Time perception and contextual drift with a naturalistic stimulus

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Abstract

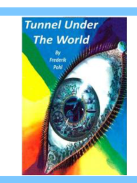
Question: How do we retrospectively estimate durations on the order of minutes? Sahakyan and Smith (2013) found that mental context change during an interval led to overestimation of that interval's duration.
Hypothesis: To estimate elapsed time, people compare their mental context at the start of the interval to their mental context at the end of the interval. Time estimates are proportional to the distance between these mental contexts.
Approach: We used neural activity patterns as a proxy for mental context (Manns, Howard, Eichenbaum, 2007; Jenkins & Ranganath, 2010), and used the distance between these patterns to predict time judgments.
Experiment: 18 subjects listened to a 25-minute story in the fMRI scanner. After the scan, subjects estimated the duration of 43 intervals from the story. Is there a correlation between the amount of neural pattern change during an interval and time estimates?

Prior work has identified some brain areas (e.g. rostrolateral PFC; Jenkins & Ranganath, 2010) involved in encoding temporal context. To see if other regions might also be involved, we first adopt an exploratory approach. Future work will test specific hypotheses about networks that encode long time scale information.

Experimental Design

fMRI session

Subjects listen to 25-minute science fiction story



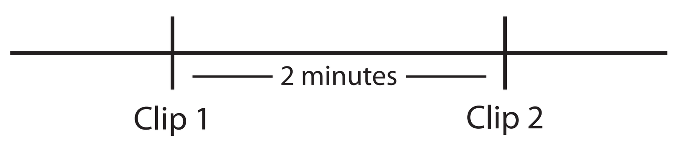
Surprise Time Perception Test

Subjects are played 43 pairs of clips from the story and estimate the temporal distance between them

Listen to Clip 1 | Listen to Clip 2

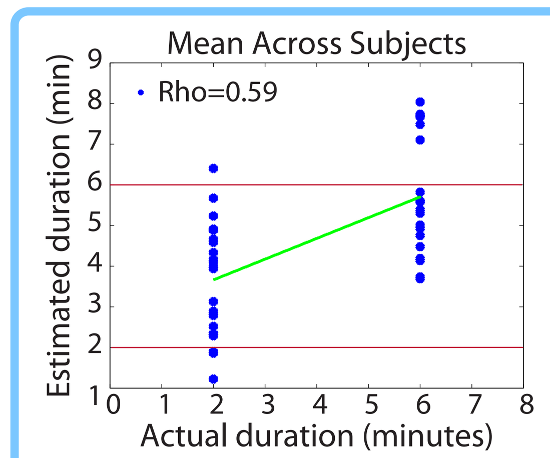
How much time passed between Clip 1 and Clip 2?
Subjects enter time estimates in minutes and seconds

How confident are you about each clip's place in the story?
Subjects rate confidence on a scale of 1 to 5



We controlled for objective duration:
Half of the clip pairs were 2 minutes apart
Half of the clip pairs were 6 minutes apart

Behavioral Results



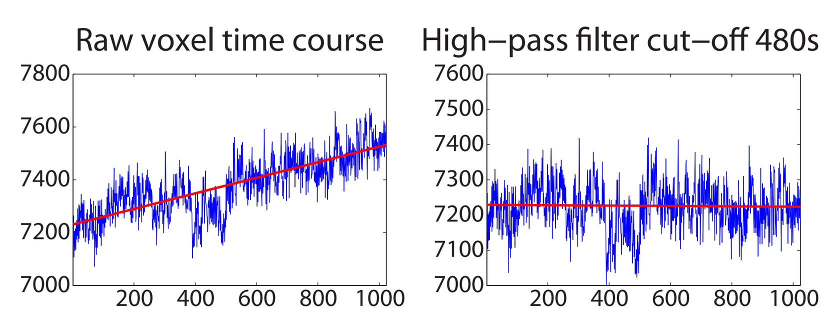
- Time estimates were highly correlated across subjects: they overestimated / underestimated the same intervals.
- Almost every subject judged 6-min intervals to be significantly longer than 2-min intervals, but there was a lot of variability in the estimated durations.

