Bachelor thesis

Artificial Intelligence

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The relation between neural states at event boundaries and memory

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Abstract

Segmenting information from the world around us enables us to remember certain events. Previous literature has shown that the way someone segments information gives insight into their ability to remember certain events. Not everybody's ability to remember events is equally good. This can be a real struggle because memory is a very important aspect of our daily lives. It is therefore beneficial to know more about how it works in humans and discover why some people are better at remembering than others. This study researched the correlation between someone's ability to remember events and the neural states boundaries during event boundaries when looking at a short movie. With neural states we mean relatively stable brain patterns. A data-driven method is used to compute the neural state boundaries from fMRI data that was collected while subjects watched the movie. The hypothesis was that people with a higher memory score have more and stronger neural state boundaries around event boundaries. Two analyses were done, one on group level and one on subject level. In both analyses no significant difference was found in the neural states around event boundaries between participants with a high memory score and those with a low score. So, we did not find a relation between someone's memory score and the strength and number of neural states around event boundaries. However, it is still interesting to research this topic further in future research.

Contents

Chapter 1

Introduction

Given the vast amount of complex and dynamic information that we receive from the world around us, we have to segment the information to be able to extract meaning from it. The boundaries between these segments are called event boundaries. Sargent et al. (2013) have discovered that the segmentation of a naturalistic stimulus can predict event memory, which is memory for everyday events. According to previous literature an event boundary is observed when there is a sudden change in the situation, whether predictable or not (Pettijohn & Radvansky, 2016; Zacks et al., 2009).

When there is an event boundary, often around the same time a relatively stable brain pattern changes to another pattern in multiple different areas of the brain (Baldassano et al., 2017). These stable brain patterns are referred to as neural states, a term introduced by Geerligs et al. (2021). The stronger a neural state boundary is, the more dissimilar the surrounding states are. Strong neural state boundaries are more likely to overlap with event boundaries than weak boundaries (Geerligs et al., 2022).

It is important to further research the underlying mechanisms of memory, as memory is a very important aspect of our daily lives. Without memory we would not be able to learn new things, recognize the people around us and remember important events. For some people remembering is an effortless process but for others it can be a real struggle. When we know more about the underlying mechanisms of memory we can hopefully help people remember events more easily.

To research the relation between memory and event boundaries often behavioral studies are performed. In multiple previous studies participants had to watch a movie and press a button when they thought an event boundary occurred and do a memory test afterward. The conclusion from these studies was that participants with a better segmentation ability remembered the movie better (Bailey et al., 2013; Kurby & Zacks, 2011; Zacks et al., 2006), where segmentation ability was defined as the extent to which a participant's event segmentation was in line with that of the whole group. Also

Sargent et al. (2013) showed a considerable step towards acknowledging that this relation between event segmentation and event memory is causal. In addition to segmenting an activity and doing a memory test, the participants in this study partook in different cognitive tests. They found that the results of the cognitive tests did not influence memory, segmentation ability remained a unique contributor to memory. Their results suggest that one's ability to segment experiences into discrete events predicts event memory. Also in the study of Baldassano et al. (2017) and Ben-Yakov and Henson (2018) they found evidence for the hypothesis that events form the basis of long-term memory encoding. In these studies they showed that the end of an event triggers hippocampal activity.

It is not only hypothesized that there is a relation between memory and event segmentation, also that there is a relation between memory and neural states. Baldassano et al. (2017) have shown that neural state boundaries overlap with event boundaries, suggesting that neural state segmentation is the source of event segmentation. Combining this with their finding that event boundaries trigger the storage of events into long-term memory suggests that neural state boundaries play an important role in memory encoding as well. Also Silva et al. (2019) showed evidence for the relation between neural states, event boundaries and memory. They showed that neural state patterns derived from scalp EEG while watching a movie, fit with the event boundaries detected by independent observers. They also found that these event boundaries trigger the consolidation of the previous event in long-term memory, tested with a free recall test after the participants had watched the movie.

The relation between event memory and neural state boundaries is not entirely clear yet, despite the fact that memory is a very important aspect of our daily lives. It is useful if we know more about the difference in brain activity between people with a high and low memory score. This knowledge can be used to further investigate the way memory works and possibly to help people remember events more easily in the future. In the current study, the correlation between event memory and neural state boundaries is researched further using someone's score on a logical memory test, which tests people's ability to remember events.

