal features of the environment.

As Lejeune and colleagues (2006) note, the psychophysics of time has been discussed similarly to other forms of perception, such as with visual and auditory stimuli. Many empirical questions have been posed, and among them, "Two principal issues arose. One concerned the relation between mean measures of time judgement and the real-time values of presented events … [and] The other issue concerned relations between variability of time judgements and the mean" (p. 129). That is, the issues of timing accuracy and timing variability. When studying how well organisms can tell time without a clock, it seems natural to compare subjective time (i.e., the individual's reported experience) with objective time (i.e., time as a metric). Timing accuracy may be questionable, particularly with longer durations, but researchers may also find timing variability important to consider. After all, if there is no universal time except the man-made construct, some may argue that organisms may have developed to detect steady patterns which would allow them to respond with low variability, even if they were consistently inaccurate.

In a sense, psychophysics tests the organism's capacity for perceiving noticeable differences between stimuli as well as how well the individual perceives stimulus changes, like in scalar timing. At least for short periods of time, humans and animals can detect, either visually or audibly, a noticeable difference between two interval lengths. Furthermore, timing perception is said to be manipulable based on how different durations of stimuli are presented sequentially (see Grondin & Plourde, 2007 and Killeen, 2014, among others, about the kappa effect). Psychophysics literature has also demonstrated that sensitivity of discrimination between two different durations decreases as the intervals increase (Grondin, 2012; Lejeune & Wearden, 2006). Based on these findings, researchers have discussed the "scalar" property of time; that is, that the individual's sense of temporal relations alter in an orderly fashion as the interval changes.

The hallmark of psychophysics is in its mathematical modeling of psychological phenomena as it relates to systematic variation of physical stimuli. In addition to using theories of timing models, much of the psychophysical literature relies upon general principles like Weber's law (Grondin, Meilleur-Wells, & Lachance, 1999; Namboodiri, Mihalas, & Shuler, 2016), which is a ratio asserted to be a constant in determining how great a stimulus change must occur for an individual to notice the difference between the two stimuli. Based on this tradition of modeling formulae to predict behavior related to time, studies conducted in this area search for inconsistencies in the established theoretical models. Even the highly cited and validated Weber's law has been challenged in that the Weber's fraction only reliably predicts behavior for a narrow range of durations (e.g., 0.2 to 2 seconds; Bizo, Chu, Sanabria, & Killeen, 2006). Grondin (2001) summarizes the scholastic style of the psychophysics domain by his comments on Weber:

> Weber's law is actually not a law, nor is it a goal; it is a guide, a principle. It helps integrate research results in an orderly view but should not prevent researchers from observing other principles, or laws, waiting to be uncovered (p. 38).

As such, the literature on time from a psychophysics is iterative, highly inductive, and results in constant meticulous recommendations for updating models.

Although the focus of this dissertation research does not focus on mathematical modeling for predicting the timing behaviors of long intervals, it is worth briefly summarizing the more commonly used timing theories used in psychophysics. It is still largely unknown how adequately these models account for timing behavior for longer durations (i.e., three or more minutes) and future studies may want to consider how the data below fit within such models.

A commonly cited cognitive theory of timing that was introduced previously is the scalar expectancy theory (SET) which "explains timed behavior in terms of an interaction of internal clock, memory, and decision processes" (Lejeune, Richelle, & Wearden, 2006; p. 130). Specifically, SET gets its name by the theory that temporal estimates are related to perceived distance to reinforcement (i.e., expectancy) and that the variance of temporal discrimination divided by the mean temporal estimates will predict responding (i.e., scalar; Lejeune, 1998; p. 132-133). Support for SET continues to accumulate (Wearden & Lejeune, 2008), although there have been studies that do not support SET (Grondin, 2012).

Other models have been developed to explain timing repertoires without an internal clock. Jones and Boltz (1989) is a cognitive model that does not utilize a central timing device. Instead, they focus on the role of attention called the "dynamic attending approach." Similar to the Poynter's change/segmentation approach (1989), the dynamic attending approach accounts for timing behaviors through attending to changes in the environment. Jones and Boltz's seminal article on the dynamic attending theory aimed to show that both "analyses of event structure are critical to theories of attending… [and] attend[ing] to events that vary in temporal coherence" are empirically viable and necessary for conceptualizing time (p. 461-462). Jones and Boltz's model is consistent with the ecological perspective that time can be thought of as events and the degree to which change occurs functions differently for the organism. As a model for predicting sensitivity to intervals of an event, dynamic attending theory holds two main assumptions: that there are "external rhythms, which are created by distal events, and internal rhythms, which actively generate temporal expectancies" (Large & Jones, 1999). Support has also been demonstrated for this perspective (Henry & Herrmann, 2014; M. R. Jones, Moynihan, Mackenzie, & Pue, 2002).

Several behavioral models exist to describe timing behaviors. One of the most common model is the Behavioral Theory of Timing (BeT; Killeen & Fetterman, 1988) wherein they "presume that the adjunctive behaviors may come to serve as discriminative stimuli for subsequent responses" and that "behavior is the mediator of temporal control (p. 274). While the foundations for this theory fit very well with behavior analysis, BeT has appealed to many scientists with psychophysical interests. BeT proposes mathematical models, based on a Poisson process wherein "the pacemaker rate varies proportionally with the rate of reinforcement" (Lejeune, Richelle, & Wearden, 2006; p. 138). Building off the idea of temporal regulation from a sequence of behavioral states, Machado (1997) proposed the Learning-to-Time (LeT) theory which is meant to address the behavior change that occurs when an organism learns a new skill (in this case, timing). These behavioral models (among others, read Lejeune, Richelle, & Wearden, 2006 for a review of the most common behavioral timing models and how they contribute to the research on animal timing) have set the occasion for much research to be done, but may also make one wonder about all the different time theories that have emerged over the past several decades.

What is promising about predictive modeling is that the search to understand timing interactions has produced a strong basis of inductive, integrative work. Embracing the values of skepticism, these scientists have been both extremely transparent about their processes and findings, and have begun evaluating their interrelatedness As Machado, Malheiro, and Erlhagen (2009) described it "examining the two models [SET and LeT] jointly has proved to be a fruitful exercise because it has led us to identify not only serious problems with each model but also important but unknown properties of timing and temporal memory" (p. 424). Establishing more systemic timing research leads to new avenues for exploration. Assessing and analyzing theories and practices across scientific domains can not only provide areas for improvement upon the theories and practices but also the synthesized findings may reveal greater unknowns to be explored. Machado and colleagues summarize this point nicely by stating "Through variation and selection our models evolve and, we hope, come to depict reality a bit more accurately than before" (p. 447). As the literature review continues, one may consider how well these other domains reference each other, and what possible good could come from doing so.

2. Timing temporal cues: Prospective and retrospective timing

In addition to using mathematical formulae to better understand timing, researchers have manipulated various procedures to investigate the various contextual factors that influence timing accuracy and variability. Killeen and Fetterman, (1988) in discussing other timing models, provide guidance on sorting time designs based on asking questions about the conditions under which timing is measured. For example, contingent behavior responding to time that has passed differs from the behavior that emerges in anticipation of a timed interval (p. 276). Subsequently, a portion of the timing research evaluates the differences between those two procedures. Prospective timing is where some form of antecedent signals to the individual (human or non) that they will be prompted to report on the duration of a stimulus after it has been presented. Retrospective timing is the opposite, where a stimulus is presented and then the individual is prompted to report on the estimated duration of the stimulus presentation. For example, a person may hear a tone for a period. After the tone stops, the individual may be prompted to report on how long they thought it was. If the person was never told previously that they would be responsible for reporting the duration of the stimulus, this would be considered retrospective timing. If the person was told in advance that would be considered prospective timing.

In a recent animal timing study, Fetterman and Killeen (2010) investigated the degree to which pigeons accurately responded to prospective and retrospective timing conditions. In their study, pigeons were exposed to two different temporal ranges, short and long. For the short range, a pigeon either saw a light for either 2.5 second or for 5 seconds; and with the long range, the pigeon either saw a light for 5 seconds or for 10 seconds. During training, red lights were associated with the short range and green lights were associated with the long range. After observing the light, the pigeon pecks one of two choice keys to indicate that it was either short or long based on that range. For example, if the light is red for 5 seconds, the correct response would be "long;" but if the light is green for 5 seconds, the correct response would be "short." In the experimental phases, the red or green lights appeared at different time points, either during the stimulus presentation (i.e., prospective), or during the choice selection (i.e., retrospective). Significant results indicated that pigeons showed greater accuracy, which is correctly identifying duration based on a particular range, in the prospective condition. There was also an additional condition which further demonstrated that the light color during the stimulus presentation exerted greater stimulus control over timing judgments than the color of the lights at the choice point.

Fetterman and Killeen (2010) make a strong case for how organisms evaluate time and the potential environmental features responsible for enhancing timing accuracy. As they put it, "The main question is what kind of behavioral mechanism can account for the difference between retrospective and prospective timing" (p. 124). When comparing cognitive versus behavioral models of timing, these findings are crucial. Fetterman and Killeen describe SET (a cognitive model), as "context independent […] Stated another way, SET is inherently retrospective, because the cognitive machinery cannot be brought to bear on the discrimination until the choice stimuli are available" (p. 124). Their data from the 2010 studies do not support SET, in that "Range information during the choice (and not during the sample) is much less useful than range information during the sample (whether or not range information is present during the choice)" (p. 124).

Many studies have repeatedly shown that organisms track time better under prospective timing conditions (Grondin, 2001). In addition to increased effectiveness, there are significant feasibility concerns with running multiple retrospective trials. When verbal humans experience multiple trials for a retrospective timing procedure, they may begin prospective timing without instruction after the first few exposures. Thus, the following studies were conducted with a form of prospective timing procedure.

3. Interference Effects

Beyond modeling or sequencing of timing cues, researchers have also investigated how well individuals track time while engaging in other, non-temporal activities. One of the most established and replicable effects in the timing literature is the interference effect (Brown, 1997). As the name implies, the interference effect "refers to a disruption in timing performance produced by a concurrent nontemporal distractor task" (Brown, 2014). The interference effect is an example of timing research that more closely aligns with a functional contextualist's analytical goals in that the phenomenon claims to identify the conditions under which and to what degree concurrent tasks or task interruption may affect timing accuracy. These research questions produce results that a more easily interpretable for scientific applications than the just-noticeable-difference studies often found in the traditional psychophysics literature.

As a brief review of the interference literature, there are some common findings worth reporting. (For more extensive reviews of the interference effect, look to Brown, 1997 and Fortin & Massé, 2000). Decades of research shows that responding allocated to nontemporal tasks disrupts timing responses, and has been demonstrated in both animals and humans. Furthermore, Fortin (1999) concluded, based on extensively reviewing the literature, that combining nontemporal tasks with temporal production resulted in significantly greater time intervals than the target duration (p. 315). In another approach to temporal interference, Dormal, Seron, and Pesenti (2006) investigated the interrelation of timing estimates and the number of stimuli presented (the quantitative element they called "numerosity"). They found that "there was a clear interference effect of numerical cues on response latencies" but that the interference was not bi-directional (p. 118; cf. Brown, 2006). That is, temporal cues did not result in a similar interference effect for numerosity. One could interpret these findings to support two claims: (1) that time is not a stimulus unto itself that can facilitate or interfere with other processes, and (2) that accurately tracking time requires some form of attending behavior.

The interference effect is related to the work Brown and colleagues have conducted on sequences of events. Brown (2014) highlighted the relation between timing and sequencing as related, and potentially competing, repertoires. His general findings showed that "concurrent reasoning tasks also increased timing variability […] finding that timing performance is very sensitive to nontemporal processing demands" (p. 95), and timing interfered with sequencing. Brown explained these findings by stating that these two processes competed for "the same pool of attentional resources" (p. 95). While behavior analysts would discuss the phenomenon in terms of response allocation, there is validity to the idea that individuals would be unsuccessful at engaging in multiple complex behaviors at the same time.

Overall, the support for interference effects in timing is vast, however, the underlying mechanisms are still contested. Wearden, O'Donoghue, Ogden, and Montgomery (2014) debated whether retrospective duration estimates actually increase due to "more information processing" (p. 293), in part because it remains a challenge to objectively define the meaning of information processing. Wearden and colleagues further added that "The role of external time markers in people's judgments of passage of time […] is an under-researched area" (p. 303). The current research aims to evaluate the effectiveness of orienting individuals to environmental changes in modifying temporal estimates.

4. Timing as attending to relevant, environmental change

Much of the literature reviewed thus far has been a cognitive account for attending as a mechanism for perceiving time. Most of their explanations of timing involve measuring behaviors as indicators for hypothetical constructs and models (e.g., accumulation of pulses that are process in an internal clock). Behavioral perspectives typically reject these postulates, however, as stated previously, there is considerable value in acknowledging the wealth of data that has been produced. Philosophical disputes aside, targeting attention as a functional variable for timing appears to be valuable.

The next empirical step is to determine which contextual changes for which durations have the greatest effect on timing accuracy and variability. Brown (1995), who has based much of his empirical work from Poytner's change/segmentation model of timing (i.e., the position that we tell time via sequences of changing events), conducted studies that would test systematic environmental change as a mechanism for timing. For example, he found that "the influence of speed may be moderated by stimulus duration" (p. 113), and that there were four consistent patterns in his studies:

> (1) stimulus motion lengthened perceived time; (2) faster speeds generally lengthened perceived time to a greater degree than slower speeds; (3) the time judgments for both stationary and moving stimuli conformed to Vierordt's law; and (4) the number of stimulus elements had only a limited influence on time judgments (p. 113).

In sum, his findings suggest that the number or the degree of complexity of stimuli are less significant than their relative change that seems to have an impact on how individuals estimate the passage of time.

Brown (1995) addressed the importance of context in timing, but there is still the missing element of stimulus and behavioral functions. He stated that his studies maintained experimental control by keeping the visual stimuli as functionally neutral. What is left unanswered is "If, however, the intervals contain a richer set of temporal cues in the form of changing stimulus events, the effects of number or size may diminish in importance" (p. 114). While Brown acknowledged contextual factors, they were primarily topographical. Quantity, size, and magnitude are all relational paradigms which gain or lose salience depending on what it's describing. A "richer set of temporal cues" may greatly alter time judgments in different directions depending on whether those cues are appetitive or aversive (p. 114). This point nicely sums up the opportunity for a behavior analytic approach to timing. Taking the strengths of the existing literature on attending and manipulating context, behavior analysts may produce helpful results regarding the stimulus functions of the changing environmental stimuli.

As final critique of the attention literature, the potential lack for generalizability of results is troubling. Most of the studies limit their intervals and durations to just a few seconds (Brown, 1997; Dormal et al., 2006; Fortin, 1999). For example, Brown (1995) found that the longer durations produced more inconsistent results. In this case the "longer durations" meant 15 and 18 seconds. It would be difficult to make predictions for durations of a minute or longer. Given that there has been extensive debate about scalar properties of timing among psychophysicists and the lack of empirical work done with longer periods of time in the cognitive literature, understanding how humans track time over longer durations is still unclear. The current research pertains only to longer durations that fit more closely with how complex human activity operates (i.e., at the level of minutes, not seconds and milliseconds).

B. Timing in behavior analysis

To say that behavior analysis as a field has been empirically silent on the topic of time would be a mistake. It would be equally flawed, however, to portray this work as equally visible as the literature presented thus far. The following sections will provide a representative sample of behavior analytic studies on time and timing, while introducing areas where the field can bolster the weaknesses mentioned in the previous section. In advocating for a more systemic exploration of time, all perspectives stand to benefit.

Historically, behavior analysts have held very particular views on time, perhaps more pronounced than in other psychological domains. Differentiating themselves from areas like developmental psychology, behaviorists embraced the position that events happen in time not because of time. Nevertheless, with Skinner's investigation of various reinforcement schedules (i.e., ratio, interval, time) and work on interresponse times with Sidman avoidance (Anger, 1963), behavior analysts have had to reconcile that what we traditionally call "time" is powerfully linked in the organism's interaction with its environment.

Time and timing have been an integral aspect of early behavior analytic research. Skinner's work on interval schedules proved interesting, particularly as it pertained to the various behavioral patterns that emerged under different contingencies involving time (Ferster & Skinner, 1957). Observing distinct behavioral patterns emerge from time-based schedules was an early fascination (e.g., Anger, 1956) and were considered established phenomena by the late 1970's (Matthews, Shimoff, Catania, & Sagvolden, 1977; Rachlin & Burkhard, 1978). The data produced from interval schedules became interesting since they greatly differed on several levels: interval versus ratio schedules (Matthews et al., 1977; Zuriff, 1970), fixed-interval versus variable-interval schedules (Catania & Reynolds, 1968), humans versus non-human animals on interval schedules (Lowe, Harzem, & Hughes, 1978; Lowe, Beasty, & Bentall, 1983).

1. Fixed-interval versus variable-interval schedules

In *Schedules of Reinforcement* (1957), Ferster and Skinner provided an elaborate account of fixed and variable interval schedules, providing hundreds of pages of cumulative records to inspect. Their primary focus was on animal models due to the availability and facility of data collection. Animal studies often detected the typical scallop pattern using a fixed-interval (FI) schedule (Skinner & Morse, 1957). The variable interval (VI) schedule, conversely, produced different patterns. According to

Ferster and Skinner (1957) “The VI schedule is designed to produce a constant rate by not permitting any feature of the [organism’s] behavior to acquire discriminative properties. In contrast, in fixed-interval and fixed-ratio schedules the fixed pattern establishes a correlation between behavior and reinforcement” (p. 326). Thus, it was commonly observed that animals would steadily respond at high rates, unless the schedule was specifically programmed to produce reinforcers contingent with low rates of responding (i.g., DRL).

Not only do patterns of responding change between FI and VI schedules, but research also demonstrated that organisms prefer VI over FI schedules when given the choice (Herrnstein, 1964). This preference is so replicable that subsequent research emerged to titrate VI schedules to find a model for creating equal preference between an FI and a VI (Killeen, 1968). These studies were the early discussions about how animal models on VI schedules were comparable to gambling behavior, and later would be useful for delay discounting research.

2. Variable-ratio versus variable-interval schedules

It has been long established that interval schedules produce different response patterns than ratio schedules. Ratio schedules, in which responding is directly linked to the reinforcing outcome which typically results in steady, rapid responding. Conversely, interval schedules can occasion any number of patterns and have noted lower rates (relative to ratio schedules) of responding that may occur in VI schedules (Zuriff, 1970). Initially, early behaviorists explained the lower rate of responding on a VI schedule as the reinforcement of long interresponse times (IRTs) “because the mere passage of time leads to an increase in the probability of reinforcement" (Cole, 1999). Learning to adjust rate of responding "based on environmental stimulus changes" led to the acceptance of the term "temporal discrimination" (Anger, 1963, p. 478). For example, Douglas Anger, a student of B. F. Skinner, published findings from his dissertation regarding the selection and shaping of IRTs under varying conditions (Anger, 1956). Another more contemporary view explained that rates of responding change based on the degree to which it directly relates with the rate of reinforcement, and as Cole (1999) pointed out that for VI schedules "there is virtually no relation between rate of response and rate of reinforcement, except at very low rates of response" (p. 320). This latter viewpoint has been described as "molar" (Baum, 1973).

The molar perspective originated from papers on measuring behavior as time allocation, rather than rates of behavior. Based on the theoretical paper by Rachlin and Burkhard (1978), the authors concluded that "Temporal distributions of behavior over fairly long periods are lawful regardless of the individual behavioral episodes (discrete responses, interresponse times, response bursts, neural events, muscle twitches, and so on) of which they are composed" (p. 44). In this paper, the authors evaluated behavior based on substitutability, or time allocation, rather than the more traditional dependent variables (e.g., rate of responding). From their position, time served as a constrained context in which *n* number of events may transpire. Engaging in one activity, such as an instrumental response (e.g., lever press), removes the possibility that the individual can engage in another behavior, like a contingent response (e.g., eating). Framing behavior as time allocation is a potentially viable approach for evaluating patterns of timing behavior.

3. Human versus non-human reactions to interval schedules

The final significant observation with interval schedules was the difference between human and non-human response patterns. Quite possibly, this body of work is the earliest empirical demonstration of behavioral differences in verbal versus nonverbal organisms in behavior analysis. Early on, behavior analysts have heavily relied on animal models for identifying principles of behavior and early FI studies done with humans reported scalloping (see Hyten & Madden (1993) for a comprehensive historical account of FI schedules with humans). According to Hyten and Madden (1993), FI studies in the 1950's claimed that scalloping occurred across species, and some researchers reported scalloping with humans.

A decade later, in the mid 1960's, researchers started providing contradictory findings, that humans very rarely produced scalloping, and then only under specific condition. In 1969, Weiner's study described the two, now commonly accepted, patterns generally produced by human subjects on FI schedules: "high and relatively constant response rates without post-reinforcement pauses (hereafter referred to as the high-rate performance); and lower response rates with post-reinforcement pauses (hereafter referred to as the low-rate performance)" (p.350). Hyten and Madden (1993) suggested that the delayed emergence of these behavioral differences between animals and humans was due to imprecise descriptions of cumulative records.

There were multiple proposals for why there would be a different pattern of responding between humans and animals. Weiner (1969) mentioned that the low rate of behavior and pausing was "contingent upon the conditioning history of subjects and response cost conditions, rather than the FI schedule *per* se" (p. 371-372). Later still, Lowe and his colleagues (Bentall & Lowe, 1987; Bentall, Lowe, & Beasty, 1985; Lowe et al., 1983) would be some of the first to produce findings that suggested these observed differences between animals and humans were due to the development of verbal behavior.

4. Time and avoidance procedures

Much has been learned about behavior patterns with respect to positive reinforcement contingencies, but an equally significant contribution to behavioral perspectives on time comes from the avoidance literature. Just as organisms engage in behaviors in a temporal contingency in "anticipation" of a reinforcer, organisms will also respond to avoid an impending punisher. As Sidman (1953) succinctly described the three accepted aspects of avoidance conditioning:

> (a) The avoidance response (R_{av}) is never paired with the noxious stimulus. (b) All nonavoidance behavior is capable of producing the noxious stimulus and acquiring aversive properties, (c) R_{av} is strengthened when it terminates exteroceptive stimulation and/or nonavoidance behavior which has become aversive through pairings with the noxious stimulus (p. 253).

What fascinated early scientists like Murray Sidman about un-signaled avoidance was that there was no programmed environmental stimulation to which the individual could respond. As he put it, the only event that could have aided the subject in successfully delaying the onset of the shock "was the nonavoidance behavior which has previously been paired with shock, and the termination of this behavior presumably provided the reinforcement for R_{av}" (p. 253). Put in another way, successful avoidance behavior assumes that "behavior can be conditioned to certain unidentified organism events that change in a consistent way with time" (Anger, 1963; p. 479).

Tracking the nonavoidance behavior as a source for temporal discrimination fits well with the assumption that time is simply a measure of change. It also fits within more contemporary behavioral timing theories (e.g., BeT; Fetterman & Killeen, 1988). Behavior analysts have not escaped the issues surrounding defining time and temporal responding. Anger (1963) proposed conditioned aversive temporal stimuli (CATS) as a helpful analytical alternative to only looking at the responses, as Sidman suggested. Anger described temporal stimuli as "the internal events, whatever they are, that provide the basis for temporal discrimination" (p. 479). Later in the paragraph, he explained that he did not necessarily view time as a stimulus or as the stimulus as possessing any temporal qualities, but he did not clearly discuss that the individual's behavior acquires stimulus functions that increase the effectiveness of tracking time (in this case, the change is the timer set to release a programmed shock).

Overall, reviewing the rich history of analyzing behavior with respect to time-constrained contingencies demonstrates that (1) lawful behavioral patterns emerge under timed conditions, (2) behavioral principles facilitate the prediction and control over behavior under timed conditions, and (3) no hypothetical entities need to be introduced to explain these phenomena. It would be naïve to propose that behavior analysis has exhausted the possibilities in timing research, or that the strong history of studying interval schedules competes with the findings in the timing research in other disciplines. In the interest of supporting a systemic development of timing research, scientists could do better to use the strengths from multiple areas to produce new and exciting findings on time and timing.

C. The gaps and future of timing research

Undoubtedly, timing research has flourished over the past century, however, there is still much work to be done. Scientists still have little understanding regarding the functions of timing repertoires in a way that would be of some pragmatic use for application. Rarely, the well-controlled laboratory studies dominate the literature acknowledge the social significance or pragmatic value of their findings. Much of the research reviewed above represents the highly-replicable findings on timing behavior for brief periods of time (i.e., one minute or less). Furthermore, most of the literature has focused on how to measure and predict timing behavior with very few researchers studying how the behaviors involved in timing are shaped to begin with. As Costall (1984) noted about Gibson's perspective on research, "How people cope with the bizarre situations dreamt up in most psychological laboratories is quite explicitly outside the scope of ecological theory" (p. 114). If one's analytic goal as a scientist is to generate a greater understanding of behavior as it occurs in natural environments, external validity should be a priority.

In the next section, the conversation turns to the role of language in developing timing repertoires. Perhaps due to the strong tradition of producing timing studies in animal laboratories, verbal behavior was not considered to be a pertinent factor. Unfortunately, as the timing research matured and developed its own corner of psychological study, a giant scientific basis for language and its impact on human behavior was growing in another. Building a program of research that would combine these two enormous domains would build a new avenue for productive research for both sides with all varieties of analytic goals.