Can we explain this variability by measuring how much neural patterns have drifted?

fMRI Data Preprocessing

Challenge in tracking mental context with fMRI: How to remove low-frequency physiological and scanner noise, while preserving components of neural activity that vary gradually over time

Solutions:
1) Used gentlest high-pass filter (cut-off: 480s / 8 minutes) that removed linear scanner drift
2) Regressed out physiological noise (breathing) using method developed by Simony et al. (in press) in our lab

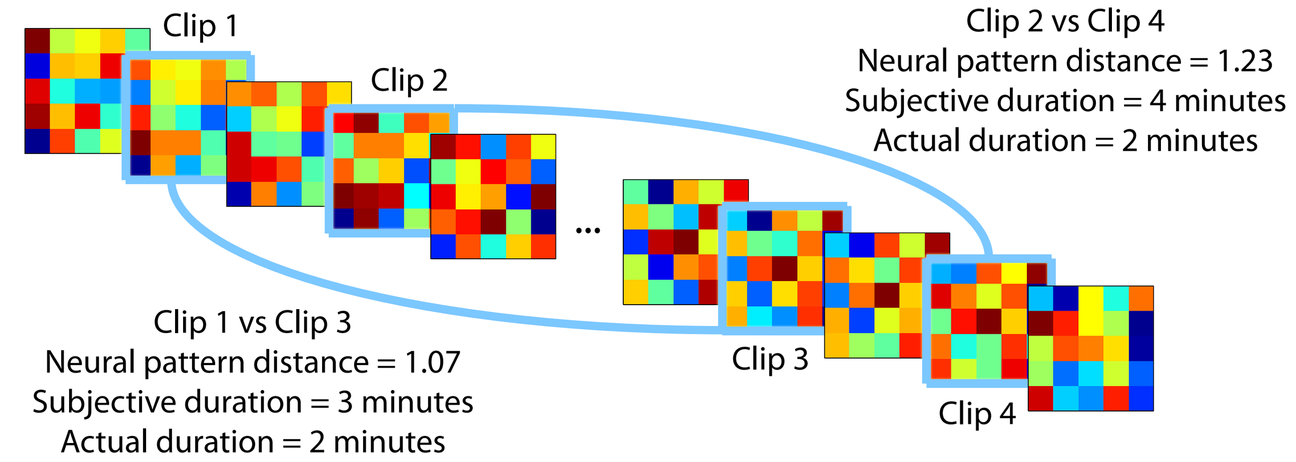


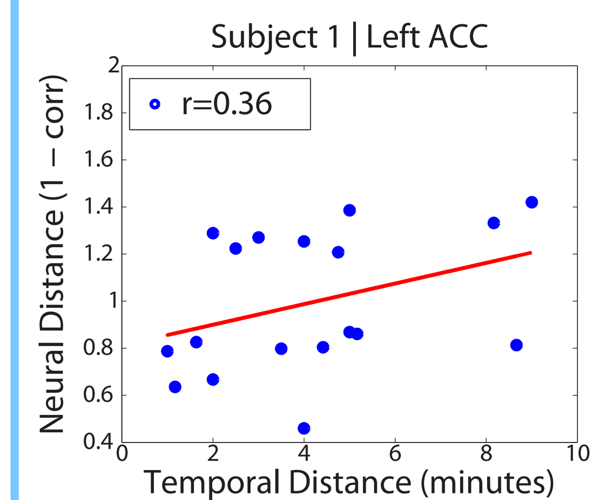
Note: we were not able to develop a preprocessing pipeline that preserved signal on timescale of six minutes (360s) while removing most of the variance due to scanner noise
=> Results presented here are solely from the 2-minute durations

Multivariate fMRI Analysis

1. Method

Correlate neural distance with time estimates for each ROI





Assessing Significance of Correlations

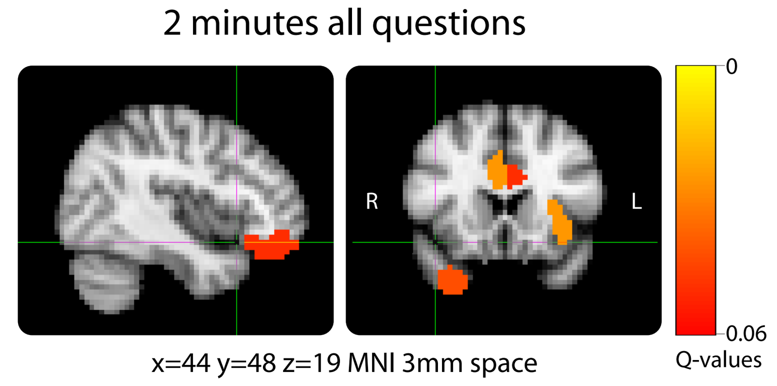
1. We used a permutation test to generate a null distribution of correlations between neural distances and time estimates