Compared to previous studies that have looked at the relationship between event segmentation and event memory, the current study will dive deeper into the relationship with neural states. Specifically, we will look at the more general connection between neural states and memory. The memory score is independent of the neural states recorded during the movie, meaning that the memory questions are not about the movie that was watched. The score is based on the logical memory part of the third version of the Wechsler Memory Scale (WMS-III). In this test participants have to recall information from orally presented stories (Stebbins, 2007). People with a relatively high score on this test appears to have a better episodic memory and are better at recall (Ahn et al., 2020). The aim of the current study is to discover if someone's memory score influences the number or strength of neural states at event boundaries when looking at a movie. The research question is: Does a higher score on the logical memory part of the Wechsler Memory Scale (WMS-III) correlate with more and stronger neural state boundaries at or around event boundaries?

The storage of events into long-term memory is triggered by event boundaries (Baldassano et al., 2017) and we hypothesize that neural states are underlying event segmentation and thus also long-term memory encoding. That is why we expect to see more or stronger neural state boundaries at or around event boundaries in the brain activity of participants with a relatively high score on the logical memory part of the WMS-III, so people that appear to have a better episodic memory and are better at recall, than in people with a lower score when watching a movie.

Obtaining neural states from brain data is not an easy task. Baldassano et al. (2017) were the first to introduce a data-driven method to extract neural states, using a Hidden Markov Model (HMM). After this, Geerligs et al. (2021) introduced another method, the Greedy State Boundary Search (GSBS) method. This second method outperforms the one of Baldassano et al. (2017) in terms of computation time, robustness, and adds the possibility to determine the number of neural states , while for the method of Baldassano et al. (2017) you have to give the number of neural states to the model. That is why in the current study GSBS is used to investigate the differences in neural states between the two groups.

In the next chapter, a detailed overview of the methods is given. The following results are reported thereafter. In the fourth chapter, a results-based discussion will follow and the thesis will end with a conclusion in chapter five.

Chapter 2

Methods

2.1 Data

In this quantitative study the population-based data repository of the Cambridge Centre for Ageing and Neuroscience (CAM-CAN) is used (Taylor et al., 2017). The participants used to create this dataset were native English-speakers with no neurological disorders. In this data repository, the participants' score on the logical memory part of the WMS-III is included. In this test participants have to recall information from orally presented stories immediately after the story and after a 30-minute delay (Stebbins, 2007). The participants also had to watch and listen to the black-and-white television drama movie: Alfred Hitchcock's "Bang! You're Dead". The movie was cropped to 8 minutes instead of the original 30 minutes, but the essential plot was maintained. During this movie-watching task, their brain activity was measured using functional Magnetic Resonance Imaging (fMRI). The details of the fMRI data acquisition and the initial preprocessing steps of the data are described in Geerligs and Campbell (2018). In the current study only the fMRI data of the medial prefrontal cortex (mPFC, MNI x = 0, y = 54, z = 22) in the left hemisphere is used, as Geerligs et al. (2022) showed that this region is one of the brain regions that has the strongest association between neural states boundaries and event boundaries. This region contained 82 voxels (voxel-size = 3 mm x 3 mm x 4.44 mm).

Age has an influence on the way events are segmented and on someone's memory (Friedman, 2013; Reagh et al., 2020), that is why only people younger than 51 are included. From the remaining 258 participants, who were aged 18-50 (mean age 36.3, SD = 8.6), two groups were created. One group contained the 132 participants with a memory score higher than average, we refer to this group as the high-score group. The other group contained the 126 participants with an average memory score or a score lower than average, we refer to this group as the low-score group. As the high-score group only contains people with a 10, 6 random participants are removed from this group to make sure that the two group sizes are equal. In Figure 2.1 the distribution of the scores and the division between the two groups is visible.

