On the Influence of Structure and Complexity in Perceived Duration

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Derek E. Zeigler

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by

DEREK E. ZEIGLER

has been approved for
the Department of Psychology
and the College of Arts and Sciences by

Ronaldo Vigo
Assistant Professor of Psychology

Robert Frank
Dean, College of Arts and Sciences
ABSTRACT

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On the Influence of Structure and Complexity in Perceived Duration

Director of Thesis: Ronaldo Vigo

Temporal perception is known to be influenced by various contextual factors and a considerable portion of the literature has explored the relationship between subjective temporal estimates (STEs) and the complexity of dynamic environmental stimuli. In general, researchers have shown that increases in stimulus complexity result in subjective time dilation. That is, complex and dynamic stimuli tend to result in STEs that are longer than STEs for less complex stimuli. In the following, the influence of stimulus structure on the perceived duration of multiple time intervals is reviewed. In doing so, we discuss an alternative approach that has been used in previous research (Vigo & Zeigler, 2013). This approach precisely quantifies the structural complexity inherent to the visual display of a temporal judgment task and has successfully accounted for STEs across multiple time intervals. Our approach is based on categorical invariance theory and one of its models (the exponential categorical invariance model; Vigo, 2009, 2011a, 2011b, 2013) and was used to model estimations of duration by participants. Further, we describe how this work can be extended to account for additional experimental conditions. Finally, we provide a comprehensive review of stimulus based variables that affect temporal processing and place these findings in the context of the relationship between perceived duration and complexity.
For my mother and father
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>3</td>
</tr>
<tr>
<td>Dedication</td>
<td>4</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>5</td>
</tr>
<tr>
<td>List of Tables</td>
<td>7</td>
</tr>
<tr>
<td>List of Figures</td>
<td>8</td>
</tr>
<tr>
<td>Chapter 1: Introduction</td>
<td>9</td>
</tr>
<tr>
<td>Chapter 2: What Affects Perceived Duration? An Introduction to Temporal Cues</td>
<td>12</td>
</tr>
<tr>
<td>2.1 Vierordt's Law</td>
<td>14</td>
</tr>
<tr>
<td>2.2 The Indifference Interval</td>
<td>15</td>
</tr>
<tr>
<td>2.3 Scalar Property of Perceived Duration</td>
<td>16</td>
</tr>
<tr>
<td>2.4 Velocity, Change, and Duration</td>
<td>17</td>
</tr>
<tr>
<td>2.5 Stimulus Complexity in Duration Perception</td>
<td>20</td>
</tr>
<tr>
<td>Chapter 3: Structural Complexity</td>
<td>24</td>
</tr>
<tr>
<td>Chapter 5: Current Experiment: An Extention of Vigo &amp; Zeigler (2013)</td>
<td>35</td>
</tr>
<tr>
<td>5.1 Methods</td>
<td>36</td>
</tr>
<tr>
<td>Chapter 6: Results</td>
<td>40</td>
</tr>
<tr>
<td>Chapter 7: General Discussion &amp; Conclusion</td>
<td>41</td>
</tr>
<tr>
<td>References</td>
<td>43</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Page

Table 1: Table adapted from Shiffman and Bobko (1974) reporting their results ..................... 46

Table 2: Proportion of correct responses for the secondary task in Vigo & Zeigler (under review) ........................................................................................................................................... 46
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>Category structures used in Vigo &amp; Zeigler (under review)</td>
<td>47</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Manipulation used in Vigo &amp; Zeigler (under review)</td>
<td>48</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Results of the stimulus motion condition reported in Vigo &amp; Zeigler (under review)</td>
<td>49</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Visual Characterization of the process of memory decay described in Vigo &amp; Zeigler (under review)</td>
<td>50</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Proposed manipulation and subsequent questions asked in the current experiment</td>
<td>51</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Results of the stationary stimulus condition</td>
<td>52</td>
</tr>
</tbody>
</table>
CHAPTER 1: INTRODUCTION

The experience of time is ubiquitous in our daily lives, yet, we are frequently surprised how biased our perceptions of time can be in certain situations. For instance, our favorite classes may pass quickly while other courses are seemingly prolonged. Likewise, for a conference presenter, time seems somehow compressed while the audience may have a more accurate perception of time’s passing. Naturally, we recognize that the external task in which we are engaged is somehow influencing our internal judgments of temporality and we intuitively attribute such variations to our interest in a topic or engagement in a task. While there may be truth to such high-level explanations such as preferences and task demands, in the current proposal, we emphasize the influence of relations and structure that have been shown to bias perceived duration.

An overwhelming variety of manipulations can be found in the temporal processing literature so it is important to preface what follows by clarifying certain terminology in order to place our discussion in the proper context. To begin with, two varieties of subjective temporal estimates (STEs) are considered in the literature—prospective and retrospective estimates. Estimations of duration are given prospectively when an individual knows before a particular interval that he or she will have to make a judgment regarding its duration and retrospectively when the individual is unaware of the impending estimation until after the duration is complete. As such, the difference between these paradigms is essentially the difference between perceived and remembered time, respectively. Empirical investigations have shown that prospective and retrospective judgments yield disparate temporal estimations with respect to objective time, leading authors to conclude that they employ different cognitive mechanisms.

As a consequence, researchers have sought to explain the processes involved in prospective and retrospective timing. It is believed that under prospective conditions, when the impending estimation of duration is made explicit, humans allocate attention to appropriate temporal cues that guide duration judgments (Zakay & Block, 1997). Conversely, in retrospective tasks, attention to time has a limited influence on temporal judgments. Rather, judgments are constructed by accessing a representation of the interval in memory. Specifically, it has been proposed that the number of contextual changes stored in memory effects perceived duration under retrospective conditions (Block, 1990). Given the recent surge of research on the topic, the primary focus of this paper is STEs of the prospective variety. However, the way in which representations are accessed in memory may be useful in explaining key empirical findings.

Additionally, it is important to discuss the canonical paradigm for studying STEs. For the purpose of studying temporal judgments under prospective conditions researchers typically employ a dual-task paradigm. That is, the interval estimation task (temporal task) is generally accompanied by an unrelated concurrent task (secondary task). The initial purpose of this concurrent task was to prevent explicit counting by participants. Incidentally, the nature of this secondary task has been shown to predictably influence the temporal task. Researchers have attempted to explain such findings by proposing that such temporal biases are elicited by temporal cues inherent to the concurrent non-temporal task.
Consequently, researchers have sought to identify such temporal cues. These temporal cues are both spatial and feature-specific attributes that are highly dependent on context and research has led to the assumption that perceived duration varies primarily as a function of feature-specific properties and that temporal biases are due to attributes of stimuli (Kanai, Paffen, Hogendourn & Verstraten, 2006; McFarland, Cacace & Setzem, 1998).