IV. Verbal Behavior and Timing

Regardless of one's philosophical premises or approaches to time, language is rarely addressed as a relevant factor for timing behavior. As Wearden (2008) pointed out, "although time perception research has made significant progress in the last 20 or 30 years, many problems remain, and for present purposes, a particular difficulty is that hardly any of the research relates clearly to language" (p. 167). Neglecting to include language as a factor in the timing behaviors of verbal humans an enormous barrier to the generalizability and applicability of most timing research.

Timing research is not the only area that has neglected to account for verbal repertoires. Despite its face validity and growing empirical basis, verbal behavior is undervalued in multiple research domains. S.C. Hayes and Berens (2004) considered the entire behavior analytic spectrum to be deficient in dealing with verbal behavior in that basic researchers do not have "the preparations and principles needed to research and understand human language" nor do applied behavior analysts have "the analytic tools needed to venture into the many domains of complex human behavior that seem to require such principles" (Hayes & Berens, 2004, p. 344). It can be argued that since 2004 there has been a surge in research systematically investigating verbal behavior in of itself and as it applies to other repertoires; but more work remains to be done.

A. Current discussions of time and language

Although the timing literature lacks much empirical work on verbal behavior, scientists have acknowledged that language serves an important role (consult Killeen & Weiss (1987) and Laties & Weiss (1963) for discussions of counting and interval schedules). Typically, when verbal behavior comes up in a timing article, the authors call attention to language in the discussion section with scant commentary on how to proceed. They are right to address the issue, like Fortin and Massé (2000) discussing the interference effect, they state "The level of expectation [in programmed pauses] was also likely to be increased with verbal instructions: Human participants expect a break when they are told that it will occur" (p. 1795). Authors should not be admonished for failing to suggest a research agenda that includes verbal repertoires. It is likely that those who sympathize with this weakness in the timing literature are also under the impression that there currently exists no functional framework for accounting for language scientifically.

Clearly timing repertoires do not require verbal behavior. As Wearden (2008) put it, "Language is certainly not necessary for organisms to show sensitivity to the temporal structure of their environment" (p. 149). Nevertheless, the argument for including verbal behavior in the analysis of human timing is powerful. For verbal organisms, language is both pervasive and intrusive into nonverbal domains (Hayes, Barnes-Holmes, & Roche, 2001; p. 48). Pervasiveness suggests that verbal humans constantly engage in verbal behavior in almost all places, at all times. Since verbal behavior cannot be removed from timing repertoires, then scientists should consider them as an integral part of the phenomenon. In a similar way, Hayes and colleagues discussed how verbal behavior intrudes into nonverbal actions, just like Fortin and Massé (2000) described the human studies on the interference effect. Although there are nonverbal aspects of timing, it is undeniable that language interacts with the nonverbal, nonarbitrary change in the environment.

In the following sub-sections, the discussion will (1) review the empirical timing work that includes language in some substantive part of the analysis, (2) introduce relational frame theory (RFT) as a suitable framework for discussing language scientifically empirically, and (3) provide suggestions on how RFT could be used to expand upon the existing timing literature.

1. Time and language during childhood

One could speculate that the only reason human species have developed a concept for time at all is due to verbal behavior. Reflecting upon past events and planning for the future, appear to be exclusively human activities. As mentioned previously, Lowe and colleagues were some of the first to discuss verbal behavior as interacting with performance under interval schedules. Almost 40 years prior to this dissertation, Lowe, Harzem, and Hughes (1978) supposed that humans behaved differently on FI schedules because “in human experiments the subject’s behaviour is not under the control of experimental variables but is controlled by self-produced cues, which vary from subject to subject” (p. 384). Their studies focused on language as a relevant variable, and demonstrated differences in human performance on FI schedules before and after human children become verbal.

Others since then have looked at how developmental factors (e.g., age, cognitive development) relate to the development of timing repertoires. Language, however, is not commonly cited as a relevant factor in of itself. For example, Droit-Volet and Wearden (2001) conducted research with young children to test timing sensitivity in a traditional bi-section procedure. They noted multiple significant findings on increased timing sensitivity with increased age, with the interpretation that older children have more developed reference memory (p. 157). Although it was not discussed, language skills are developing simultaneously with physiological development and could potentially be a viable avenue for investigation.

Gaucher, Forget, and Clément (2015) recently conducted a study on children between the ages of 2.6 and 7 years old to investigate potential variables responsible for temporal regulation. Gaucher and colleagues correlated language skills with mean proportion of reinforced responses on two different differential reinforcement of low-rate (DRL) schedules. Consistent with the results from Lowe's work, the better timing performance was positively correlated with age. Language ability, which was measured through a validated test called the Peabody Picture Vocabulary Test (4th ed.), was not significantly correlated with the degree of effectiveness of the DRL on the participant's timing behavior. Future research could dig into these findings further. If age is significantly correlated with timing, it is still reasonable to assume that some skill has developed that facilitated better timing performance. Null findings in this study do not mean that language is not affecting how humans time. With other methodologies that test language as a behavior, rather than producing a score from a single test, could potentially reveal more robust findings on how timing repertoires develop.

Some research has been done to extend the findings of Lowe et al. (1978) such as Baxter and Schlinger's work with children on multiple schedules (1990). During the 12-year gap between these articles, there has been significant contributions to the behavior analytic discussions on verbal behavior. Baxter and Schlinger addressed the possibility that multiple schedule performance with verbal individuals may be "rule governed" but their findings with pre-verbal and verbal children showed similar results to animal models. Baxter and Schlinger's binary description of verbal/nonverbal introduces an interesting issue. Just because an individual demonstrates a verbal repertoire does not mean that it has developed enough to engage in all forms of verbal behavior. Levin, Wilkening, and Dembo (1984) showed that at around age 10 effective chronometric timing and timing rules emerge in response to a continuous timing task. Furthermore, verbal timing accuracy generally improved at seven years of age. Given that the oldest participant in Baxter and Schlinger (1990) was four and a half, it makes sense that the participants' timing behavior continued to resemble nonverbal timing patterns. Verbal repertoires must develop over time to form complex rules regarding temporal relations. As will be discussed in future sections, rule governance undeniably impacts responding in schedules, however it is less clear how an individual might start using rules to aid in temporal relations.

2. Counting as verbal temporal stimuli

Most human timing literature has focused on humans who already have an extensive verbal repertoire. As adults, timing can no longer be investigated as it develops with the acquisition of language skills, but there is some work that has looked at how using language can impact timing accuracy. Although language from a functional, behavioral account has not been considered in timing research, other investigators have included verbal processes as a mediator for timing accuracy.

Verbal humans can enhance their timing abilities by chronometric counting (e.g., one-one-thousand, two-one-thousand) or by emitting some other behavioral pattern of a known length (e.g., singing). Chronometric timing is a common variable in studies investigating timing accuracy in humans. Not surprisingly, many articles mention how counting substantially increases the accuracy of one's time keeping (Gaudreault & Fortin, 2013; Grondin et al., 1999; Killeen & Weiss, 1987). In fact, Grondin and colleagues (1999) found that counting becomes effective starting at durations of 2.5 seconds. Any shorter, and explicit counting does not seem to help. What would be interesting, but remains to be seen, is the point at which counting stops being effective for long durations. Thinking about the scalability of timing, little has been said about durations lasting more than a few seconds, let along intervals of a minute or longer. It would make sense that counting seconds would lose efficacy for longer durations, but that counting sustained events (e.g., number of songs played, number of TV episodes watched) would be a related behavior that could effectively track long periods of time.

Another finding in Wilkening, Levin, and Druyan (1987) was that children performed much more reliably in their counting behavior when accompanied by rhythmic beats. Considering the amount of training musicians get on rhythm and "keeping time," it stands to reason that musicians would have a more developed skillset for tracking time. For example, Grondin and Killeen (2009) conducted a study wherein participants were asked to reproduce a sound for the same duration as was played to them. There were several conditions where participants were told to count, sing a well-known tune, or do nothing. Additionally, eight of the 20 participants had extensive musical training. The results revealed that both counting and singing for both musicians and non-musicians significantly increased their timing accuracy. Furthermore, while singing or counting individuals with formal musical training produced near perfect reproductions which was a significant difference from the non-musician group, with decreasing variability as stimulus durations increased.

Grondin and Killeen's study not only supports the clear effects of counting and singing for tracking time, but also indicates that there are certain conditions under which human timing violated the stricter models of scalar timing (p. 1653). The authors did not explicitly suggest methods to improve timing. Their data supported that timing was learned and that individuals with particular learning histories could track time differently than what general psychophysics models predict. Finally, they discussed counting and timing as "mediators" but did not explicitly call attention to these behaviors as verbal, or functioning in anyway besides serving as collateral behavior (Bruner & Revusky, 1961). Such a point is valuable, but it limits the reader from considering anything further about the significance of verbal behavior on timing, such as instructional control and rule governance.

Surprisingly, from the studies that have investigated verbal mediation as it relates to timing skills, the authors usually did not discuss functional impacts of verbal behavior. This could be due to a few factors. First, language is not often discussed or measured as a behavioral repertoire outside of behavior analysis. Rather it is often used as an indirect measure for something else. Second, some researchers have questioned whether using language for counting is timing. In fact, Grondin, Meilleur-Wells, and Lachance (1999) dedicated a whole section of their discussion to whether counting could be considered timing (p. 1001). The authors distinguished between “number processing” and “counting,” using animal models to compare with human timing. The rhetoric revolved around cognitive processes wherein the answer was attempted based on assumed internal clock mechanisms in that “Number and time information received from their respective accumulator would be placed at different sites in working memory” (p. 1002).

A behavioral perspective would take a different approach to Grondin and colleagues’ discussion by evaluating the function of the behavior in question. Counting ordinally and counting chronometrically (i.e., with a regular rhythm) function differently on time tracking, as seen in Wilkening, Levin, and Druyan (1987). Thus, in taking a behavioral perspective on timing research utilizing counting strategies, there is a sizeable gap in our knowledge of timing. By looking at language as a measurable, shapeable behavior in relation to functional timing, new programs of timing studies could begin to answer research questions with greater external validity and pragmatic value.

B. A functional account of language and timing

Thus far, it has been established that certain forms of verbal behavior effectively mediates timing responses. What remains to be seen are the various stimulus functions verbal behavior has on timing beyond serving as collateral behavior, that is, the other behavior that occurs that is not responsible for producing reinforcement. Furthermore, to repeat a theme throughout this manuscript, there is a need for timing research that can help others perform more effectively in their natural environments. The subject area has been saturated with conversations about mental mechanisms and perfecting processes, which suggests that this area of research may be ready to expand into a more pragmatic domain.

Behavior analysis has the tools to lead the expansion. As S.C. Hayes and L.J. Hayes (1989) point out "Behavioral perspectives should be well positioned philosophically to address the nature of verbal stimulation in a naturalistic manner" (p. 161). Admittedly, empirical work on verbal behavior has been latent compared to when it first became a topic for theoretical discussion. At the time, B.F. Skinner's *Verbal Behavior* (1957) provided a provocative analysis on how verbal behavior could be operationalized and studied functionally. Except for providing training in applied behavior analysis on tacts and mands, "a Skinnerian perspective has limited the nature and the scope of its investigation [of verbal events]" (S.C. Hayes & L.J. Hayes, 1989; p. 161). Several behavioral perspectives on language have since emerged, but none have produced the volume of theoretical and empirical work as Relational Frame Theory (RFT).

The following subsections briefly review RFT, specifically as it pertains to framing and rule governance, to suggest a new area for timing research. Visible critiques and defenses of RFT have already been published (Dymond, May, Munnelly, & Hoon, 2010; S.C. Hayes, 2004; Palmer, 2004), thus the conversation below will not do so. Choosing the RFT perspective resulted from there being no other theoretical account of language that (1) analyzes language as behavior, (2) with validated explanations for verbal behaviors acquiring stimulus functions as relational events, (3) which also provides a framework for studying verbal behavior as an observable behavioral event, without inferring a mental model.

1. Using Relational Frame Theory (RFT) to analyze verbal timing

In 2001, S.C. Hayes, Barnes-Holmes, and Roche published *Relational Frame Theory: A Post-Skinnerian Account of Human Language and Cognition* which synthesized and formalized several decades of fastidious theoretical and empirical research. As the title implies, RFT aimed to transcend the experimental barriers of Skinner's *Verbal Behavior*, and provide a functional and naturalistic account of verbal behavior. RFT largely relies on the premise that "deriving stimulus relations is learned behavior" (S. C. Hayes, Barnes-Holmes, & Roche, 2001, p. 22). From this, the authors present data which support that "derived relational responding is a form of generalized operant behavior" (p. 43), or as S.C. Hayes proposed nine years earlier, "relating as an action can become abstracted and brought under contextual control" (S.C. Hayes, 1992, p. 110).

Since then, many behavior analysts interested in verbal behavior have found RFT as a launching point for developing their own programs of research. As S.C. Hayes and Berens (2004) described, "To the extent that RFT is successful, behavior analysis itself will change, and do so in a fairly dramatic way" (p. 346-347). In their discussion, Hayes and Berens explained that so much of the work done in behavior analysis has not considered the additive impact of verbal behavior on nonverbal process, leaving the field with incomplete analyses. That is certainly the case with timing research.

The theoretical work on RFT mentions time and timing issues periodically because it is an excellent example of how arbitrarily applicable relational responding (i.e., verbal behavior) interacts with the nonarbitrary world (i.e., time as natural events transpiring). For example, Hayes, Barnes-Holmes, and Roche (2001) stated:

> Nonverbal events occur in nonverbal time. Sequences are nonarbitrary—they are experienced directly. The only future that is known is the past that has been experienced. Verbal organisms turn time on its head. The past is continuously verbally reconstructed as various stories about it are generated and adopted. The future is imagined (p. 48).

Early RFT literature readily acknowledged that timing is influenced by both physical stimuli (i.e., nonarbitrary) and verbal stimuli (i.e., arbitrary). This is an important first step to conceptualizing timing while accounting for verbal behavior because it accepts the historical models and data built from nonverbal timing models. The significance of investigating verbal behavior in relation to time is taking what we already know about time and add a level of complexity that the field is now poised to address. The benefit of doing so would help both those with basic or applied ambitions: "RFT research seems likely to make applied behavior analysis a more basic endeavor, and make the experimental analysis of behavior more dependent on applied results" (Hayes & Berens, 2004; p. 351).

2. Relational framing temporal events

Similar to the classical philosophers Leibniz and Kant, RFT takes a similar position of relativity. Not surprisingly, the heart of RFT is the act of "framing relationally" which was described by S.C. Hayes (1992) as "an act with a history" (p.

114). Even the principle phenomenon of RFT relies on the importance of time as changing events. Hayes continues that relationally framing is:

> not with regard to the relatae [sic] so much as it is with regard to the relating [...] that is, based on a history of deriving temporal sequences among events (the "past"), the organism is responding in the present by constructing a sequential relation between at least two events (p. 114).

We learn to associate arbitrary stimuli with the nonarbitrary stimuli based on a history of the two coexisting reliably. Furthermore, we can compare those stimuli and events to others through relations. Including relations in analyzing verbal behavior stand in contrast with traditional approaches like stimulus equivalence (Blakely & Schlinger, 1987). With the former, researchers can begin to explore how we compare verbal events to each other in addition to investigating how verbal responses are acquired in of themselves.

The RFT literature describes multiple types of relational frames, the two most relevant for timing as frames of coordination and comparison. Described as the "most fundamental type of relational responding," S.C. Hayes and L.J. Hayes (1989) discuss a frame of coordination as "one of identity, sameness, or similarity" wherein "the more *sameness* between two stimuli (in an arbitrary sense), the greater the range of function that can be derived between participants in this relation" (p. 172). Frames of coordination would be integral to identifying temporal similarity between events which could help with generalizing timing estimates or for noticing temporal patterns. For example, one might notice that it takes about the same amount of time to pack a lunch as it does to scrape off an icy windshield before work. If running late, a person may forego lunch packing in exchange for de-icing the car to get to work on time. Or in terms of patterns, one might notice that their "getting ready" routine takes 90 minutes on Monday, 85 minutes on Tuesday, 95 minutes on Wednesday, etc. Each of those temporal events share sameness in that the same preparation activities take a similar amount of time on a standardized clock. Establishing a frame of coordination around daily "getting ready" routines with an hour and a half serves as a basis for other verbal behavior, such as rule generation (e.g., saying "If I want to get to work by 9:00 A.M., I will need to get up at 7:30 A.M.).

Another helpful frame for verbal timing is the frame of comparison. Comparison frames are common, like coordination frames, as they are "involved whenever one event is responded to in terms of a known nonequal and nonopposite quantitative or qualitative relation along a specified dimension with another event" (S.C. Hayes & L.J. Hayes, 1989, p. 173). A whole body of research could be dedicated to the establishment of frames of comparison with timing. Learning that writing a final term paper takes significantly longer than the work hours available over a weekend is a helpful lesson that many people learn through experiencing the direct, nonarbitrary consequences of pulling all-nighters or handing in a late paper. Or recognizing that 90 minutes to get ready in the morning is not the same as the elapsed time between waking up and stepping into the office. By not including transit and walking time into the verbal estimate, not to mention what happens when you can't find your keys right away, many people find it challenging to arrive punctually. It is possible, if not likely, that developing a verbal repertoire to include timing comparisons, in conjunction with attending the relevant events for temporal constraints, would have an impact on human timing and self-organization with respect to temporal constraints.

To apply these terms to a larger example of acquiring verbal timing skills, one might think about how a child learns about temporal intervals through verbal and nonverbal experiences. As mentioned previously, before a certain age, young children have little understanding of continuous and overlapping intervals (Levin et al., 1984). When a child asks how much longer a car ride will be, a parent could say "five hours" or "five minutes" and get a similar distressed sigh from the inquisitor. It is not until later that a frame of coordination builds around time words and the nonarbitrary events that transpire reliably with those words. So when the child asks during the car ride how much farther to Grandma's house, a parent might say "two and a half hours" or in some cases "two *Sesame Streets* and a *Barney*." In this case, the number of episodes of the child's preferred television shows (i.e., the nonarbitrary events that transpire) coordinate with the duration of the trip to Grandma's house which coordinates with the descriptive phrase "two and a half hours."

Comparison frames are also developing in the road trip example. One episode of *Sesame Street* runs for 60 minutes whereas *Barney and Friends* is only 30 minutes. It takes no time at all for a child to learn the longer-shorter frame of comparison. Not only will children learn the shorter-longer comparison between television shows, but the relation will extend to differing durations in other contexts. Trips to Grandma's may mean watching two *Sesame Street* episodes and one of *Barney*, but one only need wait for one *Sesame Street* before eating after visiting the dentist. Additionally, the durations can take on different stimulus functions based on what the longer duration describes (e.g., watching TV or sitting in a waiting room) as well as what awaits after the duration expires (e.g., playing with Grandma or bedtime).

Learning temporal relations creates unique challenges from other, less abstract contexts. As Hayes, Barnes-Homes, and Roche (2001) described them, “Temporal frames are more inherently verbal in that they are based on the nonarbitrary experience of change, but the dimensional nature of that experience must be verbally constructed” (p. 39). It “must” be because humans developed the concept of time to begin with. Time as a verbal construct only exists in so far as we want to standardize it using common tools and language. Doing so is helpful, because it allows us to plan ahead, save for the future, or generally increase our effectiveness in a time-based society.

Studying the various functions of verbal stimuli, beyond as discriminative stimuli or collateral behavior, provides the latitude to study behavior that occurs exclusively with humans. Phenomena like delay discounting has been studied with both verbal and nonverbal individuals, however no species can problem solve and behave with respect to extremely delayed (or even hypothetical) consequences. S.C. Hayes and L.J. Hayes (1989) explain how verbal behavior makes these extensive behavior patterns possible by “greatly reduc[ing] the number of events relevant to a given consequence, when the consequence is functioning verbally” (p. 185). Verbal behavior augments stimulus control over relevant change, based on the context. The number of events have been reduced because the individual learns to discriminate that “time” only pertains to certain events, not all events. The child on the way to Grandma’s will know that it is time to put socks and shoes on when the third show is finished, without having to count the mileage signs or for some internal signal that 90 minutes have passed.

S.C. Hayes and L.J. Hayes (1989) explained that by reducing the number relevant events to a consequence, there is less or no confusion when a remote consequence is delivered. In an earlier example with the icy windshield, if a person goes through the normal routine only to find out that they also have to spend an extra seven minutes scraping ice of the car windows, they can project that they will be late for work. Because the frames of coordination and comparison were parts of the person's verbal network, the reprimand from the boss will be related to the extra prep time spent at home, not for the behavior of walking into the office.

Little empirical work has been conducted on verbal behavior and temporal relations, and what does exist pertains to another dimension of timing relating to deictic relations. RFT refers to deictic relations to "specify a relation in terms of the perspective of the speaker" (Hayes, Barnes-Holmes, & Roche, 2001, p. 38). It is important to highlight that "Frames that depend on perspective, however, cannot be traced to formal dimensions in the environment at all" (p. 39). Relations like "now" and "not-now" (i.e., past, future, later, etc.) or "before" and "after" are entirely verbal events referring to event sequence. Reviewing the few studies that have addressed temporal relations is important for acknowledging that systematically evaluating temporal frames is possible and promising. However, readers should note that temporal sequencing is a different process than establishing coordination frames of event duration (i.e., timing estimates).

O'Hora, Pelaez, & Barnes-Holmes (2005) conducted a study in which 74 bilingual college students completed both a series of complex relational tasks and the Wechsler Adult Intelligence Scale Third Edition (WAIS-III). Among the relational tasks included tests for temporal relations targeting the before-after relation, sequentially showing shapes on a computer screen. O'Hora and colleagues reported significant correlations between success on the relational tasks and performance on the WAIS-III. The participants' before-after scores were significantly correlated with the vocabulary subtest ($r = .34$, $p < .001$) and the arithmetic subtest ($r = .23$, $p < .001$). While correlational results insufficiently describe causality, these results can be useful in demonstrating the utility of RFT as it relates behavioral analyses to mainstream psychological measures. The degree to which a mastery of temporal relations relates to measures of intelligence, however, remains unclear.

A follow-up study done by O'Hora, Pelaez, Barnes-Holmes, and Rae (2008) replicated and extended their findings by running another 81 participants through the temporal relations task and the complete WAIS-III. Their results "showed that the ability to respond to temporal relations predicted performance on complex cognitive tasks" (p. 577). Another temporal element was added to the 2008 discussion when using the entire WAIS-III in that it included indices on Working Memory and Processing Speed. The authors explained that since there were no time constraints on the relational task (i.e., testing the before-after relation), successfully passing the temporal relations task would not necessarily be indicative of those measures. The results supported that rationale.

The two layers of temporality in this study serve as a good empirical example of nonarbitrary and arbitrary aspects of timing. The before-after relation is a verbal description of events (i.e., the appearance and disappearance of two different shapes in temporal relation to one another). That the event transpired is nonarbitrary, but the describing of the event is abstracted. Similarly, completing a series of tasks within an allotted period is a separate temporal event from temporal relations. There is no immediate reason to believe that one skill would generalize to the other. Thus, investigating various timing repertoires with respect to arbitrary and nonarbitrary features is important for deepening our understanding of how verbal organisms acquire and shape timing skills.

3. Rule-governance of timing behavior

The concept of rule-governance emerged to account for behavior that was not otherwise contingency-shaped. Since then, some have doubted whether rule-governed behavior is merely a form of contingency-shaped behavior. Reese (1989) somewhat unsatisfyingly distinguished the two in that contingency governance is "a [basic] function of contingent stimuli" and rule governance is "an acquired function" (p. 38). Twelve years later, Hayes, Barnes-Holmes, and Roche (2001) provided a clearer distinction of rule governance: "Whenever a frame of coordination between two such [verbal] networks serves as a source of control over behavior, it seems to us that the behavior is meaningfully rule-governed" (p. 107). Such a definition provides clearer parameters for what distinguishes behavior as rule-governed and allows for a deeper analysis of rule functions (i.e., tracking, pliance, and augmenting) as well as rule source (i.e., imposed rules versus self-generated rules).

S.C. Hayes and L.J. Hayes (1989) also discussed what it means to follow a rule. They concluded that "what we would normally call *nonverbal* events can function verbally, based on their participation in relational classes. This transfer of the functions of words to other events provides the basis for rule-following" (p. 181, emphasis in original). Identifying the interrelation of the nonarbitrary, nonverbal environment or behavior with verbal events is particularly important with time and timing. Based on the representative findings provided above, timing does not necessitate verbal behavior. But given the extension of behavioral patterns over long periods of time, it would require some mediating stimulus, like a rule, to maintain. As Haas and Hayes (2006) stated "In most human performance situations, the target behavior of interest is established at least in part through verbal rules, and verbal feedback includes feedback not just on task performance but also on the form of rule-governed behavior observed" (p. 94). Presumably, humans learn timing rules to more effectively interact with our natural and social surroundings, and contact reinforcement for successful rule following. Rules such as "wait 30 minutes after eating before swimming" or "count to 10 when you're angry" articulate a negative reinforcement contingency wherein waiting before responding reduces the likelihood of aversive events.