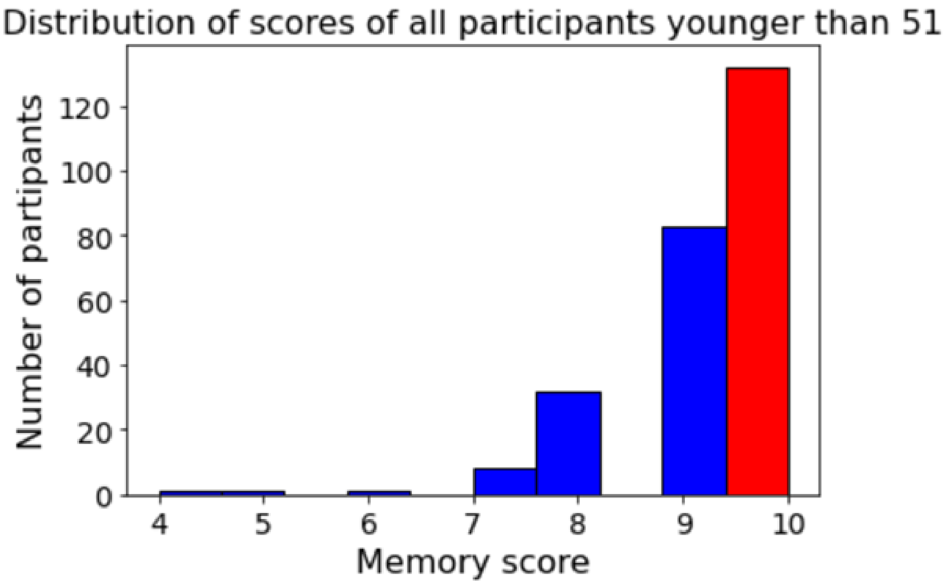

Figure 2.1: Distribution of the memory scores of the participants younger than 51. The average score was a 9. The participants with a score higher than average are referred to as the high-score group; the corresponding bars are colored red in the figure. The participants with an average score or lower are referred to as the low-score group; the corresponding bars are colored blue in the figure.

There are 19 event boundaries of the movie determined by independent observers (Ben-Yakov & Henson, 2018). Five seconds were added to these event boundaries to compensate for the haemodynamic response, which is the delay of the fMRI responses. After this, the event boundaries are converted from seconds to TRs. One TR is the repetition time, which is the time between two brain recordings. One TR was 2470 ms in the data used for this study.

2.2 Analysis

Two different analyses were performed to check if there is a significant relation between someone's memory score and the number or strength of neural state boundaries at event boundaries. One analysis at group level and one analysis at subject level. We refer to the first one as 'boundary strength at group level' and to the second one as 'fits at subject level'. The advantage of looking at the boundary strengths at group level is that hyperalignment is possible. Good inter-subject hyperalignment is preferred because GSBS is performed on group averaged voxel-level data (Geerligs et al., 2021). It is also favorable that in this analysis we can perform GSBS on the groups separately rather than on the groups together. If we perform GSBS on the groups together, as in the 'fits at subject level' analysis, it is possible that the neural states are more dependent on one of the groups, for example because of the fact that the variation in the low-score group is higher than in the high-score group. For the analysis on subject-level an advantage is that it is more sensitive. If there is an effect it will be more easily detected.

2.2.1 Boundary strengths at group level

For this analysis, the next step was to hyperalign the data. The hyperalignment method implemented in the PyMVPA toolbox is used (Hanke et al., 2009). Hyperalignment makes the intersubject brain response differences as small as possible (Geerligs et al., 2021). Hyperalignment was performed on the high- and low-score group separately. To detect the neural state boundaries the GSBS method introduced by Geerligs et al. (2021) is used. GSBS is performed on the two groups' fMRI data from when the participants were looking at the movie. In the GSBS settings the statewise detection is enabled, this makes the algorithm perform better as it is able to place two boundaries at the same time (Geerligs et al., 2022). The maximum number of boundaries is set to half the number of time points, which is 96. We chose this value, instead of the total number of time points, to reduce computation time and because in reality the number of boundaries is never bigger than the half of time points (Geerligs et al., 2021). The strengths of the neural state boundaries in the range of 1 TR before or after an event boundary are summed together for the high- and low-score group separately. Then the measure is the summed strength of the high-score group minus the summed strength of the low-score group.

