Neural dynamics of context transitions in spontaneous thoughts

Kwon Heo (h1141h@g.skku.edu)
Department of Intelligent Precision Healthcare Convergence, Sungkyunkwan University
Suwon, Republic of Korea
Center for Neuroscience Imaging Research, Institute for Basic Science
Suwon, Republic of Korea

Dasom Kwon (dasom.kwon@g.skku.edu)
Department of Intelligent Precision Healthcare Convergence, Sungkyunkwan University
Suwon, Republic of Korea
Center for Neuroscience Imaging Research, Institute for Basic Science
Suwon, Republic of Korea

Won Mok Shim (wonmokshim@skku.edu)
Department of Biomedical Engineering, Sungkyunkwan University
Suwon, Republic of Korea
Department of Intelligent Precision Healthcare Convergence, Sungkyunkwan University
Suwon, Republic of Korea
Center for Neuroscience Imaging Research, Institute for Basic Science
Suwon, Republic of Korea

Abstract:

As our experiences of the external environment change from moment to moment, spontaneous streams of internal thoughts often shift from one topic to another. To examine the neural dynamics underlying these transitions of thoughts, we identified topic or context shifts in speech using a next sentence prediction (NSP) measure derived from a large language model, while participants spoke their thoughts spontaneously during fMRI scans. We found that the NSP scores of spoken sentences systematically captured transitions in participants' internal thoughts. Furthermore, these transitions were associated with increased responses in the para-cingulate network and shifts in neural states of the default mode network. These results suggest that context transitions during spontaneous thoughts involve coordinated shifts in neural dynamics within the para-cingulate and default mode networks, providing insights into the neural mechanisms underlying the dynamic nature of spontaneous thought processes.

Keywords: fMRI; Next sentence prediction; Speech; Thought transitions

Introduction

Continuous experiences of external input can be organized into discrete events, and the boundaries of these events elicit neural responses (Brunec et al., 2018). Similar neural responses are also triggered during transitions in mental context when recalling movie narratives, indicating that neural dynamics may capture shifts in both external and internal situational contexts (Lee & Chen, 2022). Analogous to context transitions in movie recall, changing topics during spontaneous thoughts coincides with shifts in mental states (Sripada & Taxali, 2020). However, the neural mechanism underlying such shifts in internally generated context in the absence of external input remains elusive. In this study, we examined the neural dynamics of topic transitions during free speaking by quantifying the degree of context changes in one's speech based on a large language model.

Methods

Task Design

During fMRI scans, independent groups of participants engaged in three speaking tasks, ranging from spontaneous to more structured and memory-driven speech production: 1) freely expressing spontaneous thoughts without any external prompts (think-aloud, N=74), 2) alternately discussing two pre-given topics at their own pace (topic-alternating, N=64), and 3) recalling movies that they had watched (movie-recall, N=24). Following the scan, participants received a transcript of their speech and retrospectively identified topic boundaries in the think-aloud and topic-alternating tasks. For the movie-recall task, topic boundaries were denoted by the author, corresponding to movie event segmentation reported by independent annotators.

Measures of Transitions in Speech

After segmenting participants' transcribed speech into sentences, we extracted the following measures at the end of each sentence from the three speaking tasks.
Next Sentence Prediction (NSP) Using the Korean BERT model (KLUE BERT; Park et al., 2021), we obtained the NSP score, which indicates the likelihood that one sentence in a pair logically or temporally follows the other sentence. A low NSP value indicates a change in context between the two sentences, while a high NSP value suggests a coherent flow of ideas. At the end of each sentence, we computed the NSP score between the current and next sentences to identify potential topic transitions.
Sentence Embedding Similarity We obtained the embeddings of each sentence using a sentence transformer (Reimers & Gurevych, 2020) and calculated the cosine similarity between embeddings of all consecutive sentence pairs.
Pause length The silent interval between spoken sentences was measured as the length of the pause to examine the impact of sensory and motor changes in speaking behaviors associated with topic transitions.