Instructional control. Within the literature on rule-governance, there has been an emphasis on instructions as verbal antecedents augmenting stimulus control. The obvious advantage of providing instructions to change behavior is that "following an instruction allows a previously established repertoire to contact reinforcement quickly without extensive exposure to the reinforcement contingency" (Joyce & Chase, 1990, p. 252). One of the most established effects of rule governance is the resulting insensitivity of behavior to contingency changes from instructions (Törneke, Luciano, & Salas, 2008). Instructions are adventitious because they signal specific, desired behaviors without a lengthy shaping process. Danforth, Chase, Dolan, and Joyce (1990) concluded that "The instructional stimulus assisted in the acquisition of stimulus control" but was facilitated by a history of differential, nonverbal reinforcement (p. 101). Sometimes, it works too well, however, that instructions can decrease nonverbal sensitivity to direct-acting contingencies. This is problematic when considering the missed opportunities that result from incorrect rules either about ourselves our situations in which we live.

For example, in S.C. Hayes, Brownstein, Zettle, Rosenfarb, and Korn (1986) a series of studies detailed the relative impact of instructions on effective responding with respect to a multiple schedule (fixed-ratio / differential reinforcement of low rate; FR/DRL). All the participants pressed a button on an apparatus for points, and different instructional conditions were applied for different groups of participants (i.e., minimal instruction, "Go fast", "Go slow", no instruction). They used a multiple schedule to be able to make "a direct comparison of contingency sensitivity produced by high-rate and low-rate instructions" (p. 240). The authors stated that "responding on the schedules was a joint product of current consequences of responding and instructional control. Without instruction, none of the subjects made extensive contact with both types of programmed consequences" (p. 240). Participants who received inaccurate instructions followed them, despite their inadequacy. And in one case, one of their participants "made contact with consequences that contradicted the rule specified by the instructions and yet still followed that rule" (p. 241). When the participants came under the more powerful (i.e., direct acting) contingency, instructions had less impact, and others found that if participant behavior came under the control of the nonverbal contingency, instructions had little to no effect (Torgrud & Holborn, 1990). Findings of insensitive responding in the presence of instructions have also been shown elsewhere (Joyce & Chase, 1990; Shimoff, Catania, & Matthews, 1981).

The article from Joyce and Chase (1990) also discussed the desensitization of rule-governed behavior, but then also demonstrated empirically that instructions can increase variability too. In their second experiment, Joyce and Chase included a set of strategic instructions that explained ratio and interval schedules, ending with: “The best way to figure out which system of point delivery is in effect is to vary your speed of responding until you reliably earn points with the least effort” (p. 257). Most participants doubled their efficiency after reading the strategic instruction for variability. Joyce and Chase’s findings support the conclusions of LeFrancois, Chase, and Joyce (1988) that “variety training” can create sensitivity to environmental changes.

Even simple instructions are powerful enough to facilitate observation of one’s own behavioral patterns. Although there is no contingency manipulation in the dissertation studies described below, nor are there explicit consequences for the participants timing responses, the underlying assumption of the experiment is that different instructions function to reorient the individual to different events in the environment (i.e., the participant’s game playing behavior or their own breath).

In sum, many studies have shown that instructions exert powerful control over responding, and they can be elaborated upon to produce variable responding (Chase & Bjarnadottir, 1992), or establish stimulus control over derived relations (O’Hora, Barnes-Holmes, & Roche, 2004). The current research aimed to clarify what we know about timing accuracy and variability through nonarbitrary and arbitrary means. That is, the degree to which, and under what conditions, verbal behavior with respect to timing relates to the direct experience of time through change in the environment. The existing literature on instructional control indicates that using instructions to restrict participants' attention to various aspects of environmental change as a way of reducing timing variability at longer durations. Chase and Bjarnadottir (1992) state "if instructions are going to address this problem of variation, they have to tell the subject what behavior to vary, and under what conditions" (p. 192). If instructions can effectively lead a participant to vary their responding, it is likewise reasonable to assume that instructions can lead a participant to observe their own variable responding. Based on the philosophical position that timing means attending to changing events, the temporal characteristics of an interval are the qualities of the participant's behavior pattern.

Tracking. The functional process by which behavior is controlled by instructions is referred to, in the RFT literature, as "tracking." Tracking has been defined as "rule-governed behavior under the control of a history of correspondence between the rule and the way the world is arranged independently of the delivery of the rule" (S. C. Hayes, Gifford, & G. Hayes, 1998). According to Torneke and colleagues (2008), the simplest form of a track is one that specifies a direct contingency where the successful following of the rule will necessarily produce the nonarbitrary consequence (p. 149). This definition of tracking is usually followed by the common example of providing directions (e.g., getting to a bus stop).

Verbal timing as it relates to the act of judging or estimating time duration also fits best with the concept of tracking. Tracking directly relies upon frames of correspondence. Returning to the child in the car on the way to Grandma's, the parents might say "We'll be there in two and a half hours." The description "two and a half hours" might have a history of correspondence with the quantity of relevant, successive events that can take place during that time, such as two *Sesame Streets* and a *Barney.* The complexity of a verbal construct like time is that the relevant events change depending on the context. When the child becomes adolescent, "two and a half hours" might start to correspond to the length of a basketball game, or the different acts in a theatrical performance. Or later still, "two and a half hours" might describe the time it takes to write two 500 word essays in an advanced placement exam in high school. Having a better understanding of how attending and verbal instructions interact to develop timing repertoires could support the idea of instructions as tracks for timing accuracy. If the rule instructs the individual to orient to the relevant changes in the environment to effectively estimate time duration, the rule would be considered a track, and the rule-governed behavior would be track*ing*.

Unfortunately, most of the discussions on tracking have remained conceptual, so the examples and variations of functional tracking are limited. A recent review of the literature (Kissi et al., 2017), found only three empirical, peer-reviewed articles that explicitly identified "tracking" as a variable of interest (i.e., Baruch, Kanter, Busch, Richardson, & Barnes-Holmes, 2007; McAuliffe, Hughes, & Barnes-Holmes, 2014; Zettle & Young, 1987). As a result, there are not many established procedures for investigating tracking as a process.

One of the main conclusions of Kissi and colleagues' review (2017) was that terms describing functional forms of rules (i.e., tracking) should be considered "midlevel" terms, meaning they may be helpful for describing qualities of rules but are not precise enough to produce replicable effects. It could be that distinguishing between plies, tracks, and augmentals has not served much of a role in the basic studies establishing principles of verbal behavior. In broader contexts, however, the differentiations become more useful. In learning to talk about time and organize one's behavior with respect to time, the concept of "tracking" is a helpful framework for discussing the interaction between nonarbitrary time (i.e., events transpiring) and arbitrary time (i.e., temporally framing). If the instructions function as a track, then in timing studies we would expect to see at least a reduction in timing estimation variability, if not also an increase in timing accuracy. As mentioned in the previous section on basic timing research, individuals become increasingly less accurate in their timing estimates as the temporal interval lengthens. Ignoring for the moment that those highly validated findings pertain almost exclusively to intervals of under one minute, the research also indicates that verbal behavior (often discussed as counting or having some form of verbal attending strategy) can improve timing. Tracking as a scientific, functional process could serve as the missing link in explaining the connection between timing awareness and language.

Self-generated rules. It should be noted that rules can have multiple sources. Much of the rule-governance literature involves providing rules to the participants. However, there has been some work concerning rules developed by the participant through experiencing the experimental conditions. The literature often refers to this phenomenon as self-generated rules. Self-generated rules function similarly as imposed rules. For example, research supports that for participants who experience either provided rules or self-generated rules respond more effectively and faster, and experience slower extinction patterns than participants who neither receive a rule or are asked to create one (Baumann, Abreu-Rodrigues, & Souza, 2009; Rosenfarb, Newland, Brannon, & Howey, 1992).

Since the development of Skinner's radical behaviorism, behavioral philosophy does not preclude so-called "private events" like self-generated rules, and RFT similarly embraces these important events. Hayes, Barnes-Holmes, & Roche (2001) specifically described how pragmatic verbal analysis works regardless of whose behavior is being observed. Additionally, they specify the potential benefits of developing a repertoire for self-observation: "Self-monitoring and self-awareness may permit greater self-control […] In the case of problem-solving strategies, for example, responding to one's responses may contribute to evaluating the success or failure of behavioral efforts" (p. 100). When considering timing repertoires, it can be argued that most of our rules regarding time and timing are self-generated based on our own experiences. Except for particular contexts (i.e., in cooking, recipes explicitly taught that rice is cooked after 20 to 30 minutes, or in music when the conductor or written notes indicate duration of playing behavior), rules about time are derived. Future studies may find self-generated rules a rich area for investigation in timing research.

Present moment awareness: Finally, reviewing verbal behavior from an RFT perspective as it relates to time would be remiss if it did not include "present moment awareness" into the conversation. Arguably the most comprehensive and visible applications of RFT has been the traditionally psychotherapeutic intervention known as Acceptance and Commitment Therapy (ACT). ACT uses an RFT framework and aims to train psychological flexibility which is a model composed of six core processes: (a) cognitive defusion, (b) acceptance, (c) present-moment awareness, (d) self as context, (e) personally identified values, and (f) committed action (M. E. Levin, Hildebrandt, Lillis, & Hayes, 2012, p. 742). Part of ACT's notoriety is due to both its breadth of effectiveness across physical and mental health problems and its efficacy (Powers, Zum Vörde Sive Vörding, & Emmelkamp, 2009), as well as improving work environments (Bond, S.C. Hayes, & Barnes-Holmes, 2006; Herbst & Houmanfar, 2009). In the recent meta-analysis done by Levin and colleagues (2012), they conducted a component analysis wherein the criteria for "present moment" included "instructing participants to actively attend to bodily sensations, thoughts, feeling, and/or other internal experiences in the present moment" (p. 747). From the studies they identified as evaluating the present moment process, synthesized results reveal significant, positive effects with medium effect sizes, suggesting that present moment focus alone is an active component to promote wellness and psychological flexibility.

Focusing on the present is said to have therapeutic effects because it counteracts some of the tendencies as verbal humans to ruminate on the past or the future (Broderick, 2005). The literature has acknowledged that verbal behavior is a significant contributor to psychopathology (S.C. Hayes, 1992; Torneke et al., 2008), under the premise that the very repertoire that gives humans the freedom to learn quickly from the past and plan for the future is the same repertoire that allows for anxiety, depression, shame, etc. In terms of time, Hayes, Barnes-Holmes, and Roche (2001) explained it this way: "based on a history of change (the 'past'), the animal is responding to present events that have preceded change to other events. It is not the literal future to which the organism responds—it is the past as the future" (p. 113). Spending too much time responding to the past or future in the present can increase distress and decrease the likelihood of enjoying the moment.

Two common approaches to testing present moment focus is by either mindful breathing exercises or some other instructions to monitor bodily sensations. Both techniques have been found to be effective at faster pain recovery (Cioffi & Holloway, 1993), reducing dysphoric responses (Broderick, 2005), and increasing greater acceptance of repetitive thought (Feldman, Greeson, & Senville, 2010). By fostering present moment awareness, participants develop a repertoire for self-observation in the moment. Facilitating timing awareness may require a similar treatment, where effectively judging time duration requires actively attending to changes in the environment, which would include one's own activity. What is unique about mindfulness training that concentrates on the present moment is that it is typically used as attending to events as a continuous flow, rather than discrete, countable events. Whether present moment instructions will influence timing accuracy or variability remains to be seen.

4. Summary

As S.C. Hayes and Berens (2004) noted, the next step is to "do the difficult work to understand exactly how direct contingencies are altered by verbal contingencies because without that knowledge we cannot safely and directly extend our principles of behavior derived from non-human organisms to language able humans" (p. 349). The literature review presented a representative sample of the timing studies that have included language as a relevant behavior effecting timing accuracy, even if it was not explicitly stated. Overall, most of the existing time literature discussed rather than manipulated verbal stimuli or occasions verbal behavior. On the other side, the verbal behavior literature from an RFT perspective provides a sound theoretical and empirical framework for investigating the various influences verbal behavior has on verbal and nonverbal timing in humans.

By bringing a rigorous research agenda of verbal behavior to the timing literature, the possibilities for future research could develop in ways that would benefit both domains. Not only would the basic research on time gain a new level of complexity to study (i.e., various frames and rules with respect to arbitrary and nonarbitrary time), but investigating time provides a unique context to explore and refine concepts proposed in RFT. The following studies are a step in the direction of setting these mutual benefits in motion, ending with a proposed study and a discussion about where the future of timing research could go.

In sum, the provided review illuminated the wide array of knowledge that exists in two vastly important domains, time and verbal behavior, as well as demonstrating that there are empirical gaps that would explain how the two domains interrelate. Taking a functional analytic approach, the following studies begin to examine to what degree and under what conditions do verbal stimuli and verbal behavior augment the stimulus control over relevant change to track time.

The following section covers a series of three studies which took a basic methodology modified slightly in each to investigate timing behavior of three-minute intervals. The first study assessed the accuracy and variability of retrospective time estimates. The second study uses a modified free-operant procedure where the participants produced empty intervals of three-minutes by pressing a button, while being exposed to instructions to notice particular features of the participants' environment. The third study replicated the second study's procedure with the addition of an initial three-minute alarm as a discriminative stimulus. The primary aims of this research were: (a) to investigate the timing patterns produced for long durations multiple minutes over a sustained period of time as compared to similar studies for shorter durations, and (b) to identify conditions under which verbal antecedents and self-generated rules may impact timing in human participants. By researching longer durations and systematically evaluating the impacts of verbal behavior, these series of studies can begin to synthesize and add greater relevance of the timing literature to applied settings.

V. Empirical Investigations

The following three studies adhered to the notion that timing behavior is shaped by the interaction of the behaving organism and changing environmental events. Furthermore, the words "time" and "timing" are used for heuristic value, however, the philosophical foundation upon which this research is based adopts the view that time is a metric used to measure relevant change. It is environmental changes, not time, that to which the individual attends.

Two different operant responses were required in the different studies: time estimates in Study 1, and interval production in Studies 2 and 3 (see Table 2 for a summary of study methods). For all studies, participants completed Sudoku puzzles for points and the target interval was three minutes. Each study is described and discussed individually and cross-study comparisons are made at the end.

A. Study 1

The first study evaluated the relative accuracy of timing estimates for long periods of time. As discussed earlier, a potential barrier for current timing research in being easily applied is that the intervals of interest are impractically short (e.g., 60 seconds or less). Notable timing researchers such as Grondin & Killeen (2009) have mentioned that "Not much is known about the variability of long-interval estimates by humans in simpler tasks" (p. 1653). One of the aims for this first study was to measure the individual differences in timing estimates and sensitivity to larger timing patterns at three minute fixed-time intervals.

1. Method

Participants, Setting, and Materials. For the first study, participants consisted of 27 undergraduate psychology students at the University of Nevada, Reno recruited through the university's psychology subject pool. We accepted all participants 18 years of age and older. By participating, individuals earned one credit through the subject pool which is often exchanged for extra credit in their psychology course. Additionally, participants were entered into a raffle for a $25 Visa gift card. Participating automatically gave each participant one ticket entry to the raffle, but they were told that better performance in the game could win them extra tickets to increase their chances (see Table 2 for point contingencies, and Appendix A for full point-to-ticket distribution breakdown).

The study took place in a lab room that would allow for the participant to be greeted and trained in an open meeting area and then be escorted to the back of the room to work the remainder of the session at a university-networked computer. All clocks, digital or otherwise, were removed or dismantled. Participants were required to remove any wristwatch or timing device on their person, and they were asked to put their phones on silent and leave in the meeting area.

All participants, regardless of their familiarity with playing Sudoku were given instructions on how to play Sudoku, with a few strategy tips, and a sample Sudoku puzzle to complete. The puzzle matched the level of complexity of the puzzles in the computer program. Participants read the instructions on their own and then completed the puzzle. Research assistants did not assist, unless asked. Upon completion, research assistants checked for 100% accuracy and had the participants correct any errors. All training sessions were timed, and averaged 10.13 minutes (range 3 - 29).

The program used for the Sudoku task was a customized program from an open source. The program was altered so that all participants would have access to a randomly generated puzzle with 33 blank cells set at the "Easy" difficulty level. Previous pilot testing showed that the Easy setting allowed for most participants to solve between three to four puzzles in a session. No actions were allowed in the Sudoku program except to fill empty cells with numbers, clear cells, and view the instructions for the game (see

Appendix A for a screenshot of the game). There was a point contingency for playing the game. Points were awarded for every game completed, and the faster the participant completed the puzzle the more points they earned. The participant did not receive any point information except at the end of completed puzzles and in a form of a cumulative score at the end of the session.

The Sudoku program served multiple purposes. Not only did it provide a distraction task for the participant to avoid explicit counting behavior and mimic daily activity, but it also served as the platform for the participant to report how much time has passed. Once started, the program ran for 30 minutes and a message box popped up on the screen every 3 minutes asking the participant to estimate how much time has passed since either the game began or since the last message box appeared. To evaluate whether there was any noticeable, systematic difference in time estimation depending on how the question was framed, 50% of the questions asked the participant to type their response "in seconds," and the other 50% of the questions asked for a response "in minutes." The first question every participant saw was framed in seconds; afterward, the questions alternated in a semi-random fashion based on a pre-specified formula. The participant was required to type in a number before gaining access to the puzzle. No contingency was set in response to the participant's typed timing estimates.

After the 30 minute Sudoku session ended, participants completed a brief post-study survey consisting of minimal demographic information, questions about the training and program, and self-reports of personal time management skills and strategies. Participants were asked to provide their year in school, major, and previous history with playing Sudoku. Feedback questions included information about the degree of helpfulness of the Sudoku training instructions. Self-report questions asked participants to rate how well they manage their time, how long it takes them to make daily decisions and work on projects. Participants were asked to report whether they thought there was a pattern to the message box appearances (e.g., same time every time, different times in a pattern), and whether they had any methods for helping them report the time in the message boxes.

Procedure. When the participants arrived, the research assistant would have them sit in the front area of the lab. There the participants were read the information sheet about the study and were given a brief explanation about the credit and raffle. After introducing the participant to the study, the research assistant provided the participant with a one-page set of instructions on how to play Sudoku and a blank practice Sudoku puzzle to complete. Time to complete the practice puzzle was recorded and research assistants checked every puzzle for 100% accuracy. If the participant made errors in the puzzle, the cells with incorrect numbers were circled and the participant was asked to fix their errors. Once the participant completed the puzzle with no errors, they were moved to a lab computer with the Sudoku program.

Participants were given brief instructions regarding the Sudoku program, that they should complete as many puzzles as possible and that they would be asked to answer some questions while they played. Once participants started playing the computerized Sudoku task, they would be left to work alone. The research assistant sat on the other side of a partition, in case there were any questions. The Sudoku program ran for 30 minutes with the condition set to interrupt the task every 3 minutes with a retrospective timing question (for a total of 10 timing responses).

Once the Sudoku session ended, participants were told how many points they earned throughout the session, how the points equates to number of raffle entries, and then instructed to take a short post-study survey using Qualtrics.

Study design and data analysis. The independent variable in the study was the unit in which the timing question was asked. All participants were asked 10 times, every three minutes, to type in how long they thought it had been since the last time they were asked. Whether the question asked for seconds or minutes was alternated in a semi-random order based on a pre-programmed formula, to control for any order and to prevent predictable patterns.

The primary goals for the study included: determining the feasibility of the Sudoku task, general assessment of timing accuracy and variability in self-reported timing estimates, whether there are any correlations of timing accuracy and variability with puzzle playing performance, and finally gauging the social validity of the procedure. Puzzle activity was recorded on various levels: (a) number of games played, (b) amount of time spent on each game, (c) number of points earned for each game, (d) number of correct and incorrect responses, and (e) real-time mouse click records. Time reporting was also recorded and then assessed based on accuracy (time estimate difference from target time of three minutes) and variability (standard deviation of participants' estimates). Descriptive statistics were used to investigate general trends and correlations between variables. For inferential statistics, only t-tests were used to evaluate any differences between emergent groups.

2. Results and discussion

Logistically speaking, the procedure worked well to run participants through the training, game, and survey all within an hour. Sometimes time was strained if participants took longer to complete the practice puzzle during training. Two participants had to be excused from the study without completing the final survey, requiring their data to be excluded from analyses.

For the timing estimates, there was some unanticipated variability that needed to be accounted for. What quickly became evident was that many participants failed to discriminate based on time unit requested in the message box. For example, after a three-minute interval, if the participant was asked to report (in minutes) how much time has elapsed since the last question, the participant might have typed in “240.” Assuming the participant did not literally think it have been 240 minutes, data suggesting gross miscalculation was assumed to reference time in a different unit (i.e., seconds). Eleven of the 27 participants (40%) only typed responses in one unit or the other, meaning providing a time estimate in the correct unit 50% of the time.

Regardless of whether participants reported their time estimates in the requested unit (i.e., seconds or minutes), all responses were converted to seconds to assess the degree of accuracy and variability of responding throughout the session. Figure 1 depicts each participant’s average timing estimate accuracy as it relates to the variability of their estimates. Accuracy was determined as a degree of timing error. Values were calculated by taking the difference between the participant's response and the target time, in seconds. Thus, zero would denote complete accuracy, a positive value would mean that the participant was overestimating time, and a negative value would indicate underestimation. Variability was calculated by taking the standard deviation of all 10 timing estimates. Zero variability means that the person typed in the same duration every time they were prompted, and increasingly larger values indicate greater variability. Considering that the messages appeared at the same interval each time, variable estimates raise some questions.

During the Qualtrics survey, after completing the Sudoku session, participants were asked various questions about the Sudoku task and the timing questions. Particularly, they were asked to indicate if they noticed any pattern with which the message boxes appeared: (a) same time every time, (b) different times, alternating in a pattern, or (c) different times shown in no pattern. The question was meant to evaluate whether participants could tact the message appearances separately from reporting time estimates. Ten participants (37%) correctly selected the option that the message boxes appeared at the same time every time (i.e., a fixed-time schedule).

Participants were also asked in the Qualtrics survey to provide their timing method, if they had one, for how they knew what number to type in the message box. The timing strategies, when provided, varied greatly; however, the variable of greater interest became whether the participant stated a timing method at all. Nine participants (33%) indicated some form of a timing strategy. Upon further analysis, seven of the nine participants also correctly identified the fixed-time schedule of the message boxes, accounting for 70% of the participants who marked the fixed-time question option. The overlap between persons who indicated a timing method and those who correctly identified the fixed time schedule suggests that the participant's self-generated rules facilitated larger timing patterns.

Timing methods appeared to have an effect of noticing larger patterns, but it is less clear how they may have facilitated or inhibited the noticing of more molecular changes in the environment. Given the natural division in the participant sample between correctly identifying the fixed-time schedule of the messages and marking that the message appeared variably, a two-tailed t-test was conducted to evaluate whether there was a group difference on discriminating the units in the text of the message box. That is whether correctly identifying the timing pattern would be related to noticing whether the questions were asking for responses in both seconds and minutes. The t-test revealed that participants who identified the fixed-time schedule were significantly less likely to provide timing estimates in the correct unit. Participants who incorrectly guessed the question interval pattern were more likely to discriminate the textual stimuli ($t = 2.11$, $p = 0.01$; Cohen's $d = 1.15$, see Figure 2).

Other correlations and analyses produced nonsignificant effects, such as relating measures for relative timing accuracy and variability as it compares to Sudoku playing, responding in the correct unit, having a timing strategy, and self-reported time management skills. There was a small correlation ($r = .33$) between self-reported time management skills and game performance, roughly suggesting that better participant time management skills ratings were positively related to points earned in the Sudoku program.

In terms of social validity, data from the Qualtrics survey revealed several helpful findings to guide the Study 2. When asked about the quality of the Sudoku training, 15 participants (56%) indicated that the training prepared them for playing the Sudoku game either "Well" or "Extremely well." When prompted for additional comments, two participants indicated that they enjoyed the experience of learning how to play Sudoku with no participants indicating frustration or distress during the process. Reviewing the data from the survey indicated that the procedure was generally acceptable to participants, and highlighted some opportunities for improvement in the second study.

B. Study 2

The second study was conducted to begin assessing the effects of written instructions on timing accuracy and variability. The first study showed that without any programmed verbal intervention, there was a steadily inconsistent pattern of timing estimates for longer durations. The next step in evaluating how verbal behavior interacts with timing was adding instructions to see if orienting their attention to specific environmental events restricts behavior to influence timing accuracy and variability. If an instruction functioned as a track, we would expect the participant's timing estimates at least reduce in variation, if not also approach the target interval (i.e., three minutes). Based on the lessons learned from the first study, the second study was conducted to further evaluate the degree of timing accuracy, based on three-minute intervals, with several differences.

First, the Sudoku training was modified to make it more interactive, thus presumably more effective. Although most participants had indicated in the previous study that the training adequately prepared them to perform the Sudoku task, there was still a wide range of variability in the time it would take participants to complete the practice puzzle. Not only could variable completion times produce more noise in the study, but there was a logistical concern of persons running out of time to do the whole study in an hour if their practice puzzle time exceeded 10 minutes (involving roughly half of the participants run through Study 1). Although it was not the primary focus of the study, findings from the altered training are reported to demonstrate the greater exertion of experimental control in this second pilot study.

The second significant shift in the next study was how participants reported their timing response. No promising trends emerged in manipulating the unit of time requested, so there was no need to keep a typed response. To create more formal similarity with basic timing research and remove superfluous verbal responses with respect to timing, participants were asked to press a button whenever they think it had been three minutes, every three minutes. In the literature, this is called “interval production.” In particular it is an “empty” interval because the button press is meant to terminate the interval, rather than having the participant press and hold the button for a targeted duration. Typically, producing time intervals are for short periods, where the participant holds down a key for an instructed duration; empty interval production was chosen for feasibility concerns.