Accordingly, the current proposal is concerned with prospective conditions that incorporate a dual task whereby changing properties of stimuli are the locus of attention. Now that we have narrowed our focus we can proceed to talk about the relationship between these factors in detail. Accordingly, the proposal proceeds as follows. First, in order to enumerate which temporal cues influence perceived duration we provide a review of the temporal perception literature with respect to prospective judgments. In order to do so, we will trade breadth against coverage and explore a smaller set of topics in detail such as classic manipulations of stimulus complexity as well as how these canonical examples can be improved upon through the use of a mathematical model of cognitive complexity (Categorical Invariance Model; Vigo, 2009, 2011a, 2011b, 2012). Next we will review work that has tested the performance of this model in a dual task experiment (Vigo & Zeigler, under review). Lastly, we propose an extension of this study in order to further explore the role of structure and complexity in perceived duration.
CHAPTER 2: WHAT AFFECTS PERCEIVED DURATION? AN INTRODUCTION TO TEMPORAL CUES.

Immanuel Kant maintained that the experience of time is a cognitive facility so fundamental that it exists as a pure form of a priori knowledge which need not be based on experience. Regardless of the rebuttals against the existence of such a priori cognitive structures, Kant’s position highlights the seemingly innate role that temporal perception plays in all aspects of human experience. Despite its privileged status among certain philosophers, converging empirical evidence suggests that temporal perception is subjective and variably influenced by environmental factors (e.g. Block & Zakay, 1997). In this section, we review work that emphasizes the structure of temporal experience as grounded in the dynamics of environmental stimuli. To begin our discussion, let us consider a suitable quote:

“What then is time? If no one asks me, I know what it is. If I wish to explain it to him who asks, I do not know.”

-Saint Augustine

In this excerpt, Saint Augustine recognizes his concept of time as intuitive, but its origin as unknown. Likewise, while attempting to express this feeling of time we cannot help but describe our experiences in it—a certain event happened then or will happen later as compared to now. Through this syntactic example we see that time is intimately connected to events or as Gibson (1975) states, “Events are perceivable, but time is not”. If events are the foundation by which the perception of time arises, the structural
properties of these events should follow as the necessary elements to characterize its experience.

Just as philosophical analyses have proceeded in the spirit of Saint Augustine’s inquiry, experimental investigations have proceeded much in the way described by Gibson—with an emphasis on events and how changing properties in the environment influence duration perception. Such temporal cues are feature-specific variables which cause variation in STEs and are highly dependent on context. As such, research has led to the assumption that perceived duration varies as a function of these feature-specific attributes and that temporal biases are due to attributes of stimuli (McFarland, Cacace & Setzem, 1998). Indeed, just as the biological mechanisms involved in circadian rhythms use zeitgebers¹ to keep our internal time functioning properly our subjective experience of time uses temporal cues to inform judgments of duration. Although, the biological mechanisms involve longer time intervals while the judgments of duration are cognitive and involve our daily activities on a timescale of hours or minutes and even seconds or milliseconds.

Below, we review some general phenomena that occur during prospective STE tasks—such as Vierordt’s law, the indifference interval, and the scalar property of perceived duration—before proceeding to more specific phenomena—such as the influence of stimulus motion and change as well as stimulus complexity. Each of the

¹ Zeitgeber is German for "time giver," or "synchronizer." A zeitgeber is any external cue that informs the body’s internal clock as to the 24-hour light/dark cycle or the 12 month cycle. The most commonly known (and strongest) is light. Other zeitgebers include temperature, social interactions, pharmacological manipulation, exercise, and even eating and drinking patterns
following factors will become particularly relevant in the context of the proposed experiment.

2.1 Vierordt’s Law

A robust phenomenon in the temporal judgment literature is for subjects to overestimate shorter stimulus intervals in a series and to underestimate the longer intervals—an effect known as Vierordt’s law (Underwood, 1966; Vierordt, 1868; Woodrow, 1951). Indeed, Vierordt’s law is regarded as the oldest finding in the study of temporal perception (Boring, 1942; Woodrow, 1951) and has been consistently replicated across a wide variety of experimental conditions\(^2\) regardless of manipulations, indicating that the law is unaffected by the presence of other stimulus characteristics which may cause temporal biases. This effect has been interpreted in terms of the tendency for perceptual judgments in general to regress from extreme values to the mean of a stimulus range (Bobko, Schiffman, Castino, & Chiappetta, 1977; Helson, 1964). Since this effect is ubiquitous in the literature, valid studies on perceived duration that incorporate multiple time intervals should exhibit this standard pattern and will be an important point of emphasis when analyzing the data of the proposed project.

\(^2\) For instance it has been demonstrated in experiments across modalities using varying methodologies including temporal reproductions, i.e., reproducing an interval (Bobko et al., 1977; Brown, 1995; Schiffman & Bobko, 1974, 1977; Woodrow, 1934) and temporal productions, i.e., producing an interval of a given length (e.g., Brown, 1995; Brown & West, 1990; Clausen, 1950; Doehring, 1961; Hawkes, Bailey, & Warm, 1961; Spivack & Levine, 1964).
2.2 The Indifference Interval

Vierordt’s law describes a fundamental predictor of biases in perceived duration, but this relationship between relatively “short” and “long” intervals begs the question: is there an interval in between the short and long where STEs reach a point of stable accuracy? In other words, at which interval are we least biased and most accurate in our judgment of time? If Vierordt’s law is valid, there should be a cut-off point along the continuum of short and long durations where STEs become consistently accurate.

Although, such a cut-off for what is considered “short” and “long”, and thus overestimated and underestimated, has not been defined. It is believed that the point in which this reversal occurs depends largely on the task used and the frame of reference in terms of the intervals used. For instance, there are separate cut-off points for tasks lasting minutes (Yarmey, 2000; Roy and Christenfeld, 2008)\(^3\) compared to those lasting seconds and milliseconds. Such variance in the cut-off point makes any definition for “short” or “long” arbitrary given that this reversal point scales with the duration of the interval in question. In other words, STEs are highly relational and variably influenced in the context of the magnitude of other possible interval durations.