General Linear Model

We computed the linear regression coefficients of single-event hemodynamic responses in 1000 brain parcels (Schaefer et al., 2018) using timepoints from the end of each sentence to +20 seconds.

Neural State Boundary

To examine the transitions in neural states across cortical regions during spontaneous speech, we applied the Greedy State Boundary Search (GSBS; Geerligs et al., 2021), a data-driven segmentation method for detecting neural state boundaries in 100 parcels (Schaefer et al., 2018).

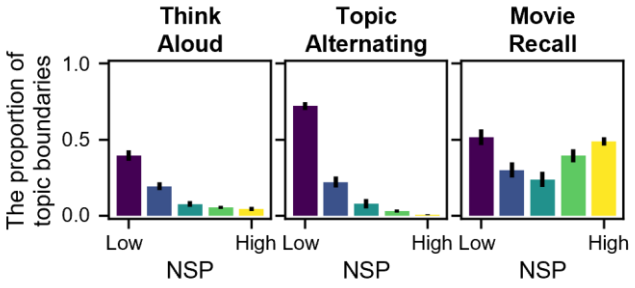

Figure 1: The proportion of topic boundaries across different NSP bins. A value of 1.0 indicates that all sentence ends in the corresponding NSP bin are topic boundaries.

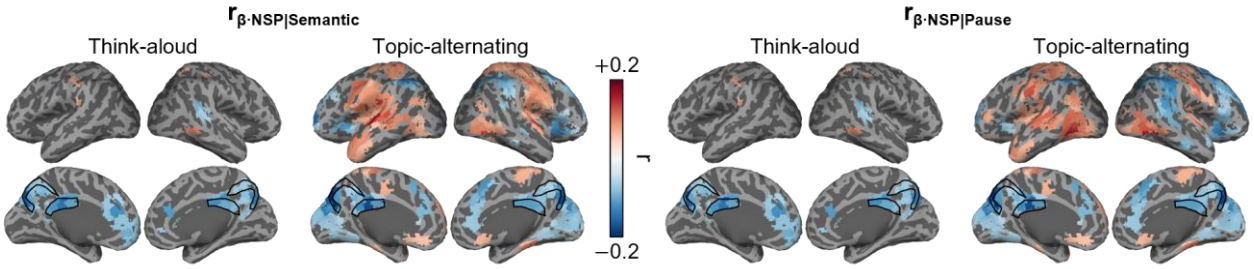

Figure 2: Partial correlations between each transition measurement and the sentence end β coefficients in the think-aloud task. Parcels with correlations higher than 0 ($p<0.05$, FDR corrected) are plotted. The regions circled by the black line represent the PCN.

Results

NSP and Speech Transition

To investigate whether NSP can identify transition points in participants' thoughts, we computed the ratio of sentence pairs including participant-annotated topic boundaries for each of the five NSP bins from low to high. In the think-aloud and topic-alternating tasks, the proportion of sentences corresponding to topic boundaries decreased as the NSP values increased (Figure 1), indicating that NSP can successfully capture the moments of transitions in spontaneous thoughts. This relationship was not observed in the movie-recall task, possibly due to its overall high narrative coherence.

NSP and Neural Responses

In the para-cingulate network (PCN: Dadario & Sughrue, 2023), significant negative correlations were observed between its coefficients and the NSP scores while semantic similarities between sentences were controlled for ($r_{\beta\cdot NSP|Semantic}$) during the think-aloud (Figure 2) and topic-alternating tasks. This result indicates response increases in the PCN when the context changed, and this effect cannot be explained by decreased semantic similarity at transitions. There were no cortical regions showing similar response increases associated with the NSPs during the movie-recall task. Responses in the PCN also negatively correlated with the NSPs while the pause length between sentences was controlled for ($r_{\beta\cdot NSP|Pause}$) during the think-aloud and topic-alternating tasks, suggesting that the effect of thought transitions is not attributable to pauses in speech production.