Thirdly, this study used a different approach of manipulating verbal stimuli to potentially impact timing responses. To do this, four groups of participants experienced difference sequences of experimental conditions. One group (i.e., Control) ran through the program without any additional instruction other than to complete puzzles and press the button every three minutes. Three experimental groups each saw a unique message either prompting them to notice specific changing events in the environment or to generate their own rule for timing.

Finally, additional questions were added to the Qualtrics survey at the end to better track the degree of enjoyment participants perceived the Sudoku task, as well as, more specific questions about timing strategies and perceived time-related abilities.

1. Method

Participants and Setting. For the second study, participants consisted of 37 students at the University of Nevada, Reno recruited through the university's various subject pools for the social sciences. We accepted all participants provided they were at least 17 years of age. Sixty-five percent (n = 24) of the participants identified as female. The sample represented all level of students at the university level from first year students to those working toward an advanced degree (Figure 3).

By participating, individuals earned either one or two credits depending on the standards set by each subject pool. Like the first study, participants were all entered into a raffle for a $25 Visa gift card. Participating automatically gave each participant one ticket entry to the raffle, but they were told that better performance in the game could win them extra tickets to increase their chances (see Table 3 for point contingencies for the Sudoku task, and Appendix B full point-to-ticket distribution breakdown). The study took place in the same lab room as the first study.

Materials and Procedure. The same materials and procedure were used for the second study as with the first. The second study includes some refinements, such as with the new training protocol and more specific questions in the Qualtrics survey. The Sudoku program also was modified to change the form of timing response required and introduced experimental conditions for groups of participants.

Based on the variability of completion times on the training puzzle, the Sudoku training was revised to Study 2. All participants, regardless of their familiarity with playing Sudoku were provided an interactive training, akin to direct instruction. In a form of backwards chaining procedure, the research assistant showed the participant a completed Sudoku puzzle and explains the rules of the game, and then the participant works through two increasingly difficult iterations of the puzzle to demonstrate basic skills (see Appendix C for Sudoku training script). After the interactive training session (usually lasting only a few minutes), the participants received a practice puzzle to complete. The same puzzle was used as what was in the first study. Research assistants did not assist, unless asked. Upon completion, research assistants checked for 100% accuracy and had the participants correct any errors. All practice puzzle completion times were timed, and averaged 6.7 minutes (range 4 - 14). This was an average decrease in practice time by 3.4 minutes from the first study where the participants read their own instructions.

The program used for the Sudoku task was the same as in the first study, with the addition of a green time button to the right side of the screen and instructions to push the button every three minutes. Instead of 10 messages appearing to ask for a time estimate, message screens only appeared at strategic times based on the condition combination of the assigned group. Four different messages were shown to various participants, with the experimental instructions prompting different behaviors. See Appendix B for a screenshot of the game and the message screen.

One of the most significant procedural changes between studies was moving from time estimate responding to interval production. A single contingency for game playing may have inhibited button pressing; thus, another point contingency was built into the program. Increasingly large sums of points could be earned for pressing the button more accurately, that is, closer to the target time of three minutes (i.e., 180 seconds). The contingency followed more of a hyperbolic function than a linear function, to discourage participants from pressing the button more frequently to earn more points (see Table 4 for specific timing accuracy-to-point breakdown). The second study combined the points earned for pushing the time button with the same point contingency for playing the game (Table 3). Just as in Study 1, however, the participant never received point feedback except at the end of the completed puzzle with a cumulative point score at the end of the task.

The same Qualtrics survey was used as before with some additional questions about gender, likeability of the task, and timing strategies. In the previous study, participants could opt out of providing a timing strategy, presumably if they had none.

Since interval production requires an operant response to signal a temporal judgment, participants indicating they had no timing strategy saw an additional question asking them why they pushed the button when they did. Either way, participants reported their own explanation for their timing response.

Experimental design and data analysis. In contrast to the first study, the second began to systematically investigate whether and to what degree different instructions influenced timing accuracy and variability. Starting at a rudimentary level, this study evaluated the relative effectiveness of instructions as timing tracks, with different groups of participants seeing a unique instruction. The first 12 participants were assigned to the Control group. They were initially run through the whole 30-minute session without seeing specific instructions, to provide a basis for stability of accuracy and variation of timing estimates for a prolonged period. These data were also used to determine the 12-minute baseline for the experimental groups, to increase the chances of participants pressing the time button at least twice before they saw the first message. From thereafter, participants were randomly assigned to one of three groups, each with its own experimental condition.

There were four possible messages the participants could have seen (Figure 4). For all participants, the message "Remember--You earn points by completing as many Sudoku puzzles as you can AND by pressing the time button every three minutes" appeared before the participant started the Sudoku program. For the participants in experimental groups, there was a 12-minute baseline of playing Sudoku and pressing the button without further messaging, and for the Control group there was no additional messaging.

The experimental conditions each included a unique instruction that was written to occasion various types of responding. The same experimental message was shown to the participant twice, at the 12th and 21st minutes. One group saw the message "As you play the game notice each time you fill in an empty cell. How does your game playing fit in with button pressing?" to orient the participant to track time as a function of their own behavior patterns (hereafter "Behavior group"). Another saw the message "As you play the game notice as you breathe in and out. How does your breath fit in with button pressing?" to orient the participant to their own physiological responding to track time (hereafter "Breath group"). And the last group saw "The next phase will be 9 minutes long. Continue to play the Sudoku game and press the button every three minutes," to set the occasion for the participant to generate their own rule to tracking time (hereafter "Self-rule group").

The conditions and messages were developed based on the available verbal behavior literature that might indicate which type of environmental change, and from which source, the verbal stimulus would most likely function as a track. The messages for the Behavior and Breath groups were attempts to evaluate whether attending to certain forms and loci of changing events impacted the accuracy and variability of timing. In the case of Study 2, the only sources for immediately observable or predictable change came from their participant: either their performance in the task or their own bodily functions (i.e., breathing). Part of the studies premise is that individuals best track time when attending to relevant stimulus change, thus providing two sources with different patterns of change could indicate what changes are more relevant for this type of timing task. A secondary interest was to take a novel look at activities that orient individuals to the present moment, which is a component of many mindfulness activities. It is not clear whether attending to a somewhat continuous change in the present, like breathing, may interfere with time tracking or enhance it. The self-rule message was developed to assess whether timing effectiveness would be similarly effective with implicit instructions.

Data analyses: For within-group analyses, each participant in an experimental group experienced two conditions, 12 minutes of baseline followed by 18 minutes wherein a message appeared twice at the 12th and 21st minute. Differences between baseline and experimental condition were evaluated within each group of participants in terms of button pressing rate, accuracy and variability. Rudimentary descriptive statistics were also used for visual analysis to investigate potential relations between timing and Sudoku performance (e.g., number of games completed, total errors). For between-group analyses, each group's results were compared with each other to determine the relative effectiveness of each instruction on timing accuracy and variability. Finally, data were compiled from the Qualtrics survey in relation to the study's findings.

3. Results and discussion

The 37 participants were roughly split into four equal groups: Control (n = 11), Behavior (n = 9), Breath (n = 10), and Self-rule (n = 7). The following results will be discussed in terms of both within-group and between group differences.

Interval production. We took three approaches to analyzing time through the participant's production of the interval: rate of button pressing, timing accuracy, and timing variability. The rate of button pressing was calculated by counting the number of total button presses per phase, per participant, then divided by the number of minutes in the respective phase (e.g., 12 or 9). Accuracy and variability were calculated similarly as in Study 1, where accuracy was determined as degree of constant error. Constant error in the literature is the absolute value of the difference between the target interval and the produced interval (Grondin & Killeen, 2009), such that any difference from the target duration (i.e., 180 seconds, 3 minutes) was evaluated the same. Variability of produced intervals was calculated by taking the standard deviation between intervals for each individual.

The individual button press rates were averaged for each of the four groups (see Table 5, Figure 5). Overall average button pressing rates remained constant for the Control group, with a gradual improvement of about 27% (difference in rate of 0.06 button presses per minute). The greatest changes throughout the session occurred for the Behavior and the Self-rule groups. The Behavior group on average experienced a steadily increasing rate in button pressing, starting with overestimating time and finishing by underestimating time (a 36% rate increase). The Self-rule group showed a different pattern than all the others in that they, on average, decreased their rate of responding with decreasing accuracy before drastically improving their button rate. The overall shift in rate at the beginning compared to the end phase was less than the change seen in the Control group. However, between the first time the Self-rule group got the explicit instruction about the 9-minute phase, and the second time, accuracy of button rate rebounds 37%. From this analysis, the differences in rate and pattern of rate did change between groups. A preliminary glance suggested that the different instructions were influencing timing as measured by button pressing rate.

Accuracy and variability were analyzed separately to provide a comprehensive view of how participants estimated time for long durations and whether there may be subtle effects occurring with the varying experimental instructions. Timing accuracy is a focal point for timing studies, but if the underlying assumption of timing is that organisms are attending to relevant environmental change, then they may not necessarily become more ‘accurate’ with respect to clock time, but reduce in variability as the individual successfully tracks patterns of change. This may look like a group showing steady inaccuracy throughout the session, but with low or decreasing variability.

Figure 6 provides the varying constant error of the intervals produced through each of the three phases, by group. Figure 7 shows the data for variability of timing estimates. Refer to Table 6 for exact calculations for accuracy and variability across groups. Through visual analysis, trends and patterns were discernable between groups. Since these data were linked to the average rates of button pressing, the trends in accuracy show similar results with some additional precision. The Behavior group, on average, changed the least and was closest to approach perfect accuracy over the 30-minute session. Both the Breath group and the Self-rule group decreased in accuracy between minutes 12 and 21; and they both reversed directions during the third phase. On average, all groups were less accurate by the end of the Sudoku session than at the beginning.

Interval variation increased over the session for all groups, with the Breath group seeing the largest group with the standard deviation of time estimates doubling between the baseline and third phase. The Behavior group's average timing estimates were the least variable by a small margin, but also changed the least across the three phases.

In addition to analyzing the variability of the intervals, we also tracked the variability of button pressing throughout the session. That is, for every 3-minute interval (10 total), each button press was tallied for each participant. Distribution of button pressing was calculated both as average button press per 3-minute interval across groups (Figure 8), and standard deviation of button pressing per 3-minute interval across groups (Figure 9). Table 7 provides the exact values and ranges for average button pressing per interval.

Puzzle performance. As a secondary focus for timing, we measured the participants' performances in the Sudoku session. Part of this research aimed to integrate additional layers to timing studies to enhance its external validity. An implicit assumption of the current research is that increasing timing awareness is a helpful repertoire for adopting effective and efficient practices; but the literature suggests that at a certain level, focusing on time may interfere with other activities. This research allowed for an initial look at Sudoku performance across groups, by considering the number and duration of games.

Figure 10 shows how puzzle completion varied across groups. In the figures the average number of games played per participant, arranged by group. For this sample, the Control and Self-rule groups completed the most number of games per session (3.5 and

3.6 games, respectively), with the Breath and Behavior groups performing below average on average (2.8 and 2.7 games, respectively). Table 8 lays out the average duration and standard deviation of game duration for each group.

Qualtrics data. In the post-experiment survey, there were a few questions pertaining to methods the participants may have developed throughout the session. In the first study, the participants who disclosed that they had a timing strategy were also more successful at identifying the fixed-time schedule in which the questions appeared. Those data could support the notion that timing strategies function as tracks for orienting individuals to changing events (i.e., time). While there were no questions to interrupt them, the rate of button presses and accuracy were compared between participants with and without a reported method. First, only 9 out of 37 participants indicated that they had a method for pushing the time button. No relation was found between groups on the average button press rate or interval accuracy.

If the participant selected that they did not have a timing method, they were prompted to describe how they knew to push the button. The qualitative data for these responses are challenging to discern much of a pattern, but apparently most participants had a limited verbal repertoire in tacting their timing responses. Fifteen (40%) of participants used words appealing to a feeling or “gut” reaction to timing. The sources for describing our temporal awareness based on feel are unclear, but the overall conclusion is that participants are generally unaware of how they track time, regardless of the accuracy and variability of their timing estimates.

The Qualtrics survey was also used to collect general demographic information and some social validity data. For example, most participants (31 out of 37) indicated that they had played Sudoku before the study and self-reported middling self-management skills (average of 4.6 on a 7-point Likert scale). We wanted to see whether participants had previous mindfulness training, which could affect their level of timing awareness before entering the study (see Figure 11). Generally participants felt prepared to play the Sudoku game after the training (Figure 12) and typically liked playing Sudoku puzzles for extended periods of time (Figure 13).

C. Study 3

Based on the findings of the first two studies, the purpose of the final dissertation study was to further determine ways by which verbal behavior may function to orient individuals to aspects of environmental change via measuring timing accuracy and variability. In addition to increasing the sample size to make the findings from the second study more robust, the third study attempted to further control for individual differences by adding a discriminative stimulus at the beginning of the Sudoku task. From the second study it appeared that timing accuracy and variability improved for both experimental groups regarding the noticing of one's behavior in the game and their breath. Although some group averages appeared to diverge, a small sample size and pronounced individual differences enhanced the likelihood of nonsignificant findings. The final study ran 61 participants, with additional feature of the protocol to reduce noise in the timing response. Because the motivation around these series of studies was to generate discussion around the various ways verbal behavior may have an impact on timing, the following results and discussion elaborate more extensively on the self-reported timing abilities and timing methods used during the task as additional variables worth considering.

1. Method

Participants. Over the course of Spring 2017 and Summer 2017 terms at the University of Nevada, Reno, 61 participants participated in the final study. All participants were accepted, provided they were at least 17 years of age. The benefits for the study were the same as in the previous studies.

Materials and Procedure. The same training materials and customized Sudoku program were used as in the first two studies. The procedure was modified to include an initial three-minute timer to signal when the participant should press the green time button for the first time. Because the experimental emphasis of these studies relied upon antecedent manipulation, there was no direct feedback mechanisms to washout any potential weak effects. The three-minute timer, then, allowed for an initial "correct trial" for every participant directly from the beginning.

The post-experiment Qualtrics survey was also updated to include race/ethnicity to the list of demographic questions and the timing related multiple choice questions were revised to more closely describe the type of timing required during the study (see Appendix D for full list of questions and coded values).

Experimental design and data analysis. The proposed study was a continuation and extension of the second study. For Study 3 there were three groups: Control, Behavior, and Breath. Similar to Study 2, participants either encountered 27 minutes of baseline condition (Control), or nine minutes of baseline, followed by two instances of the same message being presented at the 12th minute and the 21st minute (Behavior and Breath groups; see Figure 14). Although the session was still 30 minutes in length, 27 minutes were considered for analysis since the first three minutes interval production was provided to the participants through the timer, making for three phases of nine minutes.

For the current study, data analyses focused on two primary calculations for accuracy (i.e., constant error) and variability (i.e., standard deviation). From the previous studies, there was no indication of importance regarding over or under responding; thus, the absolute value describes the overall deviation from 180 seconds to streamline analysis interpretation. For aggregating the data, averages for each individual's responses were calculated, and group data were calculated by averaging the individual's averaged data. Similarly for variability, the standard deviation of each response interval was recorded and then averaged for each phase. Group reports of variability are the averaged standard deviation values for each individual.

Similar data analyses will be conducted in the proposed study with the addition of running ANOVAs for within-subject differences between repeated measures. A combination of descriptive and inferential statistics are described below.

2. Results and discussion

Demographics. The post-experiment questionnaire on Qualtrics provided some basic information on the sample participants. Of the 61 participants, 17 identified as male (27.8%), 43 as female, and one preferred not to disclose. There was a fairly even distribution of males across groups (range: 2-7). Thirty-three (54%) of the participants self-identified as “Caucasian / White” with a fairly event distribution of other racial identities: African American (*n* = 3), Asian American/Pacific Islander (*n* = 8), Hispanic/Latino (*n* = 7), Other (*n* = 7). A repeated measures ANCOVA determined that there were no significant effects between the three nine minute phases when considering gender, $F(1, 56) = .01$, $p = .91$, and race, $F(1, 56) = .46$, $p = .50$. Since the two covariates were not significant, the preceding analyses will utilize a repeated measure ANOVA. Twenty-one (34%) participants indicated they were psychology majors.

In additional to personal demographic variance, participants also reported on histories that could potentially affect the results, if biased. Participants provided information on their previous experiences with playing Sudoku or practicing mindfulness, how well they think they track time on a daily basis, and whether they had a method for pressing the time button, (see Appendix D to read the full survey questions and response options). Using a one-way ANOVA, no significant differences between groups (Control, Behavior, Breath) were found (see Tables 9-10 for descriptives and nonsignificant group differences). Overall, 30 participants indicated that they were either “very familiar” or “somewhat familiar” with playing Sudoku (operational definitions provided in Appendix D). When asked “How well do you track time in your daily life?” distributions approached a normal distribution across groups, with 29 participants (47%) indicating they track time moderately well (see Figure 15).

Within group analyses. Several within group analyses were conducted to provide some insights into the question of timing accuracy and variability over time. Most timing research, regardless of the target interval select a variety of intervals to investigate the relative accuracy and variability of timing on a scale. These series of studies have focused on the precision and consistency of time production at the same interval. Due to the novel procedure, within subject timing trends were equally as important to evaluate as the between group trends.

Regardless of the group or phase, participants often overestimated the three-minute interval, meaning that the response intervals were typically greater than three minutes (see Figure 16). Average accuracy for timing responses across all groups was 85 seconds, meaning that on average participants pressed the time button a minute and 25 seconds before or after (usually after) the three-minute mark. The average variation for the sample was 54 seconds, meaning that the average deviation of a participant's own timing estimates was within a little less than a minute.

Like in Study 2, button pressing rate was calculated as one method of depicting the relative trends of interval production over a 30-minute session. With three, nine-minute phases, accurate button rate would be one button press every three minutes, or .33 button presses per minute. In Figure 17, average button press rate was below the accurate rate, implying overestimation, despite the initial three-minute timer provided at the beginning of the program. Over the next two phases, all three groups experienced an average increase in button press rate, which approached accuracy.

To evaluate timing patterns throughout the session, intervals were recorded as frequencies in 30 one-minute blocks. For example, if a participant pressed the time button at 400 seconds into the program, it would have been recorded in the "420 second" interval, but at 421 seconds, it would have been recorded in the "480 second" interval. Figure 18 shows the average response frequency across the session for each group. One concern of the experimental design was that both the instruction groups received two brief interruptions during their Sudoku session, whereas the Control group received no message interruption. Any significant changes after the message appearance could be attributed to the interruption signaling the end of a three-minute interval, rather than the functional stimulus control of the instruction.

Looking at Figure 18, there were no significant group differences between control and experimental groups for the first few minutes after the instructions were shown to experimental groups. When comparing differences between each of the 10 three-minute intervals (i.e., 180, 360, 540…), the assumption of sphericity was violated, Mauchly's W(44) = .12, $p < .001$, therefore the Greenhouse-Geisser correction was utilized. The repeated measures ANOVA revealed significant differences within the first three three-minute intervals, where there was a substantial dip in average responding between the third and sixth minute, $F(6.99, 419.53) = 7.18$, $p < .001$, $\eta^2 = .11$, despite the fact that it was the interval immediately following the interval with the timer. There were no significant differences for any of the groups between the intervals where the messages occurred. Although variable, a cycle pattern can be detected for both the control and experimental groups. Even though the participants tended to overestimate the 3-minute target, on average there is an orderly pattern of consistent responding throughout the session.

Repeated measures ANOVAs were used to investigate any significant differences between time points for each group. Three phases were used based on the experimental design. Phase 1 consisted of activity between minutes 3 and 12, phase 2 consisted of activity between minutes 12 and 21, and phase 3 consisted of activity between minutes 21 and 30.

Timing accuracy was interpreted as a factor of constant error, or the absolute difference (in seconds) from the target interval of three minutes (i.e., 180 seconds). When considering all Study 3 participants, accuracy varied significantly between the first and second phase, $F(2, 116) = 3.92$, $p = .02$, where participants were 27.6 seconds more accurate, on average, in the first 9 minutes, compared to the second phase ($M = 98.70$, $p = .004$). Participants' accuracy was approaching significant difference in the same direction, where participants were about 21 seconds more accurate in the first phase, than the third ($M = 92.29$, $p = .05$). When looking at within-subject differences between the groups, significant changes in accuracy only occurred for the Breath group, $F(2, 38) = 4.75$, $p = .01$, $\eta^2 = .20$ (Table 11). There were no significant differences between phases for the Control and Behavior groups.

For timing variability, calculated by using the standard deviation of intervals for each individual in each phase, there was no significant change between phases. Although the variability of interval production did not significantly differ from each response between phases, accuracy and variability were positively related at the sample and group levels (see Table 12). For all groups for the whole session, the greater accuracy (i.e., the lower the constant error) significantly predicted lesser variability (i.e., standard deviations closest to zero).

Performance data were also recorded and tracked to later discuss how an interfering, non-timing task could impact timing responses. The average total games completed for the sample was 3.4 games (range: 0-10, *SD* = 1.7 games), with the average game duration clocking at 552 seconds (i.e., 9.2 minutes). Figure 19 depicts game averages across groups, no significant differences between groups were found, $F(1, 58) = 1.88$, $p = .16$.

Sudoku playing behavior was found to be significantly related to the person's self-reported familiarity with Sudoku before the study, $r = .48$, $p < .001$, where the more experienced Sudoku players generally completed more games per session. Furthermore, response rates were analyzed for entering numbers into the Sudoku puzzles. The number entry rate was also significantly correlated with reported Sudoku experience, $r = .51$, $p = .02$, where the players with more reported experience tended to enter numbers faster than those with less experience with the game.

Game playing also improved over the course of the session, $F(2, 116) = 7.23$, $p = .001$. For both the Control and Behavior groups, average game completion rate was greater in the second two phases, compared with the first (Table 13). There was no significant difference between the phases for the Breath group.

It has been well documented in the literature that an interference effect occurs during timing tasks when participants are required to do a separate, non-timing task (Fortin, 1999). Figure 20 shows a cumulative record of Sudoku activity and time button pressing over time to demonstrate the potential relation between the two activities. The relationship is further demonstrated when subdividing the sample into two groups: high rate button pressers (underestimating the interval) and low rate button pressers (overestimating the interval). Figure 21 displays the cumulative record for Sudoku activity and button pressing for the high and low rate groups. It appears that participants who pressed the time button more often also entered numbers into the puzzle at a faster rate. It should be noted that the data shown in the cumulative records are from the Control group only. A bug in the program code prevented the accurate recording of Sudoku activity in the experimental groups which prevented mapping their activity on this molecular level.

To statistically evaluate the degree of relatedness, a series of correlations were conducted to determine whether either timing accuracy or variability was significantly correlated with game completion rate. From the data collected, there were some significant correlations between timing and game playing. Both accuracy and variability were correlated with games completed for each of the three phases, as well as for the whole sessions (see Tables 14 and 15 for accuracy and variability respectively). There were few instances where there were any significant correlation between the timing metrics and the game completion. The Breath group's average accuracy was negatively correlated with game completion, $r = -.46$, $p = .04$, suggesting that the greater deviance from the target interval (i.e., greater inaccuracy) related with completing fewer games.

Between group analyses. Upon initial visual analyses, the Breath group's timing responses more closely fit with the three-minute target interval (Figure 22) and the Behavior group responses mimic the Control group. Furthermore, the within-group variability across the session could indicate the degree of stimulus control of relevant change for individuals in the same groups. Not only does the Breath group appear to be, on average, more accurate but as a group the variability of responding also appears to remain low (Figure 23). The three groups determined *a priori* (Control, Behavior, Breath) based on the experimental manipulations did not appear equal during baseline.

Despite the group separation detected in the cumulative records for accuracy and within-group variability, other figures depict some initial differences between groups at baseline (Figure 24). Steps were taken to randomly assign participants to each group. Since the assumption of homogeneity of variance for a one-way ANOVA was met, the results revealed significant differences between groups at baseline, $F(2, 57) = 3.77$, $p = .03$, $F(2, 36) = 5.31$, $p = .01$, for accuracy and variability respectively. A Tukey HSD post hoc test revealed that the Breath group's accuracy was closer to the target of 180 seconds during baseline ($M = 43.97$, $SD = 37.05$) than both the Control group ($M = 83.9$, $SD = 59.1$, $p = .06$) and the Behavior group ($M = 85.56$, $SD = 63.06$, $p = .04$). Initial group differences increase the likelihood of Type I error thus a more judicious approach to summarizing the *a priori* group data is to focus on within-group analyses (as described above).

The between-group analyses, then, were post hoc analyses investigating other potentially relevant variables such as the presence and level of complexity of timing methods, self-reported timing ability, and previous experiences with mindfulness training. The primary significant between group findings for Study 3 revolves around the timing methods that participants reportedly used during the Sudoku session. The originally intended independent variable, the presence or absence of instructions to orient the participant to different sources of environmental change, did impact the degree of complexity of self-reported timing methods. Regardless of whether the participant indicated that they had a timing method for tracking time, all participants were required to comment on what prompted them to press the time button. All open responses were coded to look for similarity of strategies in terms of methods and level of specificity (see Table 16 for coded frequencies). More often than not (21 out of 22 participants), participants who indicated that they had a method for pressing the time button, provided more specific strategies and tactics, such as counting the number of Sudoku squares filled to track time. Most of the participants who marked that they did not have a method used words like “feeling” and “instinct” to explain their behavior. No participant indicated monitoring breath as a method for tracking time.