To test if a significant difference was found we created a null distribution. We did this by creating 1000 times two random groups, which led to two equal-sized groups with participants under the age of 51. After this, we did the exact same steps as described before. So, first hyperalignment and GSBS on both groups separately. Then to obtain the difference in neural state strengths of the two groups, the strength of the boundaries in a range of 1 TR before or after an event boundary were summed together again and subtracted from the other group's sum of strengths. Finally, to see if the difference between the high- and low-score group was significant the measure of these groups was compared to the null distribution with a one-tailed permutation test.

2.2.2 Fits at subject level

In the second analysis the differences in fits of the high- and low-score group at subject-level were considered. The fits corresponded to the strength of a neural state boundary, now at subject-level rather than group-level. The neural states used in this analysis were gathered from GSBS performed on the high- and low-score group combined. In this analysis we did not perform hyperalignment. Hyperalignment on both groups combined would make the brain data of the high- and low-score group more similar and the possible differences would diminish. For every participant we looped through all the event boundaries and then took the fMRI data of that participant from the neural state before the event boundary and the neural state after the event boundary. There may or may not be a neural state boundary around the event boundary. In the situation where an event boundary is in the range of 1 TR before or 1 TR after a neural state we ignored the value of the event boundary and continued with the value of the neural state as event boundary, then the fMRI data is obtained as described before. Per subject the average of the neural state from before and the average of the neural state from after the event boundary was calculated. Then, the Pearson correlation between these averages was calculated. The Pearson correlation represents the strength in linearity between the two averages of neural states. The fit was calculated as 1 minus the calculated Pearson correlation. Then, to see if there was a significant correlation between someone's memory score and their calculated fit, the Spearman correlation from scipy stats was calculated (Jones et al., 2001–).

Chapter 3

Results

In Figure 3.1 the TR x TR matrices of the brain data of the high- and low-score groups after hyperalignment are visible, this represents the correlation per timepoint. The neural state boundaries of the high- and low-score group, detected by GSBS, are superimposed visible as the red boxes. There are no big differences visible in the plots of the high- and low-score group.

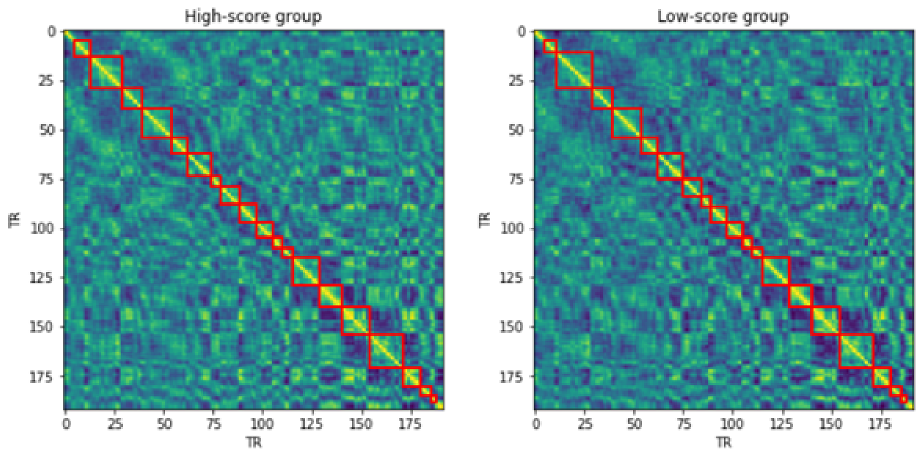

Figure 3.1: The correlation per timepoint of the high- and low-score group after hyperalignment are visualized. Their neural state boundaries detected by GSBS are visible as red boxes. The unit represented at the x- and y-axis are both TRs.

3.1 Results of the 'boundary strengths at group level' analysis

In the first analysis the boundary strengths at group level are considered. The sum of the strengths of the neural state boundaries around event boundaries in the high-score group was 15.64 and 13.81 in the low-score group. This means that the difference in strength between the high- and low-score group was 1.82. In Figure 3.2 you can see the results of this analysis. The blue bars represent the null-distribution, visible is the number of times the difference between the strengths of the random groups was the value on the x-axis. The vertical red line shows the difference between the strengths of the high- and low-score group calculated earlier. There were 904 samples that had a difference smaller than 1.82 and 96 with a difference bigger than 1.82. As there was 10% with a bigger difference the p-value is 0.10, which is above 0.05 which means that the results found are not significant. The results were similar when we excluded the participants with an average memory score.