Although researchers have not been able to agree on a single value for the indifference interval and such an interval often varies widely between participants, much work has been done to characterize the notion of such indifference interval, most notably by Treisman (1963), and many researchers have reported indifference intervals across

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\(^3\) Yarmey (2000) tested interval durations lasting 4 seconds to 80 minutes and found that the cut-off was between approximately 2 and 10 seconds. Likewise, Roy and Christenfeld (2008) also used minutes as a frame of reference using tasks that ranged from 1-15 minutes. They found that the cut-off for the reversal from overestimates to underestimates occurred between 1.5 and 2 minutes.
different methodologies (Blakely, 1951; Woodrow, 1934; Scott, 1935). Despite the
difficulty of identifying such an indifference interval, the data obtained in the current
study may be used to identify a point at which participant’s STEs become most accurate.

2.3 Scalar Property of Perceived Duration

When comparing subjective temporal estimates across multiple interval durations
the data is consistent with the scalar property of Weber’s law in the way that the standard
deviation in STEs increase approximately linearly with the length of the interval.\(^4\) This
scalar property of STEs (Gibbon, 1977) propounds that, like other perceptual processes,
bias in STEs will scale with the magnitude of the interval. That is, as the length of the
interval increases, so too should the variance in STEs. This indicates that variability in
STE grows proportional to the mean of the interval being estimated and that the variance
in STEs can be accurately predicted.

This relationship between interval duration and variability makes sense
intuitively—the lengthening of an interval allows for a wider range of estimates. For
instance, a short interval of four seconds is bounded by zero (or no duration) and not
likely to yield verbal estimates beyond ten seconds while it is quite likely that an interval
of 30s could yield estimates that range from 20s to 40s—resulting in a range of 10s for
the short interval and 20s for the long interval. Moreover, longer intervals necessarily
provide the opportunity for temporal cues to occur during the interval which could bias
perceived time and cause additional variance for longer intervals. Accordingly, this

\(^4\) This relationship has been demonstrated repeatedly across the trio of classical timing tasks—production,
reproduction, and verbal estimation (see Wearden, 2003).
relationship between interval duration and variation in STEs will be an important analytic tool in comparing the data of the current proposal to that of previous experiments.

2.4 Velocity, Change, and Duration

Since there is no known dedicated biological mechanism for keeping track of time it has been proposed that subjective temporal estimates (STEs) are made based on the number of changes in an event (Brown, 1995; Fraisse, 1963; Poynter, 1989). Consistent with this idea are several studies which have shown that STEs for dynamic stimuli are lengthened as compared to less complex stimuli. This phenomenon of subjective time dilation has many documented components that characterize its experience: the speed of an object, the distance it travels, and its temporal frequency in terms of changing features of the stimulus. We now visit each of these components in turn.

From an ecological viewpoint (Gibson, 1975), stimulus motion is a foundational source of temporal information because it is considered one of the basic “natural events of the terrestrial world” (p.297). The motion and velocity of a stimulus is a temporal cue that is of particular relevancy in the current proposal. A well replicated result is that a stimulus in motion results in STEs that are longer than stationary stimuli (Brown, 1931; Roelofs & Zeeman, 1952; Goldstone & Lhamon, 1974; Tayama & Aiba, 1982; Brown, 1995). Following this line of research, Brown (1995) aimed to test the extent to which varying stimulus velocities effect perceived duration. In his investigation, stimulus speeds ranged from 5 to 45 cm/sec and all experiments included a stationary (control) condition. Notably, Brown used multiple stimuli that travelled along lengthy and complex nonlinear pathways and five durations were used in each of five experimental
conditions (6, 9, 12, 15, and 18 seconds). Results replicated the finding that stimulus motion lengthened apparent duration. Further, Brown shows that faster stimulus velocities lead to progressively longer STEs (experiments 3, 4, and 5). In experiment four, various stimulus speeds were sampled (5, 15, 25, 35, or 45 cm/sec) and a positive linear relationship was found between velocity and STEs.

In addition to the velocity of a stimulus, Kanai, Paffen, Hogendourn, and Verstraten (2006) investigated the effects of motion coherence, spatial frequency and temporal frequency and demonstrated that temporal frequency alone determined the magnitude of time dilation. That is, even when there are no spatial changes to a stimulus (such as its speed or distance travelled), dynamic changes that occur to the stimulus itself induced time dilation. Five experiments tested STEs using various stimulus displays. Experiment one tested the motion-dependent time dilation just discussed (Brown, 1995). Accordingly, a moving or stationary black square was presented for one of five durations (200, 400, 600, 800, or 1,000 ms) and participants were asked to reproduce the duration of the stimulus by pressing the space bar. Consistent with previous research, moving stimuli were perceived to last longer than stationary stimuli and increasing stimulus speeds resulted in larger overestimates. Since the time dilation could be a result of the distance traveled rather than the speed of the stimulus, the effect of local versus global motion was tested in experiment two. In this condition, a random dot display was contained within a fixed window on the display making distance cues unavailable to participants. The velocity of the moving dots as well as the motion coherence varied across trials. Motion coherence refers to the extent to which the dots moved in the same direction. For example, a coherence of zero would mean that the dots moved in random
directions with respect to one another. Coherences of 0%, 30%, 60%, and 90% were used in experiment two. The coherence of the dots did not affect STEs, however, the speed of the dots had a significant effect on STEs suggesting that coherent motion is not necessary for motion-induced subjective time dilation. Experiments three and four tested the influence of speed, temporal frequency, and spatial frequency on STEs. In these experiments, a concentric grating expanded from a fixation point. The speed in which this expansion took place and the temporal frequency in terms of Hertz (Hz) varied across trials. This time, the speed of the expansion did not affect STEs, however, time dilation occurred as a result of increasing temporal frequency. That is, the number of changes occurring to the stimulus accounted for more of the variance in STEs than motion. This suggests that the primary cause of subjective time dilation is not motion but rather the dynamic structure of the stimulus.

In short, Kanai et al. (2006) show that the apparently robust link between stimulus motion and STEs may actually be due to other factors, namely, temporal frequency. Although many spatial factors effect STEs, the primacy of temporal frequency on the perceived duration has been demonstrated repeatedly (see McFarland, Cacace & Setzem, 1998).

In summary, the variables that characterize subjective time dilation are many but converging evidence indicates that motion and temporal frequency (such as distance and changing features) are consistent contributors to biases of STEs. While motion has been known to reliably produce variation in STEs, some studies show that this variability may be subsumed by feature-specific attributes of stimuli.
2.5 Stimulus Complexity in Duration Perception

Although many of the studies described in the previous section could be construed as representing various degrees of stimulus complexity, there are several studies that have explicitly cited complexity as the key source of bias in an STE task. In these studies, greater degrees of stimulus complexity, much like motion and temporal frequency, result in perceived time dilation. Ornstein (1969; 1970) is perhaps the first to directly study the relationship between stimulus complexity and perceived duration. As such, Ornstein has consistently found a positive linear relationship between stimulus complexity and perceived duration in both audio and visual experiments. Subsequently, several researchers have explored this relationship in detail.