To help capture this variation of timing methods, the coded responses were further consolidated into a 3-point scale of complexity: generic, simple, and complex. The generic responses were any comment that referred to an unclear explanation for time tracking, typically attributing their timing to a feeling or instinct. For example, one participant claimed “I wouldn't really think about it but every now and then I would get a thought saying ‘it feels like its [sic] been 3 minutes’ so I pressed it then.” Responses were coded as a simple method if there was a clear description of a single method that could be objectively measured or replicable. For example, one participant said that their method involved “Approximating the amount of time it took for [them] to complete a certain number of squares.” Finally, complex methods were considered to be two or more objectively measurable or replicable explanations. In this case participants offered compound strategies for their timing response, such as:

> I noticed that I was able to complete a little over 4 squares within the first three minutes. I tried to keep track of time by comparing how many I was completing

> and trying to add time if I felt like I was completing the game quicker than the first one, or I would take away time if I felt like I was completing the game slower.

Table 17 shows the count frequencies of participants with generic, simple, or complex methods across groups: Control, Behavior, Breath.

To determine whether the presence of instructions had any impact on the self-generation of rules during the timing task, a two (group) by three (method complexity) ANOVA was conducted to compare participants who saw instructions against participants who saw no instructions. A significant difference was found, $F(1, 59) = 4.85$, $p = .03$, where participants in the experimental conditions reported more complex timing methods than the participants in the control condition. This finding indicates that the instructions served a role in setting the occasion for self-generation of rules (i.e., timing method). An ANOVA was conducted to evaluate degree of method complexity and interval accuracy with nonsignificant results.

In addition to demonstrating effects between experimental groups, timing complexity was also significantly correlated with Sudoku productivity, $r = .29$, $p = .02$, such that eight percent of the variance of the number of games completed is explained by the degree of method complexity. There was no significant difference found in the number of games completed between experimental groups, suggesting that there could be some common function between the development of complex rule generation and effectively playing Sudoku, rather than there being a connection based on the instructions presented throughout the Sudoku session.

Figure 25 shows the average accuracy of timing estimates across phases, based on how well the participant ranked their ability to track time on a daily basis. The survey question was based on a 5-point Likert scale, but to condense and make for more equally-sized groups, the lowest two points ("Slightly well" and "Not well at all") and the highest two points ("Extremely well" and "Very well") were consolidated into low and high ability groups, with the middle group ("Moderately well") were coded to be in the middle. Remember that accuracy has been calculated as the absolute value of the response interval minus 180 seconds. A greater value on the y-axis, the less accurate the average. The interaction effect of timing ability over the three phases was nonsignificant.

Figure 26 shows the average accuracy of timing estimates across phases, based on whether the participant had previous exposure to mindfulness training or mindfulness-based activities. A repeated measures ANOVA produced significant differences between phases for individuals who had no previous mindfulness exposure (n = 31), $F(2, 60)$ = 4.13, p = .02, η^2 = .12, but nonsignificant differences between phases for individuals who had experience mindfulness activities (n = 28), $F(2, 27)$ = .001, p = .98 (Table 18). These results could indicate that the skills involved with mindfulness (i.e., awareness) may effectively increase time tracking over sustained periods. A one-way ANOVA to investigate group differences in phase 3 revealed nonsignificant difference based on mindfulness experience, $F(1, 59)$ = 2.22, p = .14. There was about a 33 second mean difference between the two groups at phase 3 (109.4 seconds and 76.9 seconds for "no" and "yes/maybe" mindfulness experience respectively); however, given the strong degree of relatedness between accuracy and variability in timing estimates a mean difference of a half-minute was rendered insignificant. Although these results should be interpreted lightly, future research investigating timing and mindfulness may reveal some interesting connections in terms of consistently tracking events over time.

D. Cross-study comparisons

As stated previously, the primary aims of this research were: (a) to investigate the timing patterns produced for long durations multiple minutes over a sustained period of time as compared to similar studies for shorter durations, and (b) to identify conditions under which verbal antecedents and self-generated rules may impact timing in human participants. Three studies were conducted, each a form of replication and extension upon the other (Table 2), as an initial attempt to meet those two goals. The following results considered the data from all three studies. Reviewing the data across all three studies provided multiple benefits including larger sample sizes to find replicated trends across studies as well as the opportunity to find differences between studies, particularly as it relates to the two different operant responses required between Study 1 (time estimate) and Studies 2 and 3 (interval production).

Replicating findings for long durations. Two significant findings support the interference effect, which states that when completing a timing task and a non-timing task attention to the non-timing task will inhibit timing ability. For all studies, significant group differences were found for both timing accuracy and total Sudoku puzzles completed, based on whether the participant indicated that they had experienced playing Sudoku previous to the study. For timing accuracy, on average across the whole session, participants with no previous Sudoku experience deviated significantly more from the target interval (M = 101.77) than those with Sudoku experience (M = 62.95), F(1, 114) =

16.40, $p < .001$. For puzzle productivity, participants with no Sudoku experience on average completed fewer games ($M = 2.61$) than participants with Sudoku experience ($M = 3.76$), $F(1, 114) = 8.34$, $p = .005$. In this case self-reported Sudoku experience effected both timing and non-timing task activity.

In a similar vein, a significant correlation was found between accuracy (i.e., constant error) and the number of puzzles completed, $r = -.20$, $p = .03$, such that the reduction in error (greater accuracy) was related to an increase in the number of puzzle completed. With Sudoku experience as a common link, fluency of the non-timing task appears to influence the degree to which interference is observed.

The primary cross-study findings focused on the form of timing response required in the studies. Study 1 provided 10 prompts every three minutes for the participant to type in a time estimate. Studies 2 and 3 instructed the participants to press a button, in a free-operant style procedure, to produce an empty time interval approximating three minutes. Three primary differences may implicate functional differences in timing as it relates to the relative impact of verbal behavior.

First, a repeated measures ANOVA was conducted to test the interaction of operant timing response over the three phases. The assumption of sphericity was met, $\chi^2 (2) = .35$, $p = .84$. The same main effect as demonstrated in Study 3 was replicated in that there was a significant difference between phases $F(2, 228) = 8.28$, $p < .001$, $\eta^2 = .07$. This main effect was qualified by a significant interaction between operant response and phase, $F(1, 228) = 6.06$, p < .001, $\eta^2 =.05$. At phase 1 there was no significant difference between groups ($M = 55.55$ seconds, $M = 49.03$ seconds, for time estimates and interval production respectively), $F(1, 114) = .61$, $p = .44$. However, significant differences were found for both phase 2, $F(1, 114) = 5.61$, $p = .02$, and for phase 3, $F(1, 114) = 6.11$, $p = .01$. In phase 2, time estimates were significantly more accurate than the interval productions in terms of constant error ($M = 62.00$ seconds, $M = 103.18$ seconds, for time estimates and interval production respectively). In phase 3, time estimates again more accurate than the interval productions ($M = 55.83$ seconds, $M = 96.02$ seconds, for time estimates and interval production respectively). Comparing the total variability of responding over the course of the session was also significant between operant response modalities, $F(1, 114) = 4.04$, $p = .05$, where the time estimates were less variable ($M = 48.61$ seconds) than the interval productions ($M = 62.49$ seconds).

The second finding built off the first and connects with existing literature on timing. It has been long established that timing estimates produce different results than interval production, where time estimates are typically shorter than the target interval (underestimating) and interval productions are longer (overestimating; see Table 19).

Figure 27 shows the cumulative averages of time judgments throughout the Sudoku session. The dotted line was added for reference, where data above the line indicate underestimation of time and data below the line indicate overestimation. The regression effect was observed for the participants in Study 1 who provided time estimates. They typically underestimated time, which is thinking that less time has passed than it really has, whereas the overestimates of the interval productions demonstrate that participants clicked the time button less often than they should have. For example, when the blue line for Study 1 is at 900 seconds, that means that by the 6th prompt (which occurred at 1,080 seconds), on average participants estimated that they were about 900 seconds into the session. Thus, the blue group was generally "underestimating" the time intervals (they thought the 180 second interval was generally less than 180 seconds long). On the contrary, the participants from Studies 2 and 3 were "overestimating" time because on average, their responses were greater than 180 seconds. At 900 seconds, they should have been at 5 button presses but on average they were on their fourth button press or just under.

Verbal interactions with timing responses. The final finding begins the conversation regarding the conditions under which verbal stimuli may influence timing behavior. As mentioned previously, whether the participant had a timing strategy was significantly related to correctly identifying the fixed interval pattern of the questions but were less likely to discriminate between the change in time units presented when the questions appeared. Furthermore, the participants who indicated that they had a timing strategy estimated time significantly more accurately (M = 40.14 seconds) than the participants who did not have a timing strategy (M = 65.66 seconds), $F(1, 26) = 4.84$, p = .04.

Based on the findings from Study 1, hypotheses were formed to investigate the effects of verbal strategies on timing at longer intervals. In Studies 2 and 3 the choice to have instructions presented as an antecedent independent variable was designed to set the occasion for more effective timing methods which would presumably reduce the error in interval production.There was no significant difference on timing accuracy between having a timing method and not, (M = 81. 02 seconds, M = 68.53 seconds, for having and not having a timing method respectively), $F(1, 86) = 1.17$, $p = .28$. There was an important difference between Study 2 and Study 3 in that for the latter all participants were exposed to a three-minute timer which served as a discriminative stimulus for pressing the button for the first time. The timer may have played a role in exerting greater control over timing responses since the mean accuracy for Study 3 was 73.91 seconds, which was 10 seconds closer to the target interval than in Study 2 ($M = 84.13$ seconds). This difference, however, was not significant.

Also nonsignificant but worth mentioning was the proportion of participants who indicated they had a timing method in Studies 2 and 3. As mentioned previously, in Study 2 most participants (76%) indicated that they did not have a method for pressing the time button. For Study 3, only 64% of participants indicated that they did not have a timing strategy. This small, nonsignificant decrease in the proportion of the sample without a timing method could be attributed to the timer providing more information for participants to base their timing response.

VI. Discussion

The presented series of studies were a successive replication and extension of findings regarding human timing of three-minute-long intervals over sustained periods. The results contribute not only to the basic timing literature, but represent the exploration of verbal stimuli and verbal behavior as they interrelate with different response modalities of timing. Limitations should be addressed to further explore the original variables in question, but the strengths of these findings allow for the progressive research of timing as it more directly relates to daily human experiences.

Overview of main findings. The first aim of the dissertation research was to extend timing effects to longitudinal timing at a longer interval. Despite the prolific nature of basic timing researchers, very few of the findings from these labs are easily generalizable to a natural environment. Testing longer intervals helps to support timing theories that here-to-fore only existed on a limited scale, and bring the research closer to intervals that are relevant for human activity.

For example, linking the interference effect to more naturalistic activities, like playing a game, helps extend external validity to reliable phenomena. Timing methods were an important factor in Study 3, where it was found that having more complex timing methods was significantly related to completing more Sudoku games. Results from Study 3 relate to earlier findings regarding the complexity of stimuli and its effects on timing responses. Brown (1995) found that the faster moving stimuli on a computer screen generally lengthened perceived time to a greater degree than slower speeds, but in the case of Study 3 the faster the participant moved through the Sudoku task, the more accurate the interval. Discussing interference while considering fluency of the non-timing task may be an important variable to consider. Additionally, instructional control and self-generated rules may have facilitated game performance while inhibiting interval production. More research is needed to determine how rules function differently for simultaneous tasks as it relates to the interference effect.

The cross-study comparisons revealed that, on average, participants who provided time estimates underestimated the target interval, whereas participants producing intervals typically overestimated the target interval. These results replicate what is known in the psychophysics literature as the "regression effect." By 1971 the regression effect was established enough for S. Stevens to comment on the problem of the different results obtained between "magnitude estimation" and "magnitude production." Although this known differentiation has existed for nearly fifty years, we found no study that replicated these findings for an extended interval (e.g., 3 minutes). The significant group differences between time estimate and interval production found between studies replicate the magnitude differences sited for shorter intervals (Stevens, 1966, 1971).

Furthermore, the psychophysics literature has very limited time-series data to understand tracking time over time. The cross-study findings support and expand upon what has previously been demonstrated in the lab, and we can start to develop new models around tracking time over time. Not only did a regression effect observed, but there were alsointeresting trends of timing consistency throughout a session of multiple timing trials. By only testing participants at different intervals once or twice, such as in the traditional procedures, we only get a snapshot of initial timing awareness. Particularly with interval production, repeated opportunities to produce intervals of the same length result in increasingly inaccurate responding, which was not observed with time estimates. The trend of increasing timing error over time is an important finding in of itself. With no timing feedback involved during the task there was no expectation that participants would necessarily increase in accuracy, but potentially increase in timing consistency if the verbal stimuli functioned as tracks. Observing the decreasing accuracy over time could suggest that the environmental change exerted habituation effects on the participants' timing responses. Given the initial theoretical premise that timing is a reflection of the time-bound response coming under the stimulus control of relevant change in the environment, a continuous task like playing Sudoku could result in the subtle stimulus changes losing stimulus control over the button pressing throughout the session.

The second aim of the research conducted was to investigate the various verbal stimuli and verbal behaviors that may influence human timing responses. The literature review highlighted a sample of studies that examined the role of verbal behavior as either discriminative stimuli or collateral behavior for tracking time; however, little has been said about the function of verbal behavior on timing, such as relational framing and rule following. The presented studies set to clarify several examples of how verbal behavior interacts with timing responses.

Results suggested that there could be some influence of self-generated rules around tracking time by tracking game behavior, although, the form of timing response required may have played a role on the rule's relative effectiveness. In Study 1, the participants who reported having a timing method also provided significantly more accurate time estimates throughout the Sudoku session than participants who did not claim to have a timing method. For Studies 2 and 3 however, having a method, even when accounting for the complexity of the method, had no significant effect on the timing dependent measures. Originally, the intent of the study was to examine the effects of the instructions on timing behavior. The instructions did appear to set the occasion for participants to develop timing methods that were more specific and constructive than the participants who did not see the instructions. The timing methods as a mediating factor for effective timing, however, did not reduce timing error or variability for interval production responses.

That timing methods seemed to only be effective at improving timing accuracy and consistency for timing estimates may indicate that there are particular conditions under which self-generated rules affect other repertoires like timing. Since timing estimates arguably require a verbal repertoire, this form of timing response may be more susceptible to rule governance. Interval production does not require a verbal repertoire, as demonstrated by previous animal studies (Jasselette, Lejeune, & Wearden, 1990), which could imply that rules interact differently with nonverbal repertoires. Insofar as the self-generated rules functioned as tracks for participants in Study 1, the same cannot be said for the participants in Study 2 and 3. There was a greater connection, however between timing methods and Sudoku performance. The differing effects of self-generated rules on performing simultaneous tasks could provide an additional layer to analyzing problem solving and deductive reasoning required for completing Sudoku puzzles.

Limitations. Throughout this dissertation process, several limitations were noted and are worth discussing to promote increasingly progressive verbal timing research. First, an inherent challenge to doing timing research for longer duration means that fewer data points can be collected over time. Furthermore, pronounced individual differences become even more distracting at longer intervals, which leaves room for greater variation. Study 3 attempted to control for the individual variation by adding the initial three-minute timer, but the additional discriminative stimulus did not exert lasting stimulus control over the participant's timing behavior throughout the session.

The strength of the verbal interventions selected for Studies 2 and 3 were not effective at producing an effect between groups. This could have been due to the verbal manipulations being too subtle or weak to establish stimulus control over interval production. It is too soon to say that self-generated rules do not impact less-verbally mediated timing responses, rather it could be that either: the participants selected were verbal adults with extensive learning histories with respect to time which could make them less sensitive to simple instructions, or that the instructions were too ambiguous or subtle a contingency to have an effect. The instructions were chosen based on the literature around instructional control and tracking, while also considering the most minimal verbal unit possible so as to not introduce confounding variables that may be introduced with complex independent variables. Nevertheless, replicating these studies with children or with a more explicit verbal intervention may have produced stronger effects.

Findings associated with self-reports from the post-experiment questionnaire provided a basis for making inferences about a participant's history and less observable behaviors as it relates to the main task; however, since they were measured post-hoc, claims cannot be made regarding causality of the methods as they relate to timing accuracy or task performance. Future research interested in investigating timing methods or task strategy should consider procedures (e.g., talk-aloud, silent dog method) that more directly record whether the participant is utilizing a timing method or strategy.

Finally, the time estimates recorded were not from the same individuals who produced intervals. Due to the exploratory nature of this research, the interesting differences in timing responses were discovered post hoc. Given the findings presented above, research further exploring differences in timing responses should consider more robust within-subject comparisons. While the interference and regression effects were replicated at a three-minute interval, it cannot be assumed that they are the only explanations for the trends observed. The cross-study comparisons of timing accuracy relative to operant response show promise but should not be considered definitive. For example, the target interval was exactly three minutes. With a time estimate task, it is natural to assume that participants might estimate in whole minutes, which could have artificially constrained the accuracy and variability. Other creative procedures could be used to alternate between timing estimates and interval production, perhaps using less predictable intervals (e.g., 3.6 minutes) over multiple sessions, for more robust findings.

Future research. Many new research questions have emerged as a result of these studies. With some initial promising data based on novel procedures, more externally valid timing research may be more likely. Future research could investigate and challenge the established timing effects found for shorter intervals. For example, in response to Brown (1995), one could investigate how imposed stimulus change versus rates of environmental change in the participant's control may differentially influence interval production. Future research could also explore the repertoire of developing simple and compound strategies for tasks as it relates to behavioral variability required of the types of skills required to excel at problem solving tasks, like Sudoku.

Or, researchers interested in replicating other findings with longer intervals could do multiple trials of a variety of intervals to test Weber's law and relative matching for different durations. A potential replication and extension of these studies could be done to track within-subject correlations between timing estimates and interval productions for the same interval over time. Those interested in how the regression effect might be put to use in applied settings could investigate how different timing responses might influence the one's satisfaction or comfort with a particular interval. For example, when waiting in a line, customers could be given an interval production task rather than response to reflective survey on the time spent in line. Since the research suggests that people are more likely to overestimate time with an interval production, they may find that an imposed "wait time" may go faster or be more enjoyable.

Two findings regarding verbal behavior and human timing demonstrate considerable promise. Providing time estimates appeared to be more positively affected by having a rule regarding timing; and presenting instructions about noticing environmental change did occasion the self-generation of rules. More research is needed to determine how verbal behavior interrelated with interval production. Clearly, simple instructions did not establish stimulus control over the timing response; thus, more elaborate or intensive verbal interventions may be required before patterns of interval production are found.

Furthermore, evaluating the longitudinal trends of tracking time could lead to research that answers applied questions regarding persistence, situational awareness, and time management. Without knowing how individuals report their timing experience, either by estimates or producing an interval, over time it is harder to gauge how other time-related behavior might be effected by one's awareness of time to begin with. Across Studies 2 and 3, each group regardless of level, replicated a similar pattern where timing responses decreased in accuracy from phase 1 to phase 2 and either stabilized from phase

2 to phase 3. The addition of the three-minute timer for Study 3 did successfully ensure that the first interval production was near perfect accuracy, that initial exposure did not have lasting effects. Future research could investigate how different forms and rates of timing feedback could effectively train timing accuracy and consistency.

Future research should also consider the promising connection between mindfulness skills and timing awareness. Although not significant, previous mindfulness experience also had some interesting relationships with timing. For the participants who reported experiencing some form of mindfulness activity, interval production was closer to the target interval and more stable, whereas those with no mindfulness experience displayed the overall response pattern of increasing inaccuracy over time. The studies were limited in exploring mindfulness as a functional variable in that mindfulness was not very clearly defined in the survey, and there were large individual differences in the intensity and sophistication of mindfulness exposure each participant reported having. Mindfulness experiments could add timing components either requiring time estimates of interval production throughout mindfulness training to determine the degree to which the two repertoires are related.

VII. Conclusions

The introduction of this dissertation began by referring to Matthews and Meck (2014) commentary on the problems in timing research: susceptibility of time judgments on extraneous variables, major findings only robust at the group level, and low external validity. With the three studies presented here, I hope to begin resolving those three issues. Indeed, it quickly became evident that timing is greatly affected by the surrounding context, such as the interference effect observed with participants playing Sudoku. The more that research focuses on important contextual factors, however, the more the extraneous variables become accounted for. In particular, verbal behavior is likely to be a major extraneous variable that seldom has been addressed in the timing literature. Behavior analysis also has much to offer this area in that its traditionally single-subject methodologies allow for rigorous within-subject studies that help illuminate the order of timing behavior over time. And finally, this dissertation attempted to highlight the relevance of the timing literature to applied settings and designed studies that will hopefully make it easier for translational and applied research on timing in the future.

The more we understand about how verbal behavior interacts with timing, the more we will be able to expand basic research findings into application. Most of the review and critique of the existing literature has focused on research opportunities in the laboratory. Therefore, the following discussion focuses on just a few of the possibilities of how further investigations of language and time could elevate the existing work done in applied research areas.

Scholars interested in understanding "situation awareness" also investigate the various factors that impact a person's behavior in a moment-to-moment basis. In a way, one can view those moments as extremely constricted temporal intervals, like during an emergency. Despite the explicit appeal to time and timing, there is little understanding of how timing awareness relates to situation awareness. With a better understanding about how to effectively orient an individual to relevant stimulus events for effectively track time, there could be an opportunity to shape up the repertoires responsible for developing situation awareness.

Time and timing are important factors in organizational settings. Deadlines are inherent aspects of professional life, thus those with scholarly interests in business and organizational psychology have addressed time as a feature of the work environment. A recent review on the time management literature by Claessens, van Eerde, Rutte, and Roe (2007) noted that there was no common definition of "time management," which is a similar problem to the subject of time itself. Claessens and colleagues explicitly called out the need for operationalized definitions and theoretical frameworks for studying time management, but do not include any definition or theory of "time" except to say that it "cannot be managed, because it is an inaccessible factor" (p. 256). Overall, the literature provided some general support of time management, as a construct, accounts for some variance in people's work performance and perception of control; but less is known about how these repertoires are developed, the conditions under which the repertoires are shaped and maintained, and why. Similar concerns have been noted by others, including Green and Skinner (2005) who reviews the mixed effectiveness of time management trainings. Even if it is generally accepted that time management, problem solving, and sequencing activities are related to one's learned relation to time, there is yet to be consensus on the degree and direction of this relationship. For a systemic science of timing, basic researchers may do well to disseminate their findings in a way that would be useful for researchers interested in applied issues.

The presented work attempted to serve two overarching values: (1) maintaining the tenets of functional contextualism, and (2) advocating for systemic scientific progress. As such, the following research aimed to understand time as it occurs for most people outside of a laboratory. Rather than discriminating between second-long intervals, human activity largely revolves around completing complex tasks, while engaging in various forms of verbal behavior, such as temporal framing and self-generating rules. Building a bridge between mechanistic and contextualistic programs of research will result in a mutual benefit: with new avenues for basic scientists to explore while providing a foundation for practitioners to apply relevant findings to improve timing related issues in the field. No time has ever been more appropriate like the present to call for integrative scientific work that demonstrates coherence and cohesion. A more systemic science of time, that relates the various findings and expands upon procedures in a way that enhances external validity, will undoubtedly prove to be a mutually beneficial endeavor.