Z-scored correlation value = true correlation – mean(null correlations) / std_dev(null correlations)

2. For each ROI, we performed a random effects test to assess whether the z-score was reliably positive across subjects.

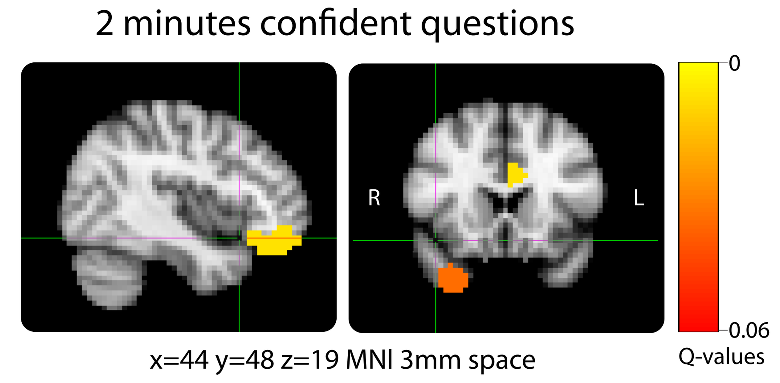
2. Multivariate Results by ROI

2 minutes all questions



Right Anterior Cingulate Cortex (ACC), Left Insula, Right Temporal Pole and Right Parahippocampal Gyrus (PHG) passed multiple comparisons correction (FDR $q < 0.05$).

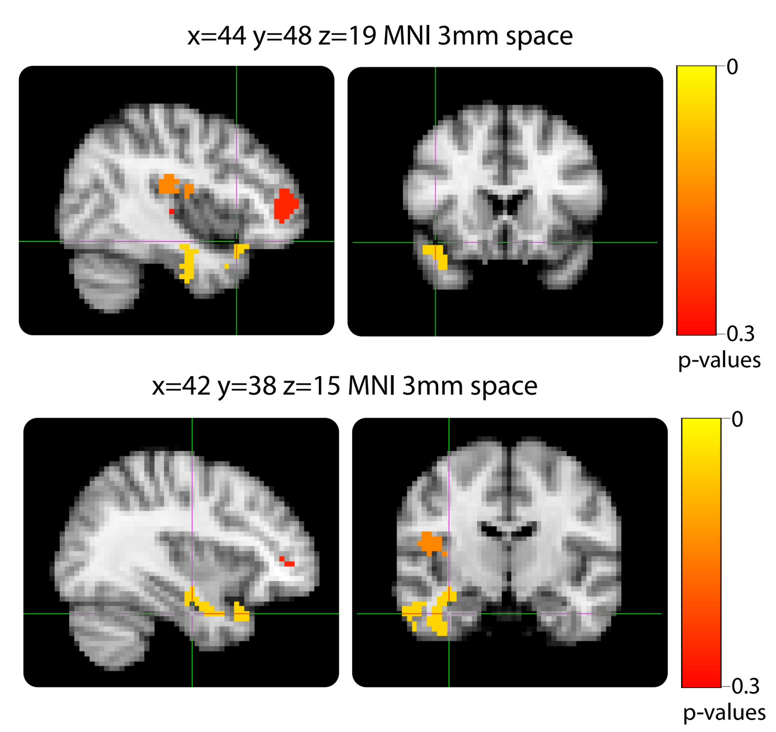
2 minutes confident questions



Left Anterior Cingulate Cortex (ACC), Right Pars Orbitalis, Right Temporal Pole and Right Parahippocampal Gyrus (PHG) passed multiple comparisons correction (FDR $q < 0.05$).