For instance, Schiffman and Bobko (1974) used a simple manipulation of stimulus complexity where arrays of light were shown to participants in three conditions which varied with regard to the complexity of the light display. In the low-complexity condition the lights came on, remained lit for the entire interval then went off simultaneously. The medium-complexity condition produced a “regular and predictable lighting pattern” where lights were flashed on and off at a constant rate. There was no repeated pattern or regularity in the high-complexity condition: lights flashed randomly in respect to one another. After the lights turned off, participants were instructed to depress a switch to reproduce the duration of the interval last presented to them. Low complexity, highly ordered conditions yielded shorter STEs compared to objective time, while highly complex, unordered stimuli yielded overestimations compared to objective time. These results led the authors to conclude that —...the more ordered and simple the stimuli defining and contained in the duration interval, the shorter the interval is
perceived; and the greater the complexity of the stimuli, the longer the interval appears” (p.158).

Table 1 shows the mean ratios and standard deviations by level of stimulus complexity presented by Schiffman and Bobko (1974). There were significant main effects due to stimulus complexity, $F (2, 60) = 7.80, p<.001$, as well as duration intervals, $F (5, 300) = 55.27, p<.001$. Additionally, as the ratios in Table 2 demonstrate, overestimations of duration were greater during the shorter time intervals while underestimation increased during the long intervals, supporting Vierordt’s law. A subsequent study using a similar array of lights (Bobko, Schiffman, Castino, & Chiappetta, 1977) found no significant main effects for complexity but rather an interaction between complexity and interval duration. The researchers do note that the effects of stimulus complexity were more pronounced during shorter durations suggesting that complexity may have a diminishing effect as the duration of the interval increases.

Correspondingly, Thomas and Weaver (1975) reported a similar relationship between stimulus complexity and STEs. Participants were shown one of three visual displays consisting of stimuli differing in their level of complexity: a black display; a display consisting of a three letter word; or a permutation of a three letter word. Participants in all conditions were shown the displays for either 40 or 80 milliseconds and asked to indicate whether the duration was short, medium or long (participants were trained on short, 20msec; medium, 60msec; and long, 100msec intervals). STEs for both the three letter conditions were significantly longer than estimates given for the blank display.
These studies demonstrate that perceived duration for complex, unordered stimuli are longer than they are for a highly ordered, homogeneous stimulus display. The degree to which these results can be subsumed by factors such as temporal frequency is relatively unknown because of methodological limitations. However, in light of the work done by Schiffman, Bobko and colleagues (Schiffman & Bobko, 1974; Bobko, Schiffman, Castino, & Chiappetta, 1977) and Thomas and Weaver (1975) there seems to be converging evidence that stimulus complexity influences STEs independently of variables like velocity and temporal frequency.

Despite successful research in this area, much remains to be understood regarding how the general characterizations of environmental stimuli determine subjective temporal estimates. Stimulus complexity has the potential to characterize the influence of a stimulus display on perceived duration so long as complexity is quantified precisely. Stimulus complexity, as we shall refer to it, is a variable that is able to capture relationships between features, regardless of dimensional configuration. A measure that is sensitive to structure is particularly useful when the goal is to describe feature specific changes that occur to a dynamic stimulus. As such, stimulus complexity in the context of an STE task can be thought of (as described by Categorical Invariance Theory; Vigo, 2009, 2011a) as the relative homogeneity or pattern inherent to features of a stimulus set.

The study of prospective temporal judgments would benefit from such a formal notion of complexity for the following reasons. First, when an independent variable is measured precisely and in general terms researchers are able to deal with all possible cases accurately. Second, given that temporal judgment tasks are highly sensitive to task conditions, a formal quantification of stimuli facilitates a more fine-graded analysis of
important factors effecting STEs. As we know from our discussion, temporal judgments are known to be biased by a variety of contextual effects. Given the many contextual effects influencing STEs, a uniform operation of stimuli would help to control for the many variables that could affect perceived duration allowing for a fine-graded analysis of particular variables of interest. Contextual effects may cause noise in experiments that do not use a formal operation, making it difficult for researchers to attribute biases in STEs to a specific variable under study. For instance, variables as spurious as the size of the stimulus (Ono & Kawahara, 2007) as well as the location of stimulus presentation (Roussel, Grondin & Killeen, 2009), among others, have been shown to cause biases in STEs.

Finally, a formal notion of complexity is needed to accurately define the structure of a stimulus so that precise quantitative and qualitative predictions can be made with regard to estimations of duration in its presence. This predictive power may be what is most attractive about a formal description. Given the complexity of a stimulus, we may be able to predict the direction and magnitude of duration estimates (i.e. whether it will be an underestimate or an overestimate and by how much that estimate will yield from objective time). This precise definition of stimuli will allow for not only a directional prediction of STEs but predictions that describe the form of the process. That is, the prediction may describe how an increase in complexity affects the temporal estimation process. In the following section we describe in detail the formal, mathematical model that will be used to quantify the amount of structural complexity in the proposed STE tasks.
CHAPTER 3: STRUCTURAL COMPLEXITY

Complexity has been thoroughly investigated within the cognitive sciences and has been formalized into a quantitative construct by several accounts (Miller, 1956; Feldman, 2000; Wang & Shao, 2003; Vigo, 2006, 2009). Most notably, such notions of complexity have been formalized into workable models of concept acquisition (Shapard, Hovland & Jenkins, 1961; Neisser & Weene, 1962; Feldman, 2000; Vigo, 2006; Vigo, 2009). Such models aim to describe the inherent complexity in a set of objects which in turn predict classification performance. While the primary focus of such models has been concept learning behavior, such conceptual representations are known to support a variety of cognitive functions. The vast utility of concepts is evident when considering the processes they sub-serve. For instance, concepts play a fundamental role in identification, classification, understanding, prediction, reasoning, and communication. Therefore, complexity as a quantitative construct is powerful in the way that such formulations have the potential to explain many cognitive processes. We believe that extending such models to account for cognitive processes outside the scope of the aforementioned processes affords many novel research avenues. Indeed, to our knowledge, the application of complexity as a formal and quantitative construct has not been applied to work on STEs, temporal processing, neural timing, or any of the time perception research.

In this proposal we consider complexity as formulated by Vigo (2009; 2011a; 2012). As such, the structural complexity of a categorical stimulus (i.e. a set of objects fixed over predefined dimensions) is directly proportional to its cardinality (number of
objects in the set) and indirectly proportional to the exponent of the degree of
categorical invariance.”