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Tables

Table 1. Various definitions of time in psychology

Author(s)	Year	Page	Definition / Description
Gibson	1975	299	A concept "abstracted from the percepts of events" and is an "intellectual achievement, not perceptual catergor[y]"
Fetterman & Killeen	2010	119	"Time is a dynamic stimulus, along which one temporal value cannot be discriminated from another until the carrier signal (e.g., a light or a tone) terminates, or at least passes some threshold value"
Hayes & Hayes	1989	185	"Time is a measure of change"
Killeen	2014	155	"Common time is an artifact, no less than mathematical time. But it is a directly, if diversely, measured artifact"
Zakay	2016	54	"Psychological time refers to a sense of the passage of [physical time] and temporal experiences related to succession, duration, simultaneity, pace and the order of perceived external and internal events"

Table 2. Study schema for successive replication and extension of procedures

	Study 1	Study 2	Study 3
Operant Procedure?	Time estimates, typed response into question box	Interval production, free-operant button press	Interval production, free-operant button press
Interval?	3 min	3 min	3 min
Intervention?	Alternating time units (seconds and minutes) in the question text	4 groups: Control*, Behavior, Breath, Self-rule *Control= no button feedback	3 groups: Control, Behavior, Breath +Addition of 3 min timer
Verbal Variables?	• Typed response • Unit of time in question • Timing pattern of question appearance • Timing method (y/n)	• Presence absence of instructions (for experimental groups) • Timing method (y/n) • Timing explanation • Self-reports about timing	• Presence absence of instructions (for experimental groups) • Timing method (y/n) • Timing explanation (w/ code for complexity) • Self-reports about timing

Table 3. Point contingency for Study 1 Sudoku program (for game completion)

Minutes	**Seconds**	**Points**
< 5	< 300	500
5-6	301-360	450
6-7	361-420	400
7-8	421-480	350
8-9	481-540	300
9-10	541-600	250
10-11	601-660	200
11-12	661-720	150
12-13	721-780	100
13-14	781-840	50
15+	841+	25

Table 4. Additional point contingency for Study 2 Sudoku program (for time button)

Time Difference (seconds from 180)	Points
0	1,000
+/- 29	500
+/- 30-59	300
+/- 60-119	100
+/- 120-179	50
+ 180	0

Table 5. Study 2: Average rates of button pressing throughout session, by group

Group	***n***	**0-12 min**	**12-21 min**	**21-30 min**	**Total**
Control	*12*	0.20	0.21	0.25	0.22
Behavior	*9*	0.23	0.32	0.36	0.30
Breath	*10*	0.28	0.35	0.29	0.30
Self-rule	*8*	0.27	0.21	0.32	0.27

Table 6. Study 2: Average constant error and variability of intervals (in seconds), by group

	Control		**Behavior**		**Breath**		**Self-rule**	
	Mean	*SD*	*Mean*	*SD*	*Mean*	*SD*	*Mean*	*SD*
0-12 min	108.40	125.37	18.68	81.46	-8.92	66.65	17.10	58.47
12-21 min	58.13	125.21	-2.10	80.23	-17.50	120.68	63.93	83.61
21-30 min	48.49	152.46	-4.20	85.11	22.06	122.53	29.03	99.45

Table 7. Study 2: Observed button presses within 3-minute intervals across groups

	Control	**Behavior**	**Breath**	**Self-rule**
n	*11*	*9*	*10*	*7*
Mean	6.55	8.89	9.00	8.00
SD	2.81	2.23	4.22	1.20
Min	4	5	3	6
Max	14	12	18	10

Table 8. Study 2: Average game duration and duration variation (in seconds), by group

	n	Duration	SD
Control	*11*	436.61	271.76
Behavior	*9*	509.84	298.59
Breath	*10*	553.82	294.35
Self-rule	*7*	414.13	177.63

Table 9. Study 3: Participant responses for post-experiment survey questions regarding relevant learning histories, for whole and by group

Question	**Scale**	***Total***	**Control**	**Behavior**	**Breath**
	Very familiar	4	1	0	3
	Somewhat familiar	26	8	9	9
	Acquainted	14	4	5	5
	Not very familiar	16	7	6	3
	Not familiar at all	1	0	1	0
	Yes	12	5	3	4
	Maybe	16	5	3	8
	No	33	10	15	8
	Extremely well	5	1	2	2
	Very well	9	4	3	2
	Moderately well	29	14	5	10
	Slightly well	12	0	7	5
	Not well at all	6	1	4	1

Table 10. Study 3: ANOVAs of group learning histories

		Sum of Squares	**df**	**Mean Square**	**F**	**Sig.**
	Between Groups	3.501	2	1.750	1.870	.163
	Within Groups	54.302	58	.936		
	Between Groups	1.67	2	.839	1.348	.268
	Within Groups	36.09	58	.622		
	Between Groups	3.488	2	1.744	1.655	.200
	Within Groups	61.102	58	1.053		

Table 11. Study 3: Within-subject differences in constant error between phase 1 (3-12 minutes) and phases 2 and 3 (12-21 minutes, 21-30 minutes, respectively) for each group

						95% Confidence Interval	
	Phase	Phase	Mean Diff	Std. Error	Sig.[c]	Lower Bound	Upper Bound
		2	-31.17	18.55	.11	-70.018	7.670
		3	-25.01	24.77	.32	-76.875	26.845
		2	-26.30	19.79	.20	-67.879	15.280
		3	-13.21	19.89	.51	-55.000	28.576
		2	-25.43*	8.695	.01	-43.634	-7.238
		3	-25.13*	9.18	.01	-44.357	-5.910

Table 12. Study 3: Within group correlations of constant error and interval variability for each group and total sample

		Phase 1	Phase 2	Phase 3	Total
	Pearson	.797**	.11	.41	.66**
	Sig. (2-tailed)	.003	.68	.10	.002
	N	*11*	*16*	*17*	*19*
	Pearson	.838**	.68**	.61**	.45*
	Sig. (2-tailed)	<.001	.003	.01	.04
	N	*13*	*17*	*18*	*20*
	Pearson	.34	.70**	.85**	.88**
	Sig. (2-tailed)	.21	.001	<.001	<.001
	N	*15*	*20*	*18*	*20*
	Pearson	.78**	.54**	.55**	.64**
	Sig. (2-tailed)	<.001	<.001	<.001	<.001
	N	*39*	*53*	*53*	*59*

Table 13. Study 3: Within-group comparison of completed game rate between phases

					95% Confidence Interval	
Phase	Phase	Mean Diff	Std. Error	Sig.	Lower bound	Upper bound
	2	-.35*	.15	.03	-.664	-.036
	3	-.45*	.18	.02	-.836	-.064
	2	-.47*	.19	.02	-.879	-.068
	3	-.47	.23	.06	-.965	.018
	2	-.10	.17	.58	-.469	.269
	3	-.20	.15	.21	-.526	.126

Table 14. Study 3: Within-group correlations of constant error and game completion for each group and total sample

		Phase 1	Phase 2	Phase 3	Total
	Pearson	-.09	-.50*	-.08	-.27
	Sig. (2-tailed)	.70	.02	.75	.24
	N	*20*	*20*	*20*	*20*
	Pearson	.50*	.25	.16	.37
	Sig. (2-tailed)	.03	.28	.49	.10
	N	*20*	*20*	*21*	*21*
	Pearson	-.11	-.35	-.50*	-.46*
	Sig. (2-tailed)	.63	.13	.02	.04
	N	*20*	*20*	*20*	*20*
	Pearson	.002	-.21	-.09	-.19
	Sig. (2-tailed)	.99	.11	.50	.14
	N	*60*	*60*	*61*	*61*

Table 15. Study 3: Within-group correlations of the variability of intervals and game completion for each group and total sample

		Phase 1	Phase 2	Phase 3	Total
	Pearson	-.17	-.02	-.18	-.30
	Sig. (2-tailed)	.62	.94	.48	.21
	N	*11*	*16*	*17*	*19*
	Pearson	.14	.42	.37	.08
	Sig. (2-tailed)	.66	.09	.13	.72
	N	*13*	*17*	*18*	*20*
	Pearson	-.14	-.16	-.24	-.40
	Sig. (2-tailed)	.62	.51	.34	.08
	N	*15*	*20*	*18*	*20*
	Pearson	-.19	.08	-.07	-.27*
	Sig. (2-tailed)	.25	.56	.62	.04
	N	*39*	*53*	*53*	*59*

Table 16. Study 3: Frequencies of coded timing methods for pushing the time button (yes, indicating that they did use a method)

Method	*N*	Adjust for difficulty	Amount of game finished	Amount of squares	Speed / rate	Counting	Ref. to 3' timer	Feeling / guess	Other
Yes	*22*	3	9	8	4	3	2	1	1
No	*39*	0	6	5	0	0	5	23	6

Table 17. Study 3: Count data of participant timing method complexity across groups

	Generic	Simple	Complex
Control	11	8	1
Behavior	6	7	8
Breath	7	11	2
Total	24	26	11

Table 18. Study 3: Within-group comparison of constant error across phases based on participant's previous mindfulness experience

	Phase	Phase	Mean Diff	Std. Error	Sig.[c]	95% Confidence Interval Lower Bound	Upper Bound
		2	-33.899*	12.487	.011	-59.401	-8.397
		3	-40.045*	14.256	.009	-69.159	-10.931
		2	-20.751	13.915	.147	-49.302	7.801
		3	-.450	15.870	.978	-33.012	32.113

Table 19. Study comparison of relative error (difference in seconds from 180 seconds) across phases

	Phase 1	Phase 2	Phase 3
Study 1	-29.59	-16.98	-3.21
Study 2	0.58	-4.01	10.52
Study 3	13.34	40.04	16.86

Figures

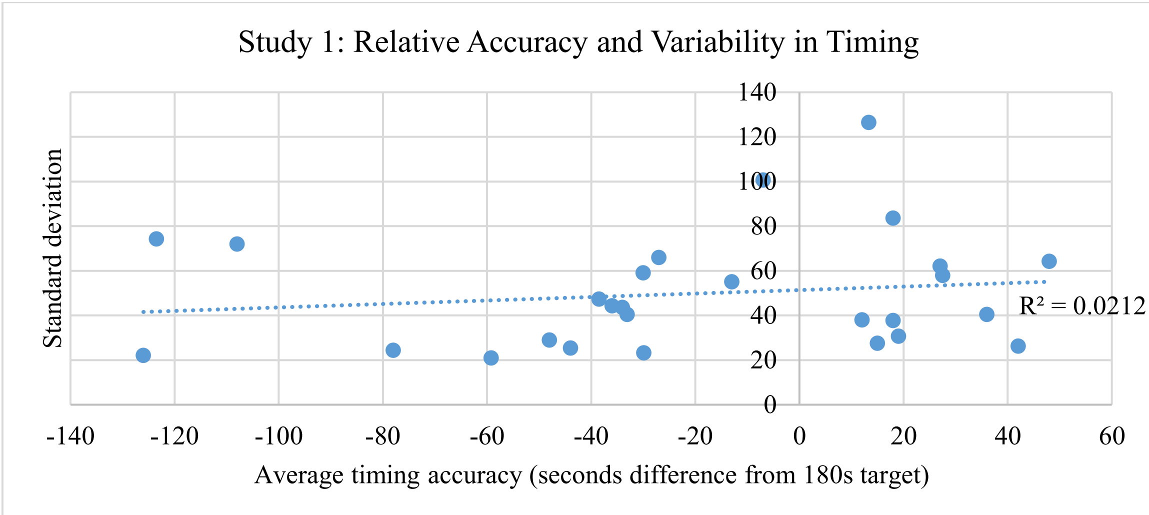


Figure 1. Each participant average accuracy of timing estimate is graphed according to the variability of their own responses. Scatter plot demonstrates the broad spectrum of individual differences, with no clear relation between the two features of timing estimates.

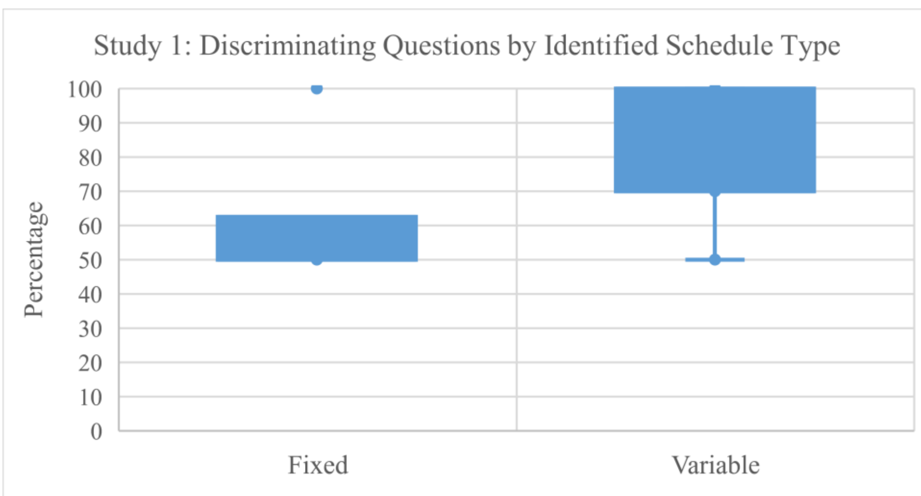


Figure 2. Two groups naturally emerged in the sample for Study 1, where 10 participants correctly identified that the questions appeared at the same time every time (i.e., a fixed schedule) and the remaining 17 replied that they thought the message boxes were varied (i.e., a variable schedule). The y-axis describes the percentage of questions (out of 10) when the participant typed in a response that was consistent with the unit requested.

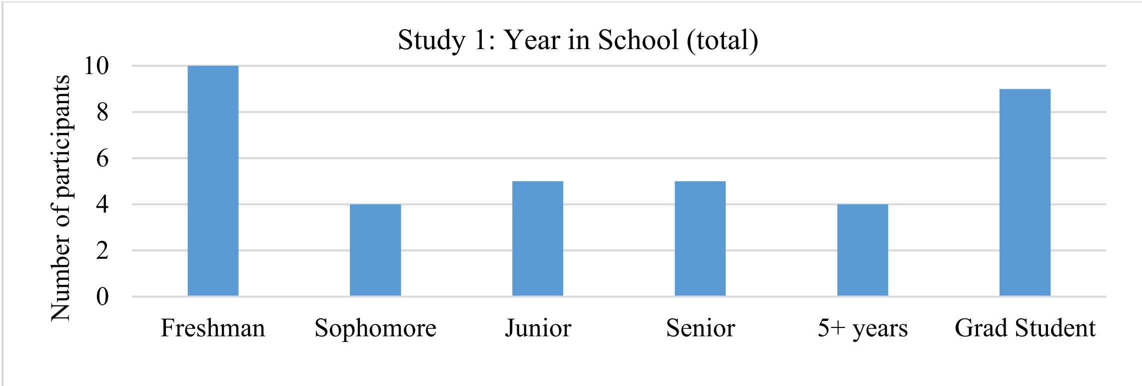


Figure 3. Breakdown of participants according to experience in higher education.

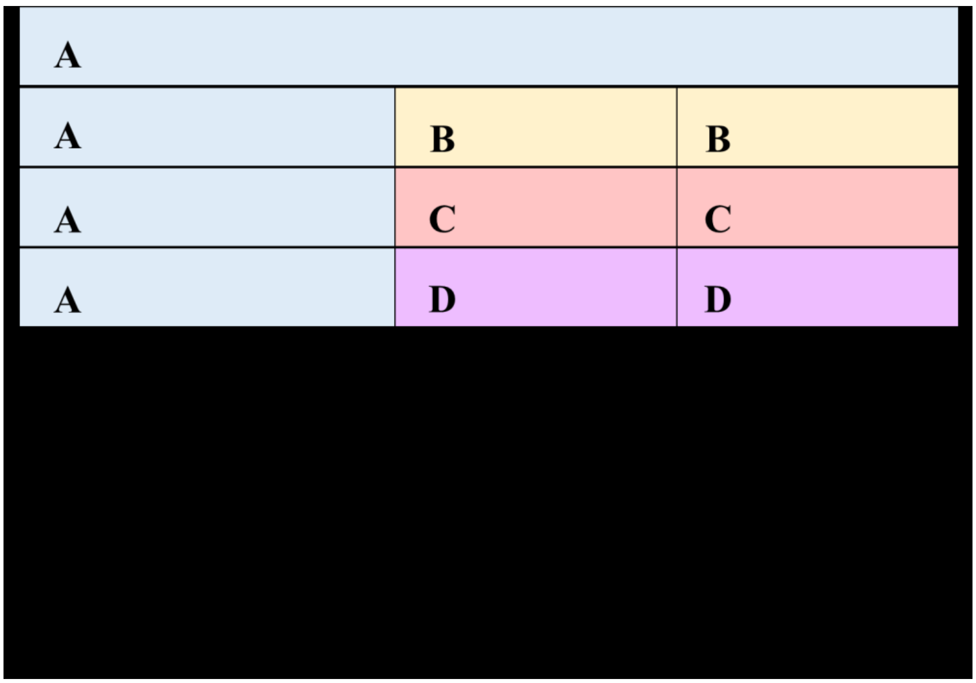


Figure 4. Experimental design for Study 2. All Sudoku sessions were 30 minutes (1800 seconds) long. The Control group as the baseline message and then had 30 minutes of uninterrupted play. Each experimental group saw statements at three different points, with the last two statements being identical.

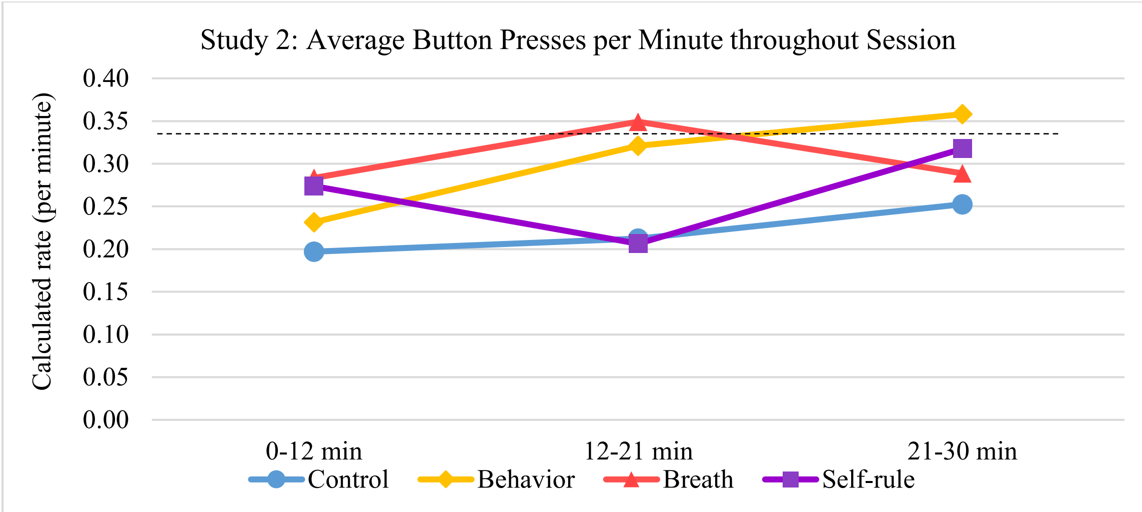


Figure 5. Average rate of button pressing throughout Sudoku session, by group. The x-axis marks the three phases and their respective durations. Each line indicates their experimental group, with the blue line (circle markers) representing the control participants, who received no special instructions throughout the game. Black dotted line serves as a reference at 0.33, which would be the rate if a participant's rate averaged 1 press per 3 minutes.

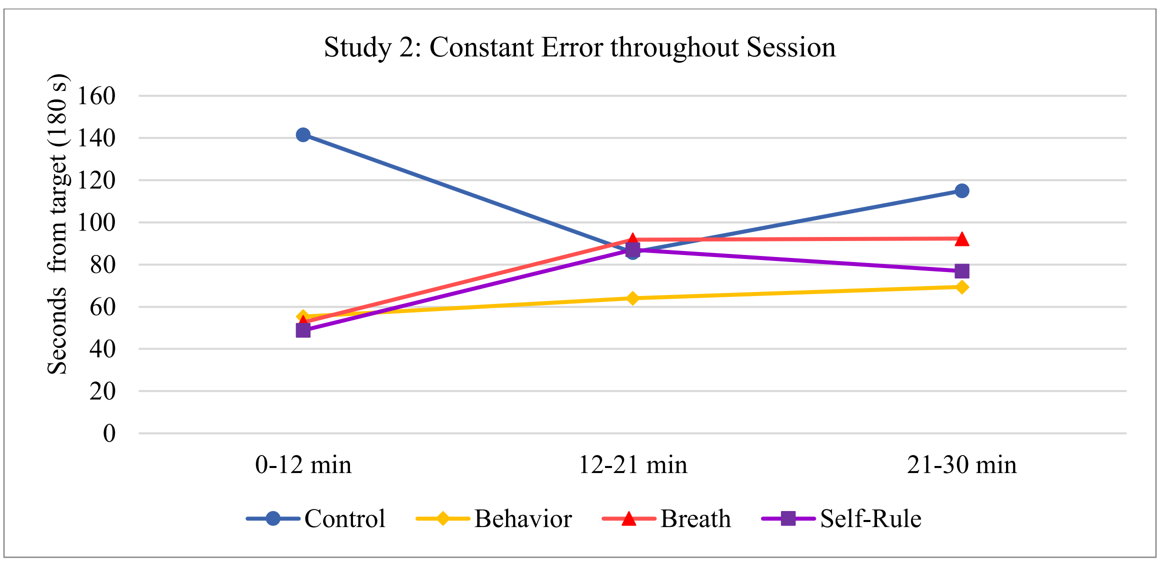


Figure 6. Average timing accuracy as measured by the absolute value of the time of the interval minus the target interval (i.e., 180 seconds). The x-axis marks the three phases and their respective durations. Each line indicates their experimental group, with the blue line representing the control participants, who received no special instructions throughout the game. The lower the value, the closer the timing estimate was to the target (i.e., increased accuracy).

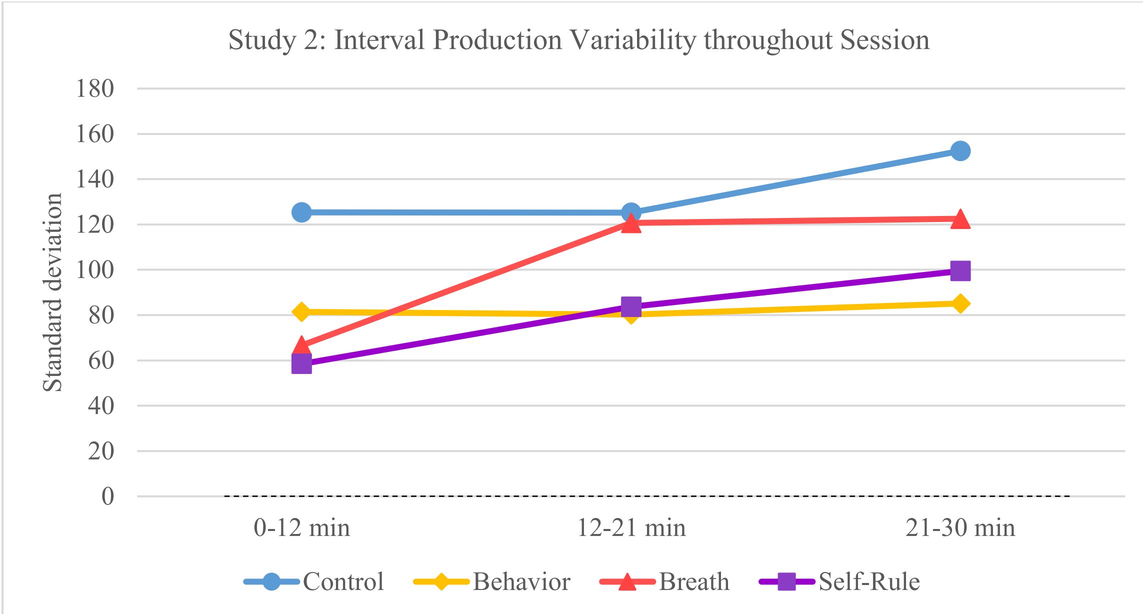


Figure 7. Average standard deviation of duration of timing estimates for groups over the 30-minute session. The x-axis marks the three phases and their respective durations. Each line indicates their experimental group, with the blue line (circle markers) representing the control participants, who received no special instructions throughout the game. Black dotted line serves as a reference at 0, which would be the variability score if a participant was 100% consistent throughout the session.

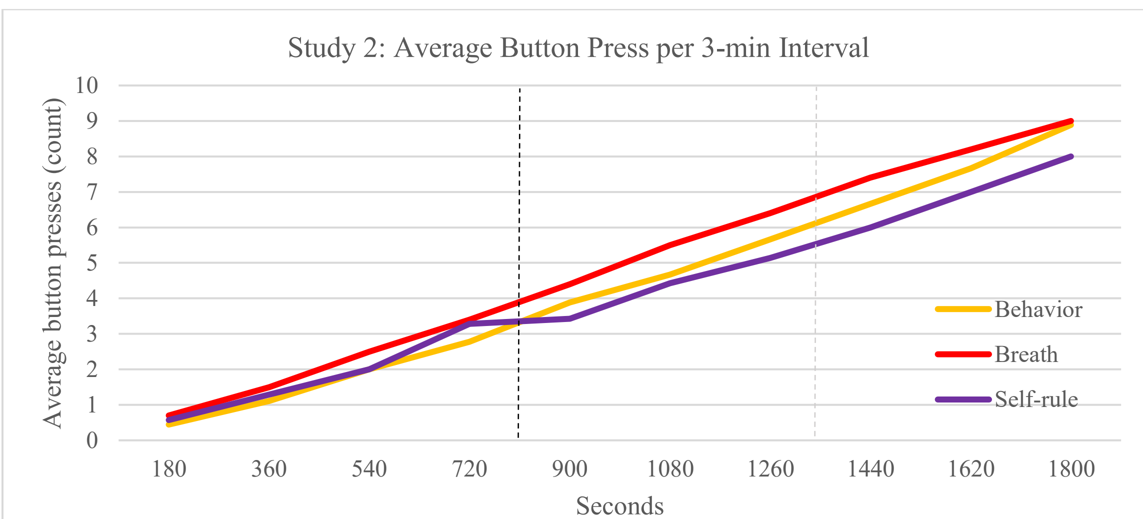


Figure 8. Average cumulative button presses per 3-minute interval calculated within each group. The dotted black line indicates where the first experimental message appeared (after a 12-minute baseline). The dotted gray line indicates where the same message appears for the second time.