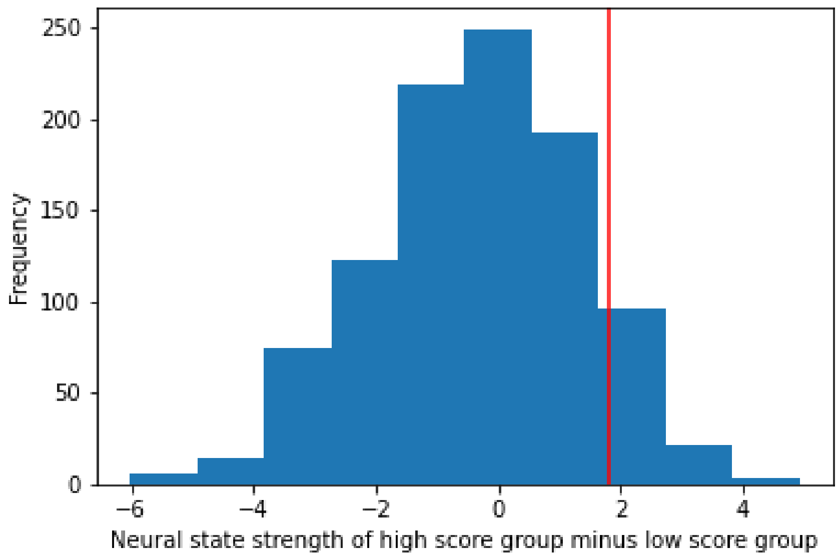

Figure 3.2: Results of the boundary strengths at group level. The blue bars represent the null distribution and the red line represents the difference between the strength of the neural state boundaries around event boundaries of the high- and low-score group. 10% of the null distribution had a bigger difference than the high- and low-score group, which results in a p-value of 0.10.

3.2 Results of the 'fits at subject level' analysis

In Figure 3.3 you can see the results of the analysis at subject-level. The fits of the different participants are plotted against their memory score. The calculated correlation coefficient was -0.017 and the corresponding p-value was 0.786. This is also above 0.05 which means that we did not find a significant correlation.

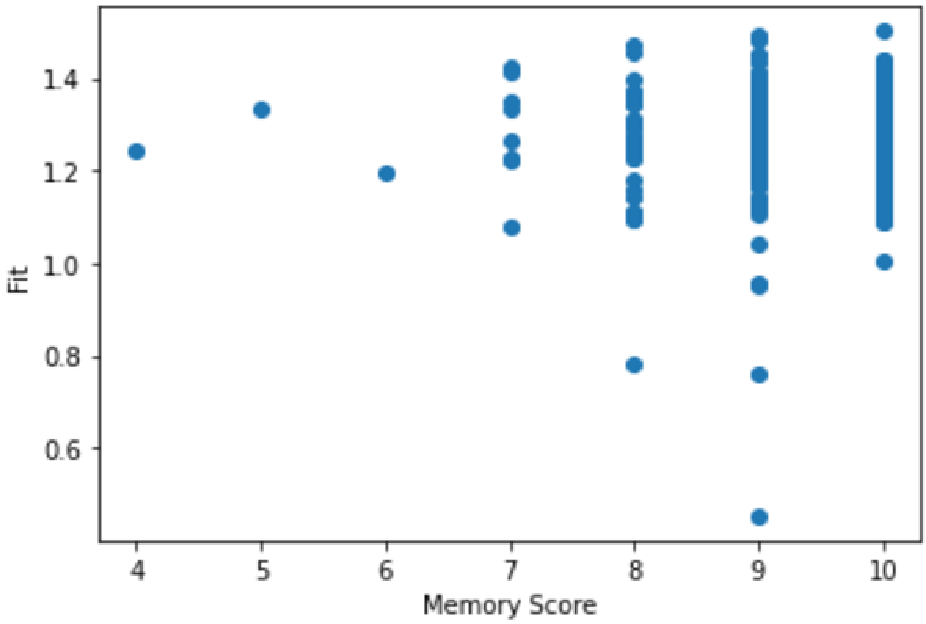

Figure 3.3: Results of the 'fits at subject level' analysis. The WMS-III score of the participants is plotted against their calculated fit. The fit corresponds to the average strength of neural state boundaries around event boundaries of a participant.