NSP and Neural State Transitions

Lastly, we examined whether context transitions in spontaneous thoughts are related to shifts in neural states. Across the think-aloud and topic-alternating tasks, the default mode network (DMN) and PCN showed a similarly low number of neural state boundaries compared to other brain regions (Figure 3A), indicating that these areas maintain a certain neural state for a prolonged period of time while generating thoughts. Notably, neural state transitions occurred more frequently following the end of sentences with low NSP scores compared to those with high NSP scores (Figure 3B), suggesting that discontinuities in neural states in the DMN are associated with thought transitions. This differential pattern was not observed between sentences with long and short pauses.

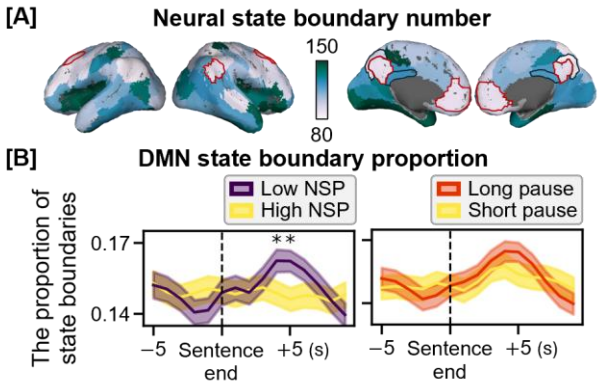

Figure 3: GSBS results for the topic-alternating task. [A]: Number of neural states boundaries for 100 parcels (Black: PCN: Red: DMN). [B]: The proportions of state boundaries in the DMN at sentence ends. The neural state boundary proportion was higher for sentences with low NSP values than those with high NSP values (* $p < 0.05$).

Conclusions

Our findings demonstrate that the NSP measures provided by a language model can reliably capture the transition moments in continuous thoughts and highlight the functional roles of the PCN and DMN in discretizing internally generated thoughts as mental context changes. These results suggest that the PCN and DMN contribute to the cognitive processes associated with context transitions during spontaneous thoughts, possibly by regulating introspective processes (Dixon et al., 2018).

Acknowledgements

This work was supported by IBS-R015-D1, 24-BR-03-04 and the Fourth Stage of Brain Korea 21 Project in Department of Intelligent Precision Healthcare, Sungkyunkwan University.

References

Brunec, I. K., Moscovitch, M., & Barense, M. D. (2018). Boundaries shape cognitive representations of spaces and events. *Trends in cognitive sciences*, 22(7), 637-650.

Dadario, N. B., & Sughrue, M. E. (2023). The functional role of the precuneus. *Brain*, 146(9), 3598-3607.

Dixon, M. L., De La Vega, A., Mills, C., Andrews-Hanna, J., Spreng, R. N., Cole, M. W., & Christoff, K. (2018). Heterogeneity within the frontoparietal control network and its relationship to the default and dorsal attention networks. *Proceedings of the National Academy of Sciences*, 115(7), E1598-E1607.

Geerligs, L., van Gerven, M., & Güçlü, U. (2021). Detecting neural state transitions underlying event segmentation. *NeuroImage*, 236, 118085.

Lee, H., & Chen, J. (2022). A generalized cortical activity pattern at internally generated mental context boundaries during unguided narrative recall. *ELife*, 11, e73693.

Park, S., Moon, J., Kim, S., Cho, W. I., Han, J., Park, J., ... & Cho, K. (2021). Klue: Korean language understanding evaluation. *arXiv preprint arXiv:2105.09680*.

Reimers, N., & Gurevych, I. (2020). Making monolingual sentence embeddings multilingual using knowledge distillation. *arXiv preprint arXiv:2004.09813*.

Schaefer, A., Kong, R., Gordon, E. M., Laumann, T. O., Zuo, X. N., Holmes, A. J., ... & Yeo, B. T. (2018). Local-global parcellation of the human cerebral cortex from intrinsic functional connectivity MRI. *Cerebral cortex*, 28(9), 3095-3114.

Sripada, C., & Taxali, A. (2020). Structure in the stream of consciousness: Evidence from a verbalized thought protocol and automated text analytic methods. *Consciousness and Cognition*, 85, 103007.