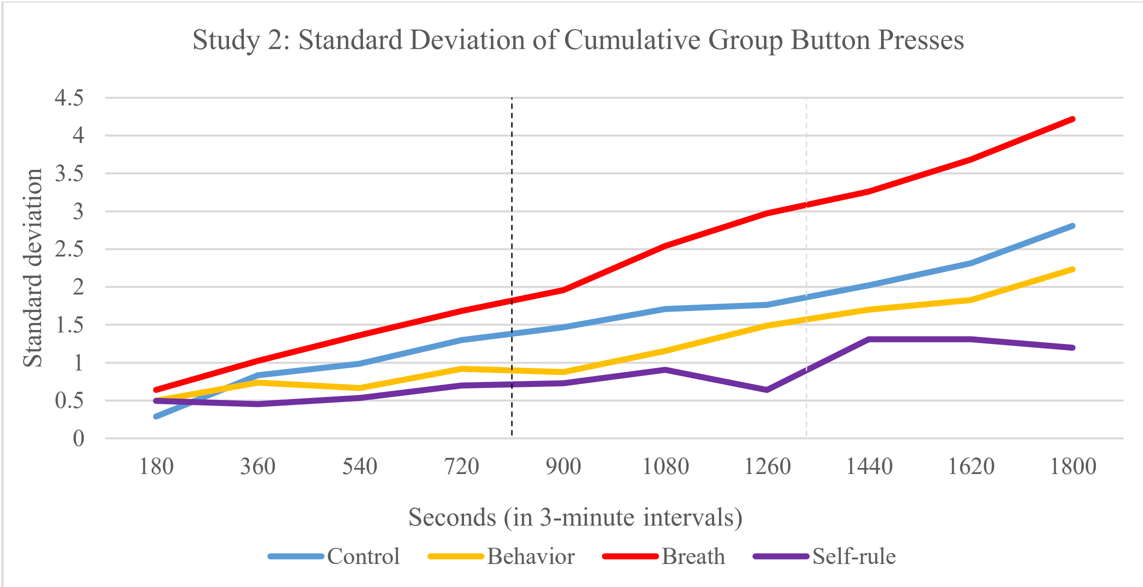


Figure 9. Standard deviation of group button presses per 3-minute interval, which accounts for the variability of timing within the group, over the course of the session. The dotted black line indicates where the first experimental message appeared (after a 12-minute baseline). The dotted gray line indicates where the same message appears for the second time.

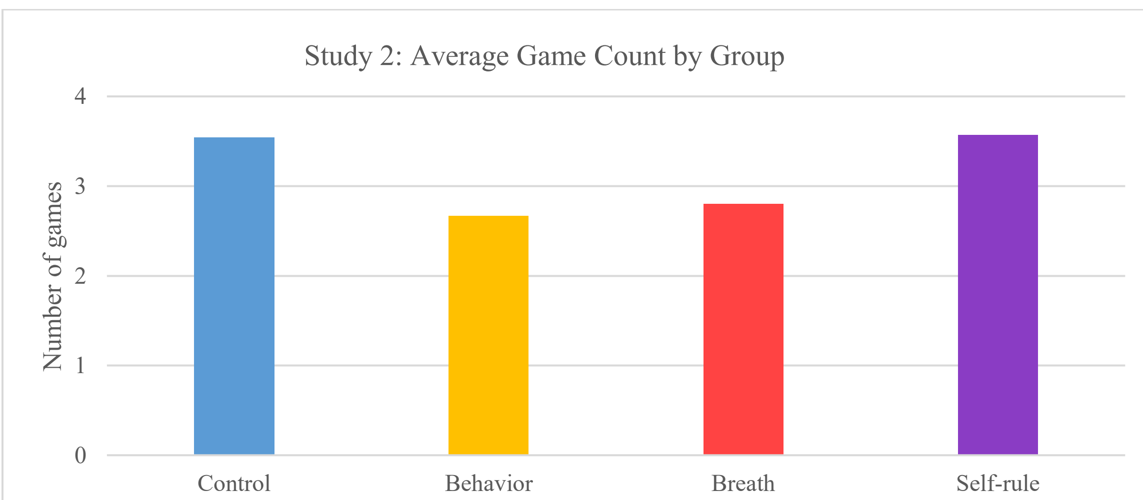


Figure 10. Averaged number of games per participant separated by group.

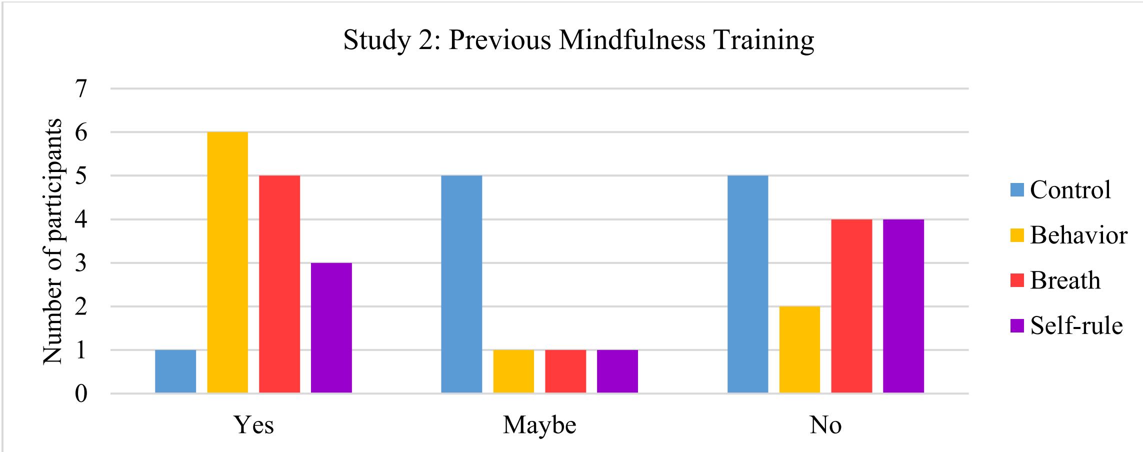


Figure 11. Distribution of participants across groups who have experienced mindfulness training previously.

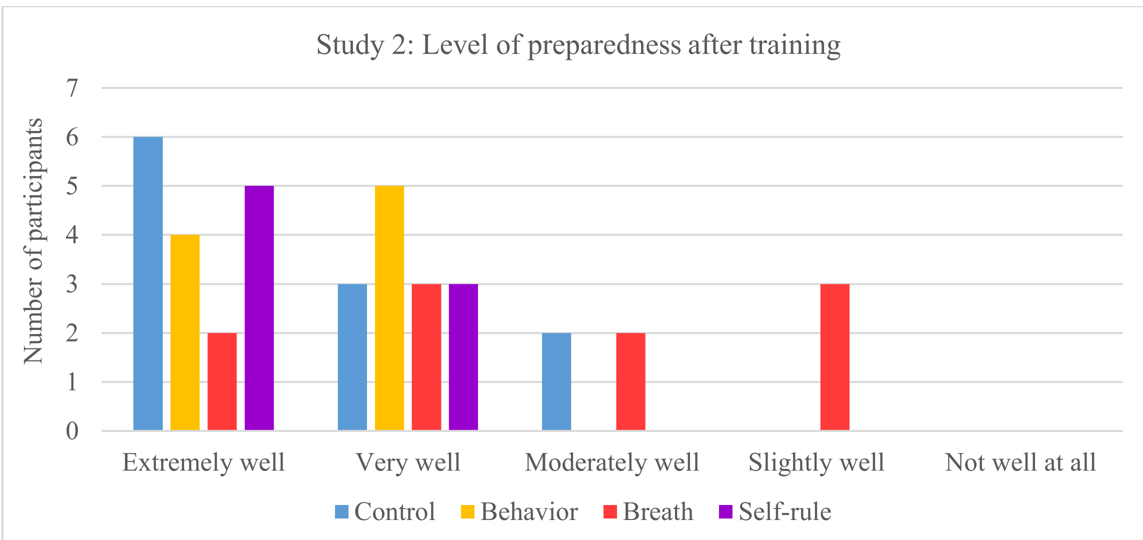


Figure 12. Distribution of participant rating their level of preparedness to play the Sudoku program after training.

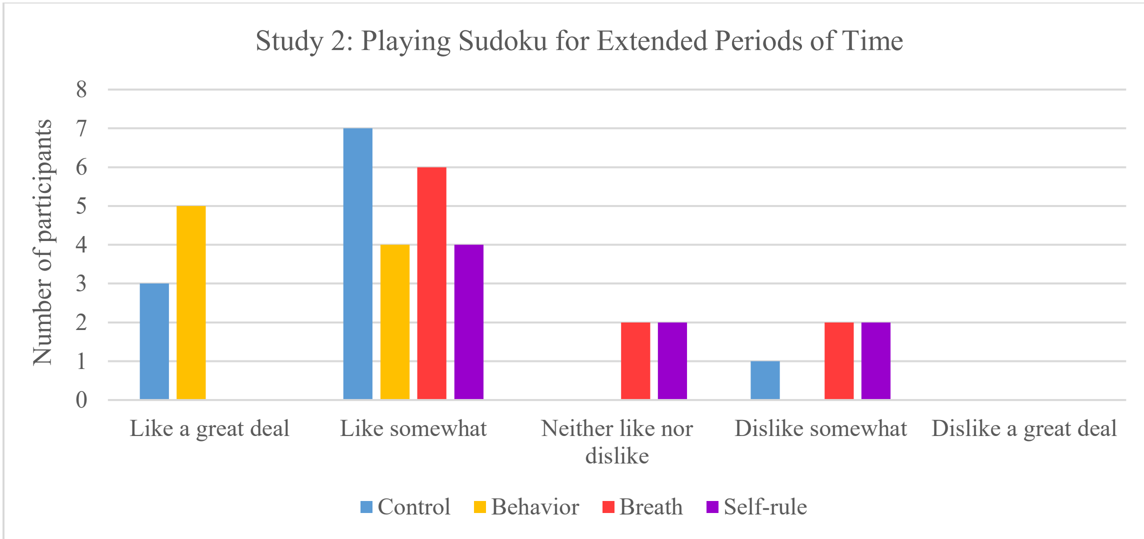
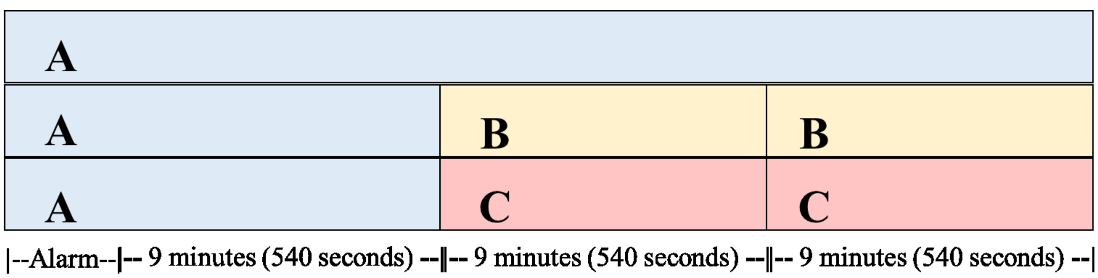


Figure 13. Distribution of participant impressions of playing Sudoku for extended periods of time.



A	**Remember--You earn points by completing as many Sudoku puzzles as you can AND by pressing the time button every three minutes.**
B	**As you play the game notice each time you fill in an empty cell. How does your game playing fit in with button pressing?**
C	**As you play the game notice as you breathe in and out. How does your breath fit in with button pressing?**

Figure 14. Experimental design for the Study 3. All Sudoku sessions were 30 minutes (1800 seconds) long, with a timed alarm sounding after the first 3 minutes (180 seconds). After which, the Control group as the baseline message and then had 27 minutes of uninterrupted play. Each experimental group saw statements at two different points. Repeated measure analyses looked at the three nine-minute phases (3-12 min, 12-21 min, 21-30 min).

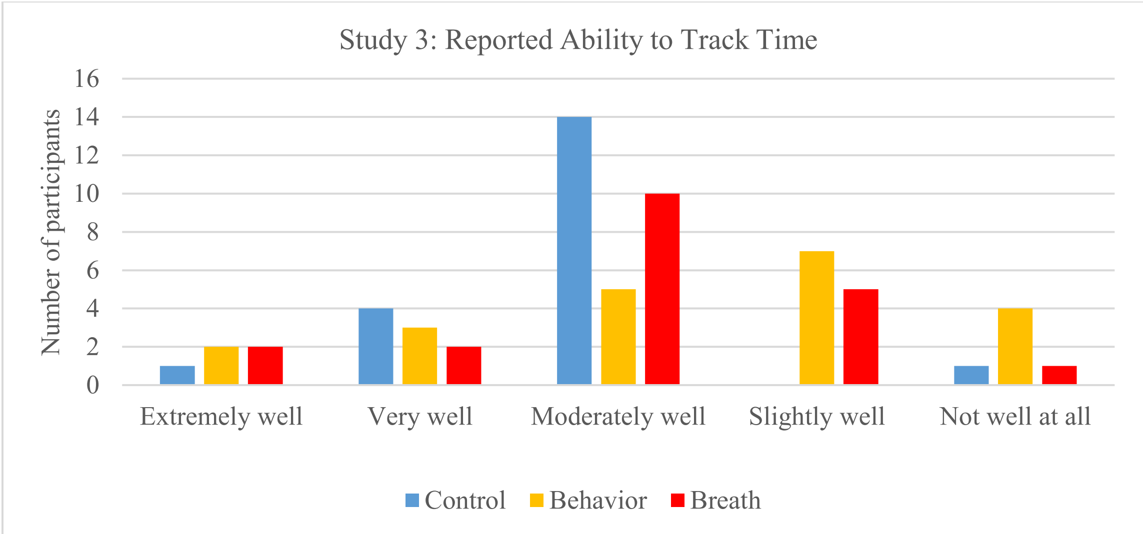


Figure 15. Distribution of participant responses to the question "How well do you track time in your daily life?" organized into groups.

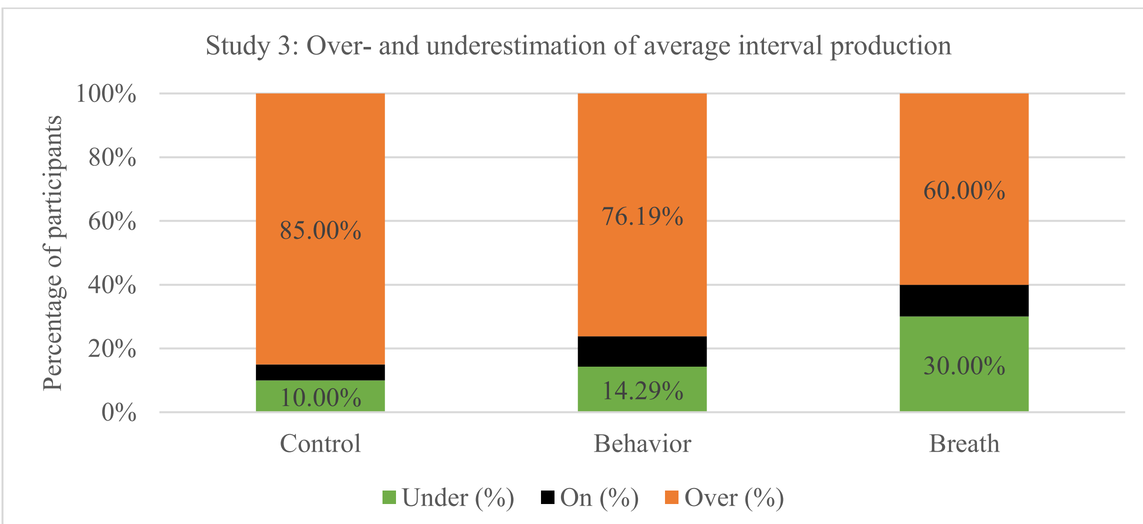


Figure 16. Percentage of participants who pressed the time button fewer than 3 times in 9 minutes (called "Over" in orange), exactly 3 times (called "On" in black) and more than 3 times (called "Under" in green).

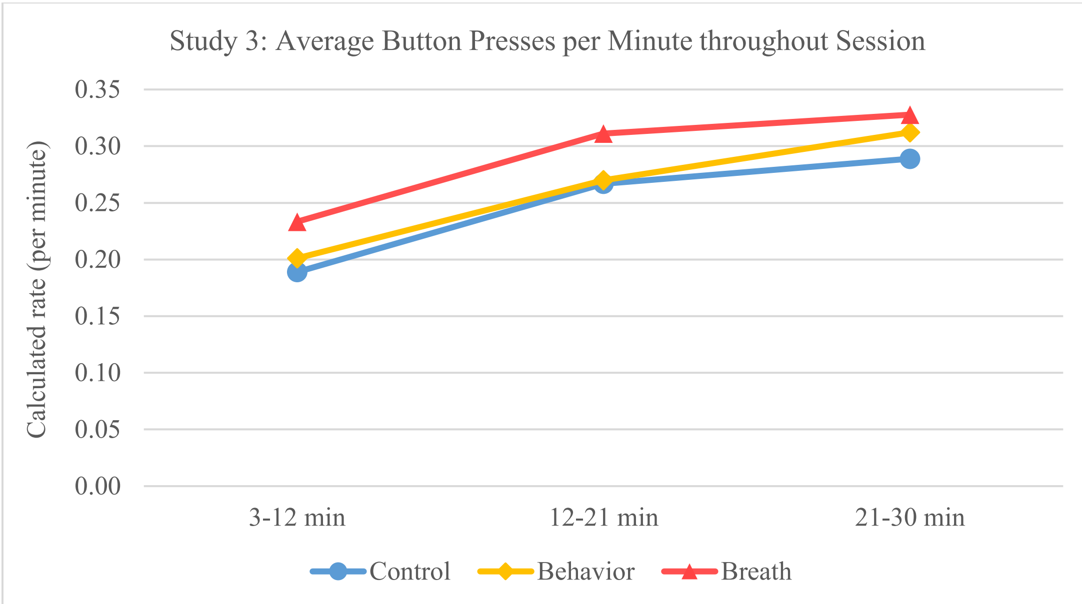


Figure 17. Calculated average for button presses per minute based on the average number of button presses per phase, divided by the nine-minute phase. Accurate rate was considered .33, or 1 button press per three minutes.

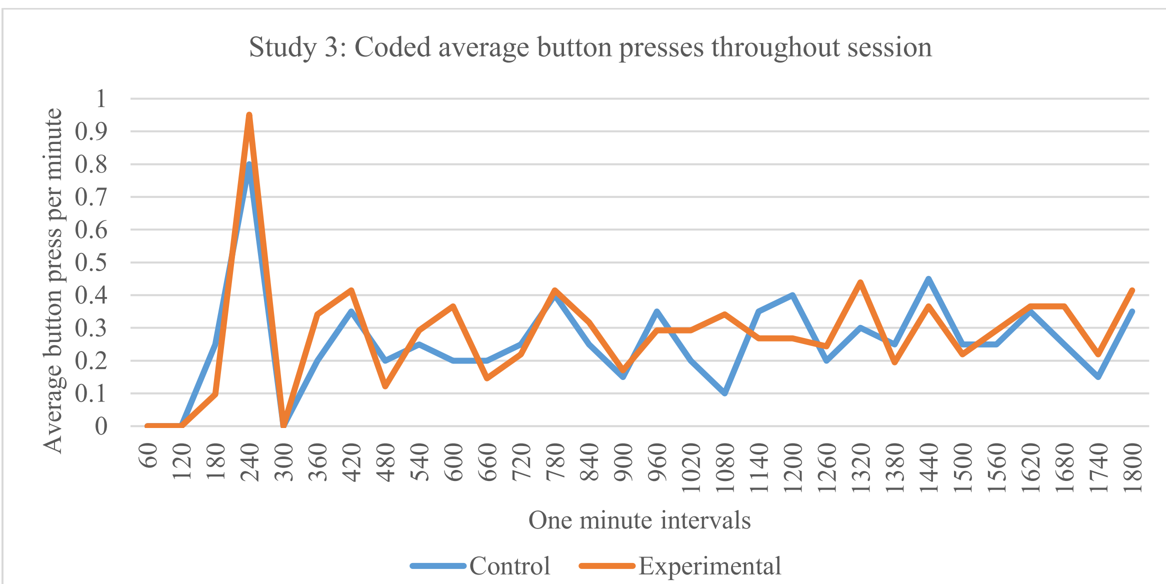


Figure 18. Average timing responses (i.e., button presses) were organized into 30, 1-minute intervals for the 30-minute session and recorded the individual response frequency that occurred during each time block, and then averaged for the whole group.

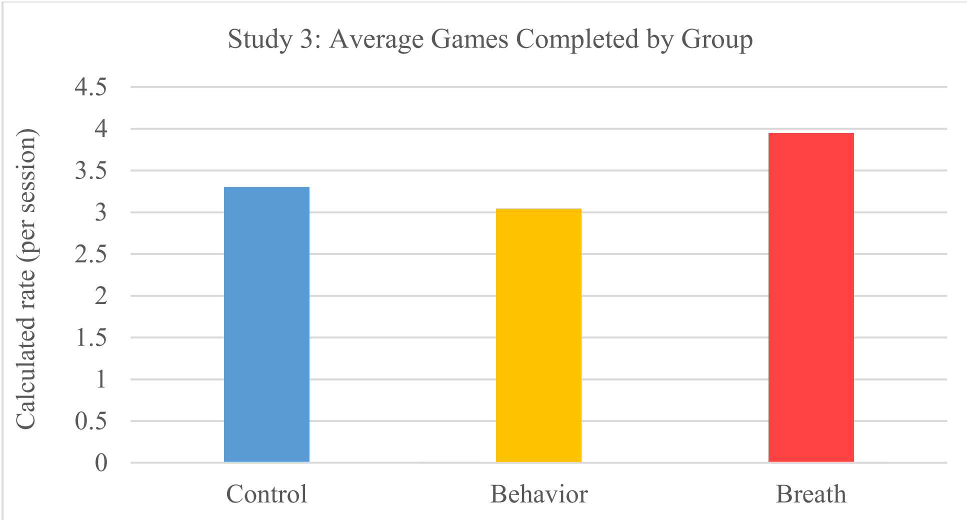


Figure 19. Average number of completed games, organized by group.

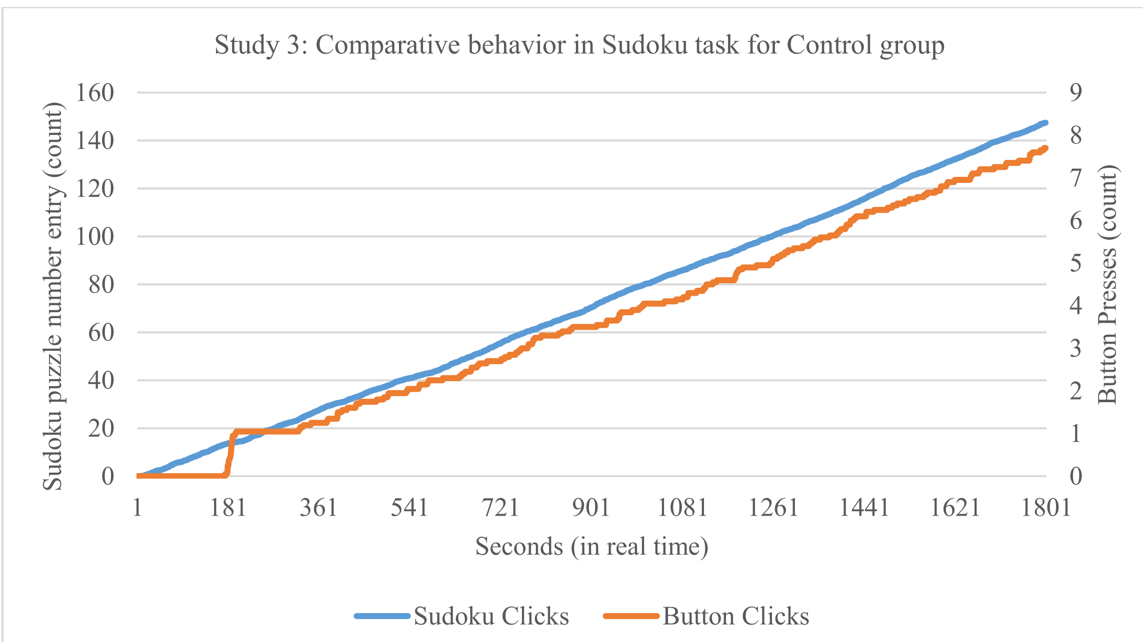


Figure 20. Cumulative record of program clicks, for entering numbers into the puzzle ("Sudoku clicks" measured on left y-axis) and pressing the time button ("Button presses" measured on the right y-axis) for the Control group (n = 20).

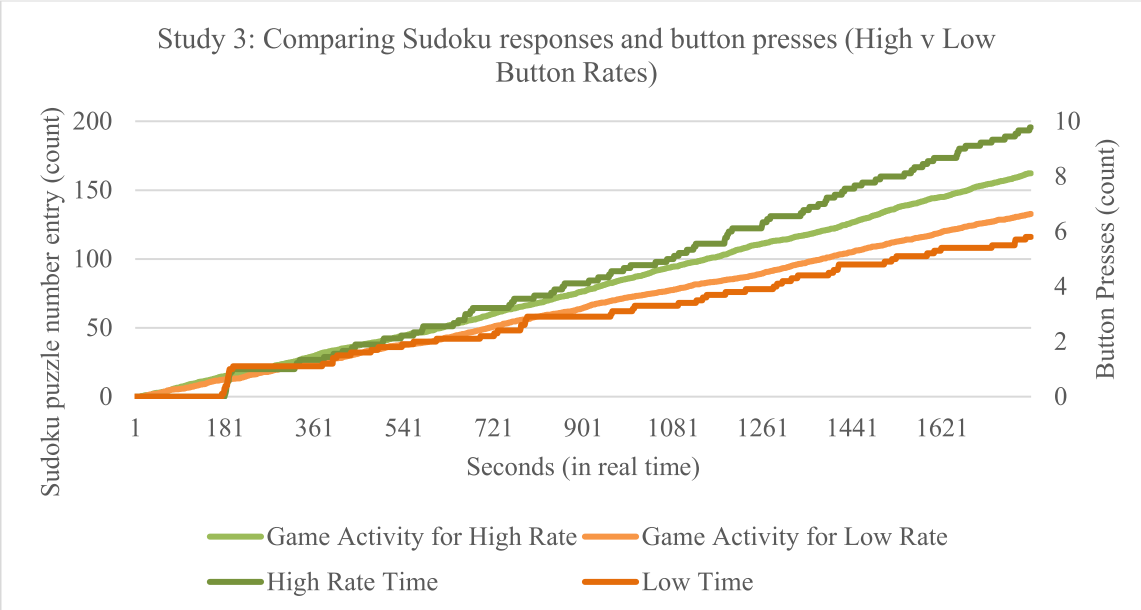


Figure 21. Cumulative record of program clicks, for entering numbers into the puzzle ("Sudoku clicks", measured on left y-axis) and pressing the time button ("Button clicks", measured on the right y-axis) for the Control group (n =20). Data grouped based on determined "high rate" and "low rate" button pressing groups and the corresponding participant data for Sudoku activity.