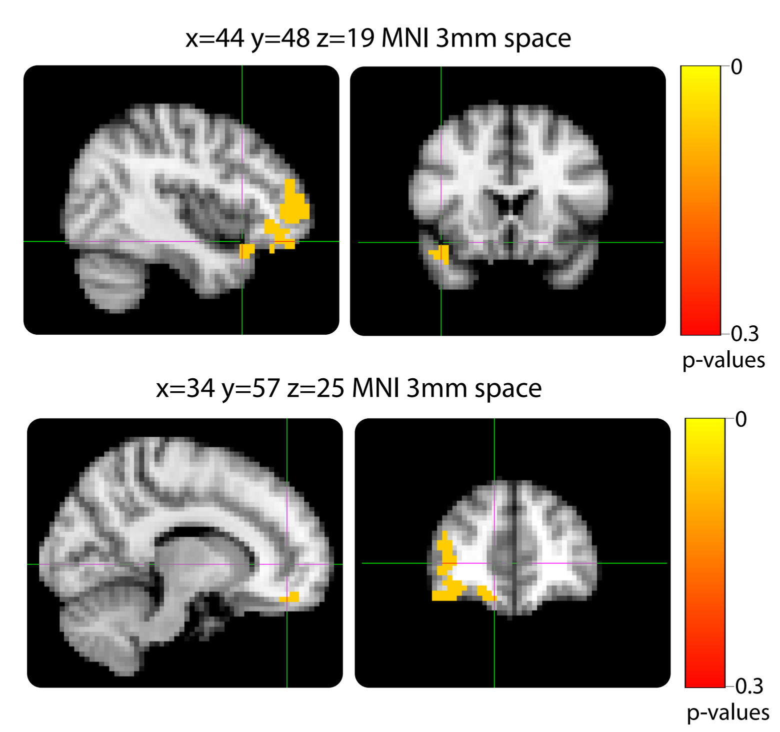
3. Multivariate Results by Searchlight (3x3x3 voxels)

2 minutes all questions



Right Middle Temporal Gyrus (MTG), PHG, Perirhinal and Temporal Pole
$p < 0.05$ FWE-corrected

2 minutes confident questions

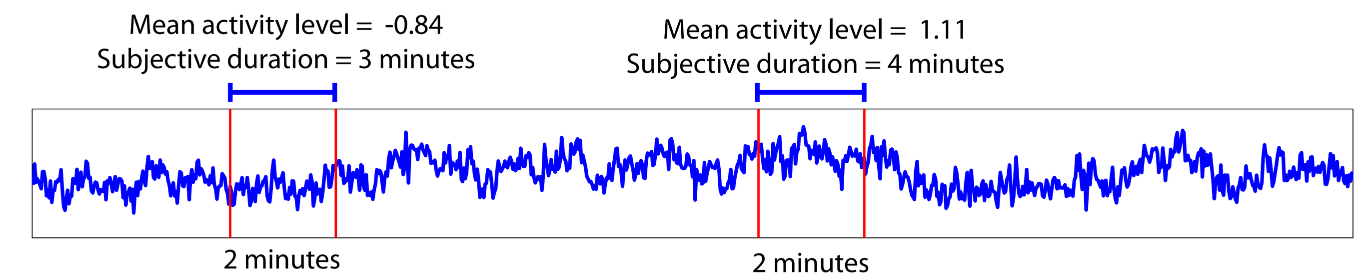


Right Pars Orbitalis and rostral Middle Frontal Gyrus (BA 10) $p = 0.05$ FWE-corrected

