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Scale invariance of temporal order discrimination using complex, naturalistic events

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Recent demonstrations of scale invariance in cognitive domains prompted us to investigate whether a scale-free pattern might exist in retrieving the temporal order of events from episodic memory. We present four experiments using an encoding-retrieval paradigm with naturalistic stimuli (movies or video clips). Our studies show that temporal order judgement retrieval times were negatively correlated with the temporal separation between two events in the movie. This relation held, irrespective of whether temporal distances were on the order of tens of minutes (Exp 1–2) or just a few seconds (Exp 3–4). Using the SIMPLE model, we factored in the retention delays between encoding and retrieval (delays of 24 h, 15 min, 1.5–2.5 s, and 0.5 s for Exp 1–4, respectively) and computed a temporal similarity score for each trial. We found a positive relation between similarity and retrieval times; that is, the more temporally similar two events, the slower the retrieval of their temporal order. Using Bayesian analysis, we confirmed the equivalence of the RT/similarity relation across all experiments, which included a vast range of temporal distances and retention delays. These results provide evidence for scale invariance during the retrieval of temporal order of episodic memories.

1. Introduction

Scaling laws describe the existence of processes or patterns that are repeated across different scales of analysis (Kello et al., 2010). Scientific laws characteristically hold over a range of scales, such as the Gutenberg–Richter law for earthquake magnitude, the structural self-similarity of fractals, and animal foraging patterns. In cognition, examples include Zipf's law (1949) to model the relationship between occurrence frequency of a word and its frequency rank, and Steven's law (1957) to characterise the relationship between the magnitude of a stimulus and its perceived intensity.

Several lines of evidence have indicated the presence of scale invariance in memory. For example, the shape of serial position effect curves in serial and free recall exhibit scale invariance. As long as the ratio between the interval between items and the interval between study and test is kept constant, the slope of the recency curve remains unchanged (Bjork & Whitten, 1974; Glenberg, Bradley, Kraus, & Renzaglia, 1983; also see Chater & Brown, 2008 for examples in other cognitive domains). Another type of scaling law was discovered when free recall of items from semantic memory was compared to animal foraging behaviours (Rhodes & Turvey, 2007). The authors found

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that the inter-response time intervals of searching for items from memory conform to the Lévy distribution, which is commonly seen in animal foraging (Viswanathan et al., 1999). In another free recall study, Maylor, Chater, and Brown (2001) asked participants to recall what they did (or would do) in the previous (or next) day, week or year, and found that the rate of item recall was unvarying across recall span.

According to local distinctiveness models, memories can be located by their position along a timeline, such that recent items occupying "nearer" and more discriminable locations are easier to retrieve than items stored at locations more distant from the current point in time (Neath, Brown, McCormack, Chater, & Freeman, 2006). This is opposed to the more traditional global distinctiveness models, which instead assume that the distinctiveness of items is determined by their distances from all items to be discriminated (Murdock, 1960).

Taking the local distinctiveness assumption into consideration, the Scale-Invariant Memory, Perception, and Learning (SIMPLE) model proposed by Brown, Neath, and Chater (2007) states that items in memory are stored in terms of their location on a timeline that extends from the present backwards to the past. Importantly, in the context of encoding-retrieval tasks, the model takes into account not only the temporal distance between events at encoding, but also the time between the encoding and the retrieval of these events (i.e., retention delay). For instance, two different memory traces encoded 5 versus 25 s in the past will be as confusable with each other as two traces encoded 5 versus 25 min in the past (5:25 for both cases). The actual temporal distances are magnified by 60 times, but the *scale of similarity* between the two events in question is kept constant (temporal ratio = 1/5), akin to other amplification examples shown in memory tasks of varying time scales (Laming, 2010; Morin, Brown, & Lewandowsky, 2010; cf. also Weberian compression, Shepard, 1987). The local distinctiveness principle in retrieval has been tested in studies employing simple probe items, such as words (Murdock, 1962), as well as studies targeting more complex, real-world situations (da Costa Pinto & Baddeley, 1991). Here we capitalised on this concept and examined the local distinctiveness effect across several experiments covering a vast range of temporal intervals. Critically, this then allowed us to test the hypothesis of scale invariance by comparing the effect of distance/delay on retrieval performance across different datasets.

Accordingly, we measured temporal order retrieval performance for events with temporal distances in the range of 0.5–31.7 min (Exp 1 and Exp 2) and 0.60–4.96 s (Exp 3 and Exp 4), and with retention delays of 24 h, 15 min, 1.5–2.5 s, or 0.5 s for Exp 1–Exp 4 respectively (see Table 1). For each trial in each dataset, we combined temporal distance and retention delay into a single measure of "memory trace similarity". The similarity scores were computed using the SIMPLE model (Eq. (1) in Brown et al. (2007), p. 544; see also detailed procedure in Section 3.1). For each subject, on a trial-by-trial basis, we used the similarity scores as predictors for the observed data (i.e., retrieval times, RT). The resultant RT/similarity slopes were then compared across the different datasets. Under the scale invariance hypothesis, we predicted the existence of a fixed relationship between retrieval performance and similarity across the wide range of temporal distances of events and retention delays. This was formally assessed using both standard AVOVAs and Bayesian statistics.

Table 1
Description of materials for encoding, retrieval tests and participants in each of the experiments. For the retrieval test, the range of temporal distances (TD) are reported in both video frames and in seconds. A second of movie contained 25 frames. The retention delays are reported only in absolute time (i.e., in min or s). (*) Fifteen of the 29 participants in Exp 1 (the same behavioural data was previously reported in Kwok et al. (2012)) and all of the 17 participants in Exp 3 performed the tasks inside an MRI scanner. SEM is the standard error of the mean.

	Exp 1	Exp 2	Exp 3	Exp 4
Participant details				
Number of participants	29*	15	17*	15
Mean age (SEM)	25.6 (0.8)	23.1 (0.8)	25.8 (0.8)	25.3 (1.0)
Encoding materials				
Length of movies (in time)	42 min	42 min	7.72–11.40 s	7.72–11.40 s
Length of movies (in frames)	59,432	59,432	193–285	193–285
Retrieval test				
Retention delay	24 h	15 min	1.5–2.5 s, variable	0.5 s
Shortest TD: in frames/in s	821/33	2485/99	15/0.6	15/0.6
Longest TD: in frames/in s	47,678/1907	51,045/2042	124/5.0	124/5.0
No. of trials	100	160	96	96

2. Material and methods

2.1. Participants

A total of seventy-six subjects participated in four experiments. Each of them participated in only one of the experiments (see Table 1). All subjects had normal or corrected-to-normal vision and signed an informed consent statement approved by the Santa Lucia Foundation (Scientific Institute for Research Hospitalization and Health Care) Independent Ethnics Committee, in accordance with the Declaration of Helsinki.

2.2. Paradigm overview

All four experiments were memory studies making use of cinematic materials so as to allow us to model human memories of relatively more naturalistic episodic information (see Fig. 1). This highlights the distinction between natural vision (e.g., movies, see Furman, Mendelsohn, & Dudai, 2012; Haxby et al., 2011) and conventional visual memory studies which often use simpler stimuli (e.g., lists of words). The memory traces created during movie watching should resemble our episodic experience in daily life more closely than lists of unrelated words. In Exp 1 and 2, participants watched one relatively long movie during encoding (duration: 42 min). After either a long (24 h, Exp