Notions of invariance are ubiquitous to the physical sciences and invariance
principles are foundational to a broad set of topics which include relativistic mechanics,
magnetism, and branches of mathematics (e.g. topology). Vigo (2009) introduced a new
notion of invariance named categorical invariance. This novel notion of invariance may
be construed as the degree of Gestalt homogeneity of a stimulus (see Vigo, 2011; 2013
for an explanation). As such, categorical stimuli that have high invariance are easily
learned and recalled by humans. In order to compute the degree of categorical invariance
of a categorical stimulus we must consider the number of objects in the set, the number of
dimensions, and the possible values of those dimensions. Consider a categorical stimulus
consisting of three objects with three binary valued dimensions of color (either white or
black), shape (either round or square), and edge design (either smooth or graded). We
start by converting the values of these dimensions to either “0” or “1” such that
x=1=white, y=1=round and z=1=smooth. To demonstrate, consider a set of objects using
these encoded digits: \( \mathcal{F}=\{111,110,101\} \). We must now perform dimensional
transformations on the objects in agreement with these dimensions. For instance, we
transform the values of the first dimension (color, in this case) by assigning the opposite
digit to all of the objects. We obtain what is called the perturbed set along the color
dimension: \( \mathcal{F}'=\{011,010,001\} \). Now, we count the number of objects that the perturbed set
and the original set have in common. Comparing the original set to the perturbed set, we
see that there are no objects in common after transforming the dimension of color:
\{111,110,101\}, \{011,010,001\}. Thus, zero out of the three objects remain in the set after perturbing the color dimension. The same perturbations should then be made for the remaining dimensions. When obtaining the perturbed set for the dimension of shape \{101,100,111\} we see that two out of the three objects have remained the same \{111,110,101\}, \{101,100,111\}. Upon each transformation, or perturbation, the ratio of the objects that remain in the category after it has been perturbed is calculated. The individual ratios that are attained are a measure of the partial invariants of a category with respect to that particular dimension. When these ratios are arranged in a vector we obtain what Vigo refers to as the ‘logical manifold’ (Λ) shown below:

\[
\Lambda(\vec{F}) = \left(\frac{0}{3}, \frac{2}{3}, \frac{2}{3}\right)
\]

In order to compute the overall degree of categorical invariance from the logical manifold we simply take the Minkowski distance (typically set to the Euclidean) from the zero manifold (i.e. 0,0,0). Accordingly, with respect to the current example, this step is represented by the following equation:

\[
\Phi(\vec{F}) = \sqrt{\left(\frac{0}{3}\right)^2 + \left(\frac{2}{3}\right)^2 + \left(\frac{2}{3}\right)^2} \approx 0.94
\]

Therefore, the overall degree of invariance \(\Phi\) of the stimulus set is .94. Again, this may be considered a measure of homogeneity of this set of objects or the amount of
pattern or coherence inherent to the categorical stimulus (for technical details see Vigo, 2009; 2011; 2013). With this, we can now proceed to compute the perceived degree of structural complexity ψ. Remember; the structural complexity of a categorical stimulus is directly proportional to its cardinality $p$ (i.e. size of the category) and indirectly proportional to the exponent of the degree of categorical invariance $\Phi$ as shown below:

$$\psi([111,110,101]) = pe^{-\Phi(\overline{F})} = 3 \cdot e^{-0.94} \approx 1.17$$

As a result, in this case of this category structure, the degree of structural complexity is approximately 1.17. With this measure we may assign a degree of structural complexity to any set of objects that are defined over any number of dimensions. Furthermore, it should be noted that the model has been extended to compute the complexity of sets that include continuous dimensions (Vigo, 2013). That is, dimensions that are not only constrained to binary values (either $0$ or $1$) as in the previous example (either black or white) but also to continuously valued dimensions (between zero and one, i.e., $0$…$0.5$…$1$) for the purpose of accounting for the many ill-defined cases that contain such in-between dimensional values (grey-scales in the case of the color dimension).

In previous work, Ronaldo Vigo and I used this measure of complexity in order to explore a possible link between structural complexity of a stimulus set and perceived duration (Vigo & Zeigler, under review). This work was inspired by our belief that the cost involved in processing categorical stimuli of varying complexity may influence
temporal judgments in a predictable manner. In the following section, we review this
work and describe an interesting relationship that was revealed between structural
complexity and perceived duration.

Vigo and Zeigler (currently under review) aimed to characterize the general role between stimulus structure and complexity on perceived duration. To do so, we applied the categorical invariance model (CIM; Vigo, 2009), described in the previous section, to precisely quantify the complexity inherent to an STE task. Specifically, we tested the performance of CIM in a dual task experiment that involved an STE task followed by a task which demanded that subjects attend to features of a categorical stimulus.

Participants were shown a dynamic stimulus in the form of a single object that traversed the length of a large computer monitor (30 inch monitor rotated 90 degrees) so that the object fell from the top of the screen to the bottom (approximately 2 feet). The categorical stimuli used in the experiment were chosen so that the complexity of the falling stimulus varied between trials. Four dimensional reconfigurations occurred to the stimulus while falling. Each object stream corresponded to one of six category structures that are traditionally used in the human concept learning literature (see Vigo, 2006; Shepard, Hovland, & Jenkins, 1961). Examples of the six structures used in the study are shown in Figure 1. Additionally, two object streams with two different structures labeled “Type II” and “Type VI” are shown in Figure 2. Using CIM, the following complexity ordering is obtained for the six structure types: I(.97), II (1.47), III (1.68), IV (1.68), V(1.97), VI(4.00).

As a consequence of the varying complexity between structures the dimensional changes of the dynamic stimulus varied between trials. Additionally, we varied the amount of objective time it would take for the object to traverse the screen by using three
interval durations: short [3s-6s], intermediate [10s-20s], or long [22s-55s]. After the stimulus disappeared at the bottom of the screen, participants were presented with a prompt where they were first asked “how long did it take the stimulus to travel from the top of the screen to the bottom?” followed by an additional question about the dimensional changes that took place: “how many times did each feature appear while the stimulus was present on the screen?” (see Figure 2 for an illustration). Using the keypad, each subject gave a duration judgment for each of the six category structures in each of the three intervals.

The obtained data exhibits an interesting relationship between structural complexity, the length of the interval and perceived duration. Specifically, we found a positive monotonic relationship between STEs and structural complexity in the short interval, no relationship in the intermediate interval, and a negative monotonic relationship in the long interval. Therefore, the way in which stimulus complexity biases perceived duration seems to depend on the length of the interval in question.