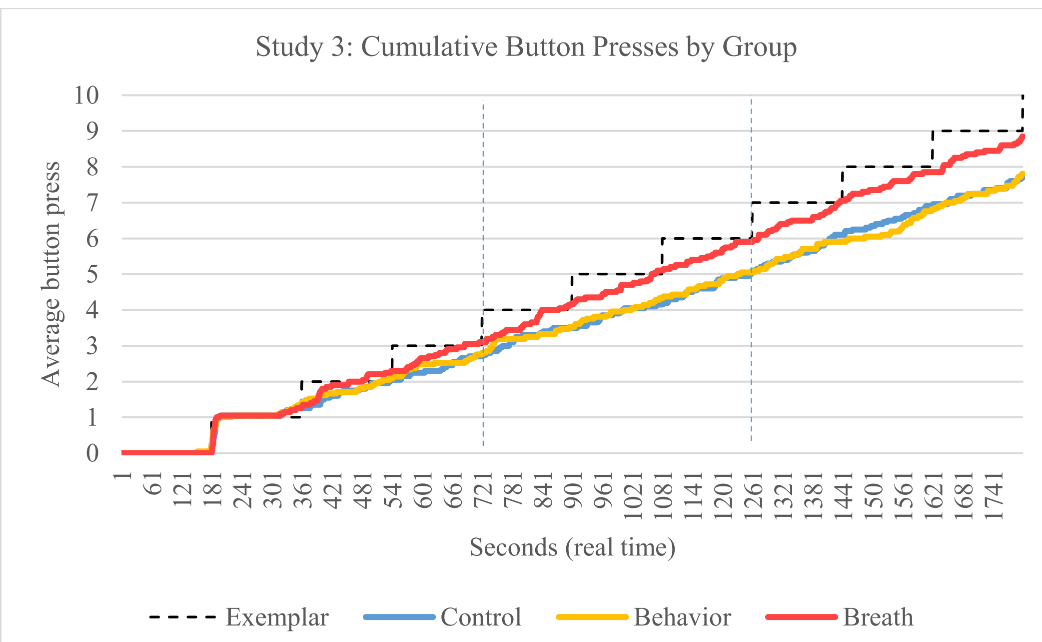


Figure 22. Averaged cumulative timing responses recorded in real-time seconds. The dotted black line in dictates what perfectly accurate and precise responding would look like across the session. The vertical dotted blue lines indicate where the messages appeared for the instruction groups (i.e., behavior and breath).

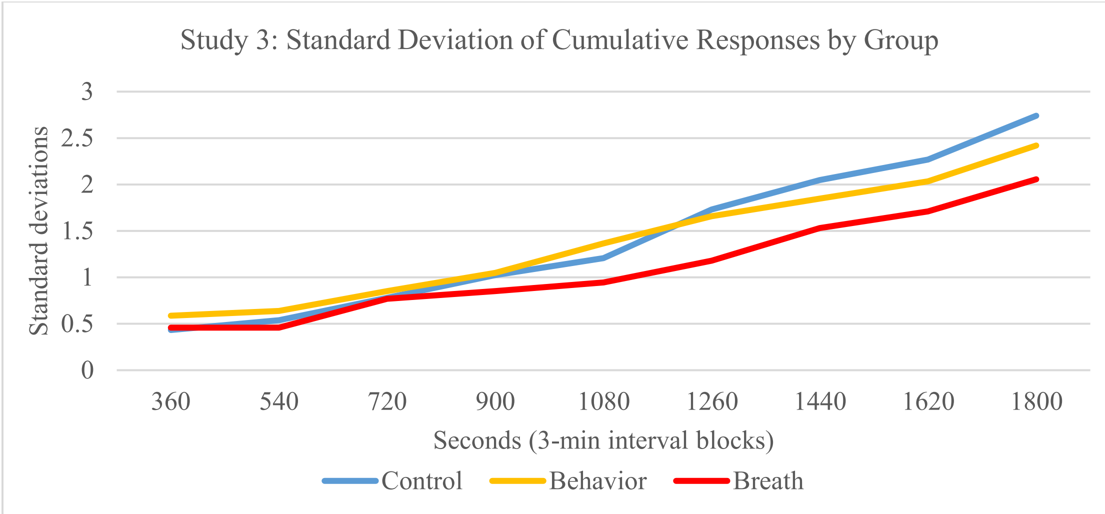


Figure 23. Within group variability, calculated by averaging the standard deviation of each individual's cumulative responses (recorded frequencies in 9 three-minute intervals) for each group. Steeper slopes indicate greater within group variability over time, whereas flatter slopes suggest greater within-group response consistency.

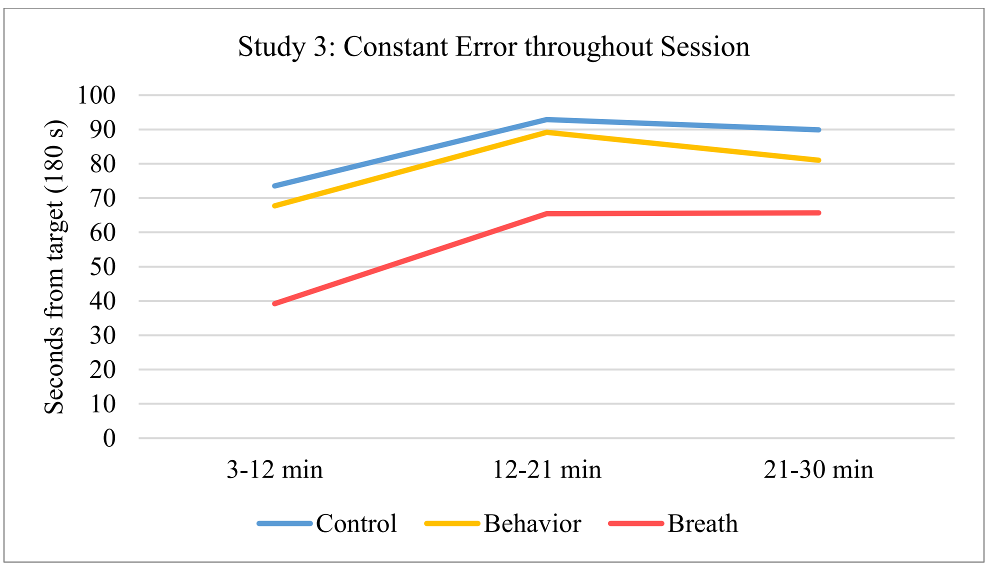


Figure 24. Group averages of timing accuracy (absolute value of the response difference from the target of 180 seconds) across the three nine-minute phases within the Sudoku session.

Figure 25. Comparing timing accuracy throughout session based on participant's self-reported ability to track time on a daily basis. Well (green line) consolidated the participants who indicated that they track time either "Extremely well" or "Very well." Medium (orange line) consists of the participants who responded "Moderately well." Poor (grey line) consists of participants who marked either "Slightly well" or "Not well at all."

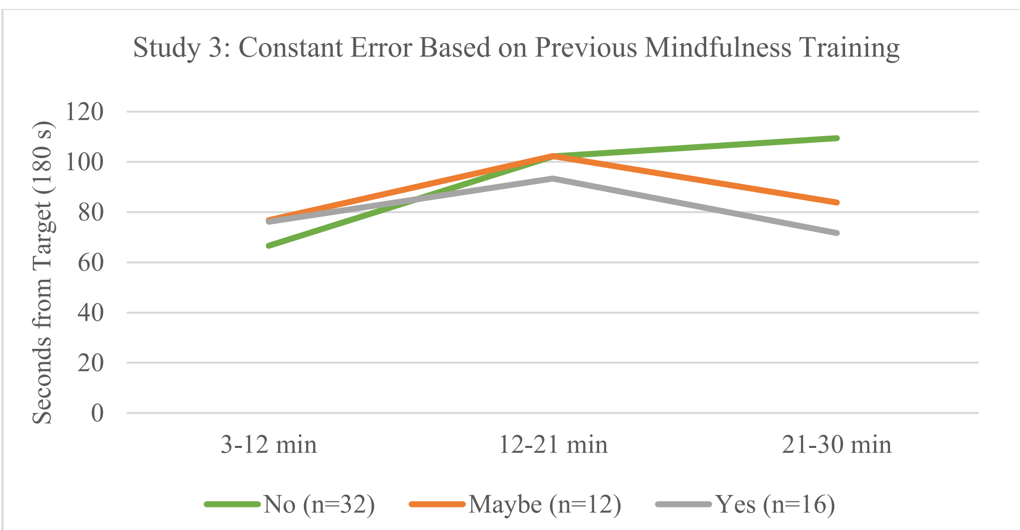


Figure 26. Comparing timing accuracy throughout session based on participant's previous experiences with mindfulness activities.

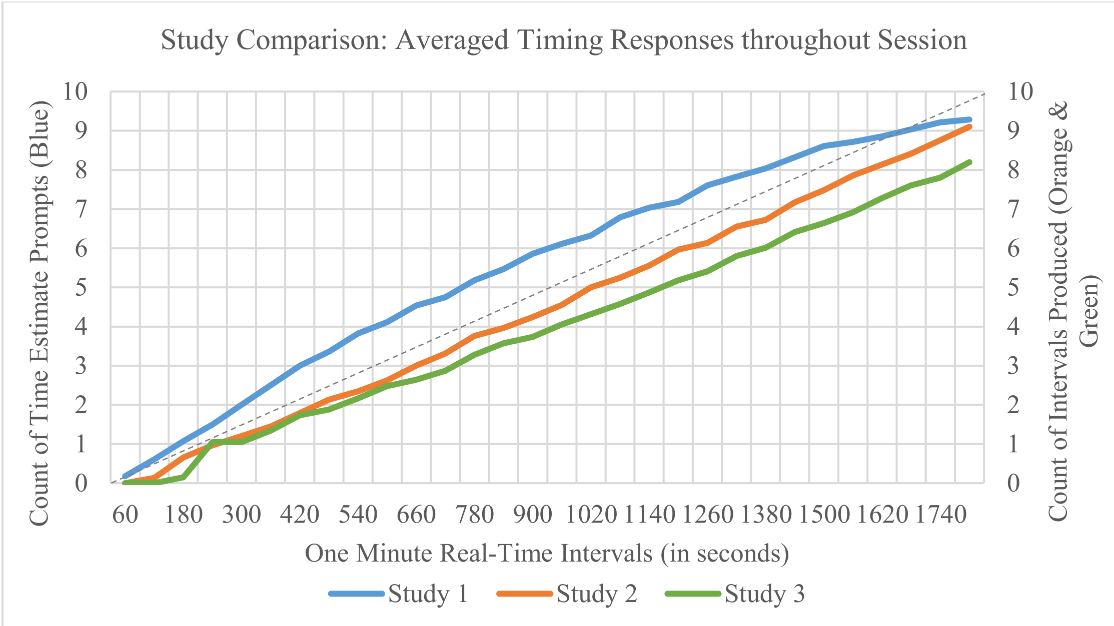
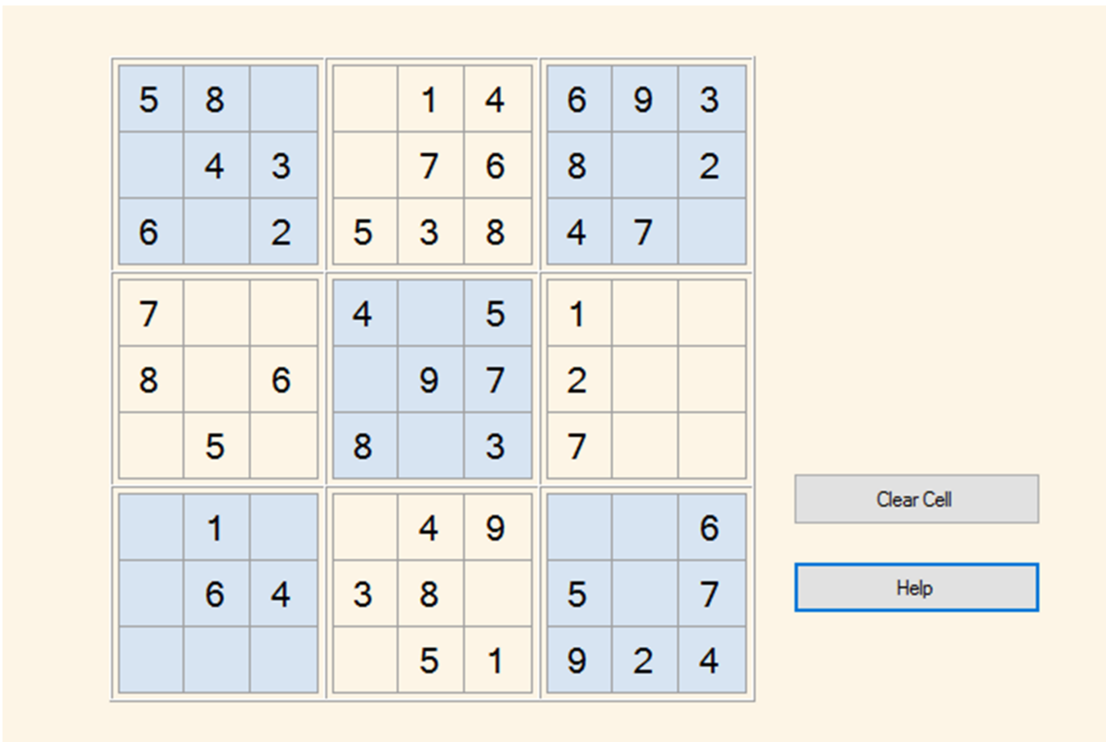


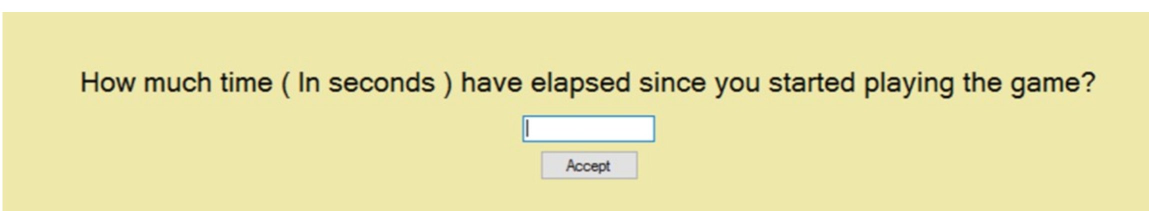
Figure 27. Averaged cumulative timing responses for each of the three studies. Study 1 (blue line) represent the hypothetical cumulative estimates of time throughout the session. The primary y-axis indicates each instance the question prompted the individual to type a time estimate. The x-axis then for Study 1 marks the estimated 'time into session' at each question. Study 2 (orange line) and Study 3 (green line) represent the cumulative seconds into session that participants completed each interval by pressing the time button. The secondary y-axis indicates each instance, on average, when participants pressed the time button. The x-axis for Studies 2 and 3 marks the 1-minute bins into which the interval data were categorized.

Appendix A

Study 1: Sudoku Program Arrangements

Below are screen clips depicting both the Sudoku interface and the message box prompt for the participant to type in a time estimate. Sudoku puzzles were randomly generated but programmed to remain at about the same level of difficulty, with only 33 empty cells. The message box presented is an example of the first question asked, every subsequent question asked for a response since the last time the question was asked. Performance in Sudoku program correlated with number of tickets entered into the raffle for each participant. Table for point-to-ticket distribution listed at the bottom.



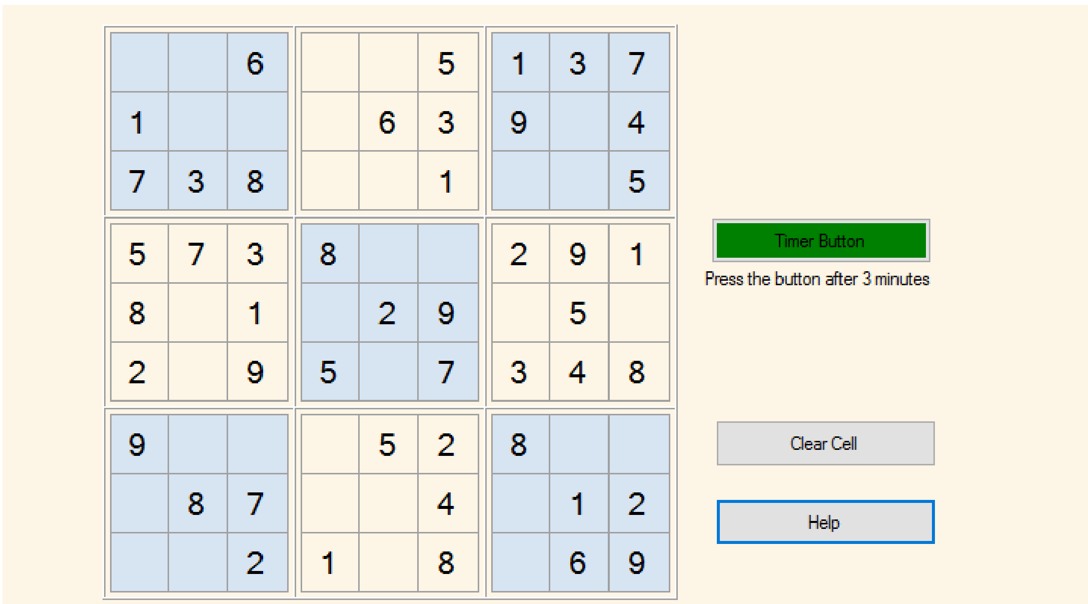


Points earned	# of tickets
0-750	1
751-1250	2
1251-1700	3
1701-2100	4
2101 +	5

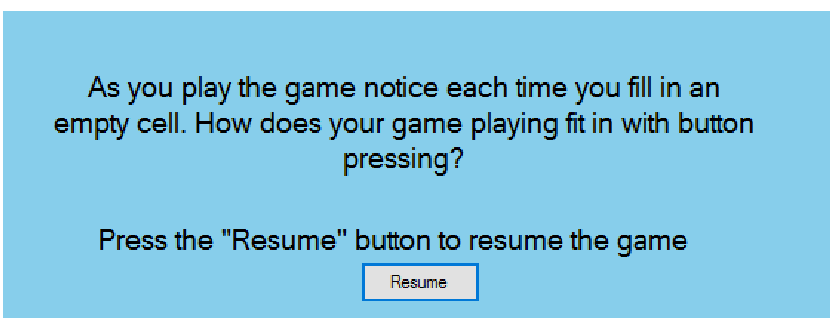
Appendix B

Study 2: Sudoku Program Arrangements

Below are screen clips depicting both the Sudoku interface with the green timing button, and sample screen of the phrases for the experimental conditions. Sudoku puzzles were kept at the same level of difficulty as in Study 1. Performance in Sudoku program correlated with number of tickets entered into the raffle, for each participant. Table for point-to-ticket distribution listed at the bottom.



Above: Program interface with time button; Below: Example screen message for the Behavior group.



Points earned	# of tickets
0-2,000	1
2,001-6,000	2
6,001-9,500	3
9,501-12,000	4
12,001+	5

Appendix C

Study 2: Sudoku Training Script

How to Play Sudoku (SCRIPT)

Sudoku is a puzzle game that relies on deduction. The game is on a 9 x 9 grid with 9 squares that are each 3 x 3 (so nine boxes in each square).

Your objective is to fill all of the squares so that the numbers 1-9 appear exactly one time in each row, column, and 3X3 box. (Show a column, row, and box)

To finish the puzzle, each of the 9 squares must be filled with the numbers 1 through 9.

As you can see, some of the spaces are already filled in so you just have to fill in the blank spaces with the remaining numbers.

<u>There are two rules to Sudoku:</u>

1. No number can repeat on a given row or column. Look at the blank cell in the top left corner. The number missing in that row and column is "2".
2. No number can repeat in the same 3x3 square. The number "2" can only be in this 3 x 3 square once. [Point out that there is a "2" in the 3rd row and 2nd column which means the "2" cannot go in the other blank cell.]

<u>Here are some tips on how to play the game:</u>

1. Use process of elimination. If you see one number in a column, row, or square, then that number cannot be placed in the same column, row, or square.
2. Use the numbers already on the board to determine which numbers go where. This is NOT a guessing game. Guessing can lead to making errors that are difficult to find later.

[Flip the instruction sheet over to reveal the ‘mini’ practice puzzle. Have them identify a blank square and have them tell you what numbers belong in the blank cells. **Once they get 3 right in a row, direct them to the Practice Puzzle.** If they make a mistake, tell them the correct answer and explain why (1) their answer was wrong, and (2) why your answer is right.]

3	9	1	2	8	6	5	7	4
4	8	7	3	5	9	1	2	6
6	5	2	7	1	4	8	3	9
8	7	5	4	3	1	6	9	2
2	1	3	9	6	7	4	8	5
9	6	4	5	2	8	7	1	3
1	4	9	6	7	3	2	5	8
5	3	8	1	4	2	9	6	7
7	2	6	8	9	5	3	4	1

[Write the current time on the Practice Puzzle sheet. Hand it to the participant.]

Once you have completed the practice puzzle, let me know. I’ll double check to make sure your answers are correct. Once you complete it without errors, you will move on to the real Sudoku game on the computer.

If you have any questions, feel free to ask.

Reference: http://www.sudoku.com/

Appendix D

Qualtrics Survey Questions for Final Study

[Survey Title] Diss Time - Study 3 (DISSERTATION)

Research assistant name:

Participant #

What year are you in school?

- 1 (Freshman) (1)
- 2 (Sophomore) (2)
- 3 (Junior) (3)
- 4 (Senior) (4)
- 5+ years (5)

What is your major? (If you have not selected a major yet, type "Undeclared.")

With which gender do you identify?

- Male (1)
- Female (2)
- Transgender (3)
- Other (4)
- I prefer not to answer. (5)

With which race do you identify?

❍ African American / Black (1)
❍ American Indian / Native American (2)
❍ Asian American / Pacific Islander (4)
❍ Caucasian / White (6)
❍ Hispanic / Latino (5)
❍ Other (7)
❍ I prefer not to answer. (8)

Are you an international student?

❍ Yes (1)
❍ No (3)

How familiar were you with Sudoku before today?

❍ Very familiar (I play Sudoku regularly.) (1)
❍ Somewhat familiar (I've played Sudoku a few times.) (2)
❍ Acquainted (I knew the rules, but not sure if I've completed a game.) (3)
❍ Not very familiar (I'd heard of Sudoku, but didn't know how to play.) (4)
❍ I had never heard of Sudoku before today. (5)

After the Sudoku training, how well did you feel prepared to play the game?

❍ Extremely well (1)
❍ Very well (2)
❍ Moderately well (3)
❍ Slightly well (4)
❍ Not well at all (5)

Which phrase fits closest to how you felt about playing Sudoku for an extended period of time?

❍ Like a great deal (1)
❍ Like somewhat (2)
❍ Neither like nor dislike (3)
❍ Dislike somewhat (4)
❍ Dislike a great deal (5)

How well do you track time in your daily life?

- ❍ Extremely well (1)
- ❍ Very well (2)
- ❍ Moderately well (3)
- ❍ Slightly well (4)
- ❍ Not well at all (5)

Have you ever received training in mindfulness or participated in mindfulness-based activities?

- ❍ Yes (1)
- ❍ Maybe (2)
- ❍ No (3)

Display This Question:

If Have you ever received training in mindfulness or participated in mindfulness-based activities? Yes Is Selected

Briefly describe your experience with mindfulness training and activities.

Did you have a method for estimating how much time had passed while playing the game?

- ❍ Yes (1)
- ❍ No (3)

Display This Question:

If Did you have a method for estimating how much time had passed while playing the game? Yes Is Selected

What was (were) your method(s) for estimating how much time had passed while playing the game?

Display This Question:

If Did you have a method for estimating how much time had passed while playing the game? No Is Selected

Describe what prompted you to push the green button. (If you never pushed the green button, please type "Never pushed button.")

Display This Question:

If Did you have a method for estimating how much time had passed while playing the game? Yes Is Selected

Did your timing method change over time?

- Yes (1)
- No (3)

Display This Question:

If Did your timing method change over time? Yes Is Selected

How did your timing method change over time? (Please provide details such as: what rule you may have used and/or if anything around you prompted you to change your strategy.)

Do you have any other comments or feedback about the study that you'd like the experimenter to know?