Univariate fMRI Analysis

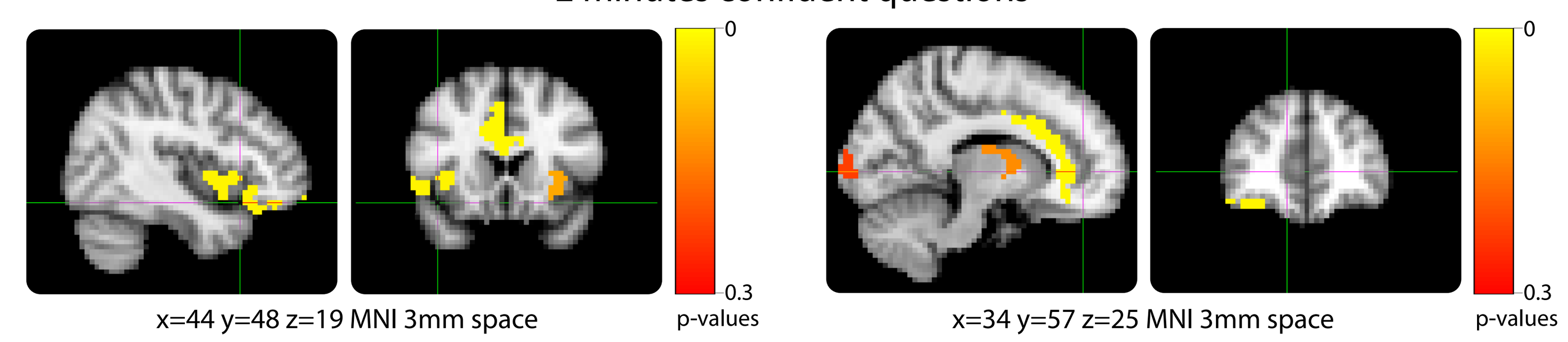
1. Method

Relate mean voxel activity during the interval to time estimates



2. Univariate Results

2 minutes confident questions



Bilateral caudal & rostral ACC, Insula, right Putamen and Pars Orbitalis (OFC) $p<0.05$ FWE-corrected

Discussion

Pattern change predicted time estimates in several regions that have been previously shown to encode temporal context:

- Parahippocampal gyrus is hypothesized to belong to a posterior-medial network involved in representing situational models (Ritchey & Ranganath, 2012)
- Our clusters in the right perirhinal and right middle temporal gyrus (MTG) overlap with regions found by Ezzyat and Davachi (2011) to predict segmentation of memories into events. More segmented memories have been linked with longer time estimates (Block and Zakay, 2008).

We also identified additional regions: bilateral insula, dorsal ACC, right putamen and pars orbitalis

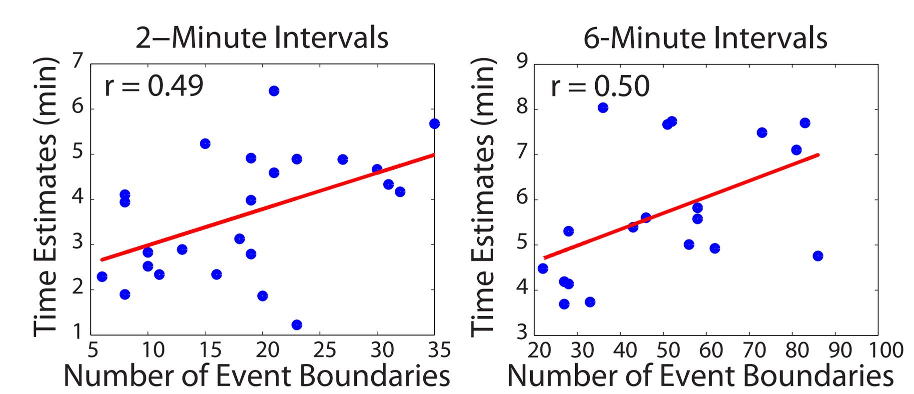
- Activity in anterior insula, dorsal putamen and inferior frontal gyrus has been found to correlate with subjective time dilation (Craig 2009)
- Caudal ACC activity has been found to increase following unpredicted shifts in task contingencies (Alexander and Brown, 2011; Behrens et al., 2007).
- Orbitofrontal cortex has been hypothesized to encode the current state of a task, analogous to a situation model (Wilson et al. 2013).

Ongoing Work

1. Long Temporal Receptive Window Regions

Hasson et al. 2008 developed techniques to isolate regions that integrate information over long time scales and are important for narrative comprehension. Does pattern change in these regions correlate with time estimates?

2. Relating Time Estimates to Event Boundaries



Nine additional subjects were recruited to segment the audio story into events. Subjects pressed a button when they thought an event had ended and another was beginning. We correlated the amount of boundaries in 2 and 6-minute intervals with subjects' duration estimates for those intervals.

Next step: relate fMRI pattern change to the number of event boundaries in an interval

References

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