To put it differently, for short intervals (of approximately 3-6 seconds), more complex stimuli result in average STEs that are longer than less complex stimuli. Although, as the length of the interval increases, our data suggests that this positive relationship disappears in a kind of indifference interval for complexity (between 10-20 seconds). However, when the interval exceeds a particular duration (past approximately 20 seconds) more complex stimuli result in shorter STEs than less complex stimuli.

We interpreted this change in relationship in the context of a gradual decay of stimulus information that takes place in short-term memory (STM). Previous work on STM suggests that the memory trace for attributes of stimuli may decay in proportion
with the delay between presentation and recall (Jonides, Lewis, Nee, Lustig, Berman & Moore, 2008; Peterson & Peterson, 1959; Wilson, Scott & Power, 2011). Accordingly, we explained the moderating role of interval length by suggesting that memory traces are more vivid for object streams in the short interval and are thus more easily recalled upon retrieval. When the object stream is on-line in STM, STEs are consequently influenced by the structural complexity in a predictable manner—in accordance with the positive monotonic relationship.

Conversely, with longer intervals, the patterns detected in the categorical stimulus are fleeting due to the decay of relational attributes in STM encoding. As a consequence of the decay of information over longer intervals, the degree of subjective complexity does not conform to the complexity detected in shorter intervals. Instead, the loss of information in the form of detected regularities results in poor temporal estimates for such long intervals. Correspondingly, the poor memory traces for long intervals results in a search which aims to amplify the features of stimuli retained in memory. The additional cognitive load involved in this search takes resources away from the temporal estimation process and results in subjective time compression. That is, subjective temporal estimates are shorter when compared to objective time. This subjective time compression is consistent with theoretical arguments put forth by other researchers (Zakay & Block, 1996) which describe a limited capacity system whose resources must be distributed between temporal estimation and the processing of concurrent stimuli.

In summary, we explained the moderating role of interval length by suggesting that there is an incomplete detection of stimulus patterns as a result of decay of the corresponding memory trace in the short-term memory store. This decay of stimulus
information increases with the length of the interval resulting in underestimates for longer intervals. Additionally, as the length of the interval increases, participants must perform a more exhaustive search in memory for the featural configuration shown during presentation. This search results in underestimates for more complex stimuli due to added difficulty in the search process. As a result, the slope of the positive linear trend in short intervals reverses from positive to negative as the length of the interval increases.

Additionally, apparent from the obtained data are consistencies with known phenomena in the STE literature described in the introduction. For instance, our data was in accordance with Veirdordt’s law which states that short intervals will be overestimated relative to longer intervals. Accordingly, the short interval was the only interval to be overestimated with respect to the objective passing of time while the longest interval was underestimated to a greater extent than the intermediate interval.

Likewise, our data was consistent with the scalar property of Weber’s law. As such, the standard deviation in STEs increased approximately linearly with the length of the interval (Short, $\sigma = 1.98$; Intermediate, $\sigma = 5.64$; Long, $\sigma = 11.76$). Consequently, like other perceptual processes, biases in STEs scale with the magnitude of the interval.

Additionally, aside from the opposite direction of the effect of complexity in the long interval there was also a reduction in the magnitude of the effect. A diminished effect for complexity in long intervals has precedence in a study mentioned earlier (Bobko, Schiffman, Castino, & Chiappetta, 1977). Using their lighting array paradigm, Bobko et al. report that the effect of stimulus complexity were greater for shorter intervals and suggest that the effect of complexity on perceived duration may diminish as the duration of the interval increases. The results of our study support this claim.
Additionally, we considered the possibility that differences in the velocity of the stimulus may have affected perceived duration. For instance, the average velocities of the stimuli in the three intervals of our study were as follows: short (14.33 cm/sec), intermediate (4.3 cm/sec), and long (1.68 cm/sec). Consistent with previous research reviewed in the introduction (Brown, 1995) it is likely that the difference in velocity between trials may have biased perceived duration. Indeed, the data from the Vigo & Zeigler show subjective time dilation—the ratio of STEs were higher for faster velocities and lower for slower velocities (ratio of STEs: short, 1.11; intermediate, .72; long, .63). A multiple regression analysis using complexity and velocity as predictors of STEs showed that velocity does appear to account for a significant portion of the variance in STEs. Overall, our results corroborate the findings of Brown (1995). Although, it is also likely that the overestimations for the shorter intervals and the underestimations for longer intervals have more to do with the duration of the intervals than the velocities of the stimuli (as predicted by Vierordt’s law). The main goal of the current proposal is to tease apart the role of stimulus complexity and stimulus velocity on perceived duration.

Table 2 presents the percentage of correct responses for the secondary task in Vigo and Zeigler. That is, this table depicts the average proportion participants correctly identified the number of times a particular feature appeared during the display. Overall, participants found this task difficult as indicated by consistently low proportions of correct responses across types. Interestingly, performance remained fairly consistent within types regardless of the duration of the interval. Performance on the secondary task remains fairly consistent within types regardless of the interval duration. We see this as evidence that participants are particularly sensitive to the structure of the stimulus and as
further evidence that the complexity of these stimuli may be influencing STEs. Additionally, if velocity was consistently influencing the secondary task we would expect to see differences as a result of the interval duration. However, this is not the case and performance on the secondary task seems to be influenced by the structure of the categorical stimulus.

In summary, Vigo and Zeigler provide evidence that both motion and complexity are sources of variance in the processes involved in duration perception. Motion contributes to the phenomenon of subjective time dilation where faster speeds are perceived as longer with respect to objective time. When the velocity is held constant there is an additional effect of complexity of the stimuli whereby more complex stimuli are judged as longer in short durations and progressively shorter, with respect to objective time, as the length of the interval increases. These data corroborate a history of empirical data with respect to motion (Brown, 1995) and complexity (Shiffman & Bobko, 1974), however, we were able to characterize the influence of complexity on perceived duration in terms of the categorical invariance model.
CHAPTER 5: CURRENT EXPERIMENT: AN EXTENSION OF VIGO & ZEIGLER (2013)

The current document includes an extension of the original paradigm presented in Vigo and Zeigler whereby in comparing the results, we can analyze the effect of motion and complexity in more detail. Recall that in the previous study we presented participants with a stimulus in motion, while the complexity and duration of the stimulus varied between trials. Thus, on each trial the stimulus was in motion, although for varying lengths of time. Here, we examine STEs of participants using the same paradigm but using a stimulus that stays motionless in the center of the screen. In comparing the results between these two conditions we can accurately describe the effect of motion on perceived duration. Additionally, we may compare the effect of motion to that of complexity and evaluate main effects for these variables as well as any interaction between them.

Again, this stationary stimulus condition is motivated by empirical findings by Vigo and Zeigler. Isolating complexity as an independent variable allows us to better characterize its role in STEs. Additionally, with respect to motion, this condition acts as a control and complement to the condition presented in Vigo and Zeigler. The extent to which motion is needed to induce biases in STEs is a central research question of the current report. This being said, we hypothesize that the stationary stimulus condition will yield similar performance patterns as those reported by Vigo and Zeigler. That is, we expect to find a positive monotonic relationship between STEs and structural complexity in short intervals, no relationship in intermediate intervals, and a negative monotonic relationship in long intervals. We expect to see such biases in perceived duration because
of our belief that complexity is a key source of variance in perceived duration. Motion is known to be a main independent variable in STEs but we hypothesize that varying degrees of complexity will be enough to cause biases in perceived duration, even in the absence stimulus motion.

5.1 Methods

Using a program written in Matlab version 7 and Psychophysics Toolbox version 3, a dynamic stimulus is presented to participants on a 30” monitor (rotated 90 degrees) in the center of the screen. Participants are seated approximately 4 feet away from the display. While situated in the center of the screen, stimulus dimensions change in accordance with one of the six 3[4] structure types. There was no blank display between dimensional changes; the objects appeared as a single stimulus that transformed its features continuously. The amount of time the object is visible on the screen varied between blocks. Intervals are short, intermediate, or long (as in Vigo & Zeigler, under review). Subjects are presented with a prompt where they are first be asked “how long was the stimulus present on the screen?” whereby participants give an estimation of duration in seconds by using the keypad on the keyboard. Following this prompt, participants are asked “how many times did each feature appear while the stimulus was present on the screen?” The participant is prompted to recall each possible stimulus feature (resulting in six total recall judgments per trial; 3 dimensions × 2 values each). The purpose of this concurrent task is to ensure that participants carefully attend to the object. Using the keypad, each subject gives a duration judgment for each of the six 3[4] category structures in each of the three intervals. The six stimulus structures as well as
the interval durations are randomly presented to participants and counterbalanced throughout the experimental session. Instructions are given to participants during the consent procedure as well as verbally during a practice trial. These instructions specifically state not to count or tap during the experiment. The following excerpt is read by participants during the consent process:

If you agree to participate, you will be asked to pay attention to an object that will change in a number of different ways. The object will appear on a computer monitor for different durations. After the presentation of the object you will be asked a couple of questions. The first prompt will ask you to indicate the number of seconds you believe the object appeared on the screen by using the number keys on the keypad. The second prompt will ask you a question regarding how the features of the object changed while it was on the screen. **PLEASE DO NO COUNT OR TAP DURING THE EXPERIMENT.** If you have questions at any time, please ask the experimenter.

Figure 5 shows the manipulation and subsequent questions asked during the experimental session.

There are several possible ways to analyze the data. First, we must test for Vierordt’s law by regressing interval duration on STEs. As expected from Vierordt’s law, significant main effects should be found for the duration of the interval. Specifically, we should see, on average, overestimates for shorter stimulus intervals and underestimates in longer intervals. Additionally, we must test whether these data exhibit the scalar property of perceived duration. In accordance with previous research, standard deviations in STEs should increase approximately linearly with the duration of the interval.
More central to this thesis is the role that particular object based variables play in biasing STEs. Motion and structural complexity are notable among possible key sources of variation. As such, the primacy of these variables should be tested by performing a repeated measures ANOVA to examine how such factors affect STEs. This analysis will reveal any main effects for these variables and uncover interactions between the variables.

Furthermore, the results of the current experiment are compared to the results of Vigo and Zeigler. The only difference between these conditions is the stimulus in motion in the previous experiment and the motionless stimulus in the proposed condition. As such, comparing average STEs for each interval between conditions reveals the effect of motion/velocity on perceived duration. Comparing these conditions reveals whether or not stimulus complexity is a source of variation in STEs independent of motion or rather only a source of variation when interacting with stimulus motion.
CHAPTER 6: RESULTS

The ratios of duration estimates are plotted in Figure 6 such that 1.0 on the y-axis corresponds with perfect accuracy. Apparent from the obtained data are consistencies with known phenomena discussed in the introduction. Consistent with Vierordt’s law, the ratio of subjective time to objective time was higher in short intervals and increasingly lower in the intermediate and long conditions. Additionally, consistent with the scalar property of Weber’s law, the standard deviation in STEs increased approximately linearly with the length of the interval (Short, $\sigma = 2.14$; Intermediate, $\sigma = 2.81$; Long, $\sigma = 5.00$). Again, the scalar property of STEs (Gibbon, 1977) propounds that, like other perceptual processes, biases in STEs will scale with the magnitude of the interval. Both Vierordt’s law and the scalar property are robust phenomena that characterize subjective temporal estimates across many experimental methodologies and are useful when determining the validity of experimental data.

As indicated by Figure 6, all intervals yielded average estimates that were shorter than objective time. This is in contrast to the experiment reported by Vigo & Zeigler which employed a stimulus in motion. The motion condition yielded average overestimates of duration in the short interval and underestimates for the intermediate and long intervals while the stationary condition yielded average underestimates for all durations. In fact, all three intervals in the stationary condition yielded reduced average ratios in subjective estimates when compared to the motion condition (Motion: Short, $\bar{x} = 1.11$; Intermediate, $\bar{x} = .73$; Long, $\bar{x} = .62$ and Stationary: Short, $\bar{x} = .90$; Intermediate, $\bar{x} = .54$; Long, $\bar{x} = .43$) indicating that, on average, the stimuli in motion resulted in perceived time dilation relative to the stationary stimuli. Paired-sample t-tests
for unequal variances, i.e., Welch’s t-tests, indicate significant differences in each interval when compared between conditions (Short, \( t(457) = -5.17, p < .001; \) Intermediate, \( t(329) = -6.14, p < .001; \) Long, \( t(372) = -7.44, p < .001 \))

In addition to the effect of motion between conditions, much like the results reported in Vigo & Zeigler, there seems to be an additional effect of stimulus complexity on STEs within each interval tested, as indicated by regressing stimulus complexity on the ratio of subjective and objective time: Short, \( R^2 = .02, r = .14; \) Intermediate, \( R^2 = .38, r = .62; \) Long, \( R^2 = .54, r = -7.4. \) Again, we direct your attention to Figure 6 which depicts these relationships in a scatter plot and redirect your attention to Figure 3 so that you may compare these results to those obtained by Vigo and Zeigler in their use of a stimulus motion condition. While the strength of the relationship between stimulus complexity and average ratios of STEs is not as strong in the stationary condition as in the stimulus motion condition, the obtained data does exhibit the same general trend. That is, a positive relationship in relatively shorter intervals changes to a negative relationship as the length of the interval increases. Taken together, these two conditions show corroborative evidence for the independent effects of motion and complexity on perceived duration.
CHAPTER 7: GENERAL DISCUSSION AND CONCLUSION

Although the relationship between structural complexity and STEs was not as strong in the current experiment as they were in Vigo & Zeigler, we still see evidence for the process of memory decay described in Chapter 4 and depicted in Figure 4. It seems that as the length of the interval increases, the relationship between structural complexity and STEs goes from a positive relationship (or no relationship) to a negative relationship in longer intervals. Given the differences between these conditions, it is evident that more research is necessary to make definitive conclusions regarding the role that stimulus complexity plays in subjective temporal estimates. That being said, we suggest that future research be measured against our memory decay hypothesis.

In doing so, there are certain methodological concerns that should be addressed. For instance, an open question is the level of subjectivity in temporal estimates. For instance, it might be that there are large individual differences in STEs between participants. In the current research, we have assumed that there are not large differences in subjective estimates across participants, which could be a possible limitation of the current study that should be addressed by future research. We recognize that the results in the current experiment were conducted with a protocol in which a different sample was used for the motion and stationary conditions. This may introduce noise in the data if large individual differences exist. We suggest that future research test the current findings using a protocol where participants are exposed to both stimuli in motion as well as stationary stimuli. This would control for the possibility that the differences found between the motion and stationary conditions were not due to individual differences in STEs.
An additional methodological issue concerns the strength and saliency of the stimuli used in the current experiment. It is possible that the differences between the structures used were too similar with respect to their structural complexity to yield significant differences in STEs. In turn, this would result in the increased possibility of a type II error. That is, a strong relationship may exist between structural complexity and STEs that was not captured by the 3[4] structures. We believe that stronger relationships between structural complexity and temporal estimates may be found when using structures with a different number of objects and different dimensional configurations. As such, we suggest that future research test alternative category structures in order to further explore this relationship and extend the findings reported here.

In conclusion, these results support a large and growing literature that shows subjective time dilation for stimuli in motion (Brown, 1931; Roelofs & Zeeman, 1952; Goldstone & Lhamon, 1974; Tayama & Aiba, 1982; Brown, 1995; Gavazzi, Bisip, & Pozzo, 2013). Additionally, in accordance with evidence reported by Vigo & Zeigler, we have found preliminary support for a memory decay hypothesis that describes the relationship between structural complexity and STEs. Lastly, we hope that this report inspires future research on the burgeoning topic of perceived duration and hope that the categorical invariance model (Vigo, 2009; 2011a) and its generalization, the GIST-M (Vigo, 2013), are tested further as they are extended to other cognitive and perceptual domains.
REFERENCES


Gavazzi, G., Bisio, A., & Pozzo, T. (2013). Time perception of visual motion is tuned by the motor representation of human actions. *Scientific reports, 3*


Table 1.
*Table adapted from Shiffman and Bobko (1974) reporting their results.*

<table>
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<th>Time Interval (in sec.)</th>
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<th></th>
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<td>Ratio</td>
<td>SD</td>
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<td>SD</td>
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<td>0.27</td>
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<td>0.22</td>
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Table 2.
*Proportion of correct responses for the secondary task in Vigo & Zeigler (under review).*

<table>
<thead>
<tr>
<th>Interval</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>Total</th>
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<td>.21</td>
<td>.47</td>
<td>.09</td>
<td>.28</td>
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<tr>
<td>Inter.</td>
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<td>.23</td>
<td>.18</td>
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<td>.28</td>
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<tr>
<td>Long</td>
<td>.56</td>
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<td>.26</td>
<td>.15</td>
<td>.48</td>
<td>.05</td>
<td>.25</td>
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<tr>
<td>Total</td>
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<td>.26</td>
<td>.18</td>
<td>.49</td>
<td>.076</td>
<td>.27</td>
</tr>
</tbody>
</table>
Figure 1.
Category Structures used in Vigo & Zeigler (under review).
Note. Image adapted from Vigo & Zeigler (under review). Examples of category structures used in the present study. These consist of four objects defined over three dimensions: color (black or white), shape (circle or square), and edge (smooth or graded). The illustration shows the stimuli of each type denoted by the corners of a cube where the sides of the cube represent dimensions. Corners with circles represent members of the category whereas empty corners represent non-members of the category.
Figure 2.
*Manipulation used in Vigo & Zeigler (under review).*

*Note.* Image adapted from Vigo & Zeigler (under review) showing their manipulation and subsequent questions asked during the experimental session. Arrows in the two panels (A) are meant to illustrate the path of motion taken by the dynamic stimulus. The stimulus appeared as a single object which fell in a smooth continuous path from the top of the screen to the bottom. After the stimulus disappeared at the bottom of the screen the participants were given questions about the duration of the falling object (B) and the dimensional transformations that took place as the object fell (C). (D) shows an alternative illustration of the stimulus display which highlights the locations where the object changed its features while falling.
Figure 3.
Results of the stimulus motion condition reported in Vigo & Zeigler (under review).

Note. Image adapted from Vigo & Zeigler (under review). Average subjective estimates of duration for the 3[4] category structures. Average STEs are plotted in terms of the ratio of subjective estimates to objective time on the y-axis and as a function of structural complexity as measured by CIM on the x-axis. Categorical stimuli are divided into the three intervals used in the experiment: Interval 1 (short), Interval 2 (intermediate), Interval 3 (long). Data for types III and IV were combined since these structures contain the same structural complexity. The linear fit is provided and the R-squared value is given for each interval.
Figure 4.
Visual characterization of the process of memory decay described in Vigo & Zeigler (under review).
Figure 5. Proposed manipulation and subsequent questions asked in the current experiment.

Note. Display sample showing the proposed stimulus manipulation and subsequent questions asked during the experimental session. Stimuli shown in panel (A) are serially presented to participants in the same location on the monitor and stimulus presentation is preceded by a fixation cross indicating where the stimuli will appear. After the four objects of the categorical stimulus are presented, participants are given a question regarding the amount of time that passed from the moment the first object appeared until the last object disappeared (panel B). Subsequently, participants are prompted with questions regarding dimensional transformations that occurred during stimulus presentation.
Figure 6.
Results of the stationary stimulus condition.
Note. Average STEs are plotted in terms of the ratio of subjective estimates to objective time on the y-axis and as a function of structural complexity as measured by CIM on the x-axis. Categorical stimuli are divided into the three intervals used in the experiment: Interval 1 (short), Interval 2 (intermediate), Interval 3 (long). Data for types III and IV were combined since these structures contain the same structural complexity. The linear fit is provided and the R-squared value is given for each interval.