Chapter 4

Discussion

The aim of this study was to discover if someone's memory score influences the number or strength of neural state boundaries at event boundaries when looking at a movie. We hypothesized that a higher score on the logical memory part of the WMS-III correlate with a higher strength in neural state boundaries at or around event boundaries when looking at a movie. However, in the analysis on group level as well as on subject level we found a p-value higher than 0.05. This means that we did not find a significant difference between the neural state boundaries of the high- and low-score group and no significant correlation between someone's memory score and their neural state boundary strengths.

It was unexpected to see that we did not find a significant difference. That is why we decided to do some extra checks. We compared the TR x TR plots from before and after hyperalignment of the 'boundary strengths at group level' analysis (see Appendix A), in which the correlation per time-point and the neural states superimposed are visualized. It was unexpected to see that the data after hyperalignment seemed to have weaker boundaries. So it is a possibility that the hyperalignment step went wrong. However, since we found that the within-group Inter-subject correlation (ISC) increased with hyperalignment and the between-group ISC did not (see Appendix B), it is likely that hyperalignment was successfully implemented in the 'boundary strengths at group level' analysis. Geerligs et al. (2022) used the same dataset and got expected results, this also makes it unlikely that the limited number of time-points was an issue. Another point worth mentioning is that GSBS doesn't always work perfectly. A limitation of the study is that in both analyses we got the measure of interest by only running GSBS once. However, as it is likely that hyperalignment went well and that GSBS works correctly most of the time, we assume the results we found are valid and that there is indeed not a significant correlation between someone's memory score and the strength of their neural state boundaries around event boundaries.

Another limitation of this study is that there was low variability in the memory scores. It was also the case that the high- and low-score group did not have an equal amount of variability in memory scores. This was caused by the fact that the average score of the logical memory part of the WMS-III of the participants was really high. As a result, the high-score group only contained people with a 10 and the low-score group contained all the people with a 9 or lower. As many participants scored high, the participants may not have had a lot of difference in brain data either. A score of '9' could still be considered high, but they were classified as 'low' because of the data distribution. Another disadvantage, only in the 'boundary strength at subject-level' analysis, of the difference in variance between the two groups is that the influence of hyperalignment could be different in both the groups. If we assume that there is a relation between one's memory score and their brain data, it is possible that hyperalignment had a bigger influence in the low-score group than in the high-score group.

Another thing to keep in mind is to which extent the logical memory part of the WMS-III actually tests episodic memory. A memory score is a snapshot and not always representative for other moments in time. When we compare neural states in the movie to memory for a different story, we are making the assumption that the ability to separate information into meaningful states is a trait of participants that is stable across situations and types of information to be memorized. However, it could also be more related to circumstances. When someone has a high memory score it does not mean that this person always remembers everything very well. It could be the case that when this person watched the movie they were not paying attention and thus do not remember a lot from it. This could lead to situations where some people in the high-score group actually had poor memory of the movie.

As the research question is based on previous literature it is still interesting to research this topic more extensively. It is still important to find out what the differences are between people that are very good in remembering events and people that are less good. When we know how it works, we can try different methods to see if it is possible to make people remember certain events better. An interesting future research is to see if we could train people with a low memory score to end up with a higher memory score with the use of event boundaries. For example by helping people with being more conscious of the different events happening, which could lead to different neural states and better event memory.

It is still likely that there is a connection between someone's ability to remember something and their neural states. For future research it could be interesting to do similar research with a different memory test. A memory test that gives results with more variance in the two groups and of which we have more proof that it is representative of event memory in natural situations. It would be useful to have a memory test with a longer duration or that can be done more than once to reduce the chance of coincidence.

Also a memory test that directly asks questions about the movie, rather than having the movie data and the test completely independent, might be interesting to use in the future. This way, we would make the link more direct and relate the memory for a movie to neural states during that movie.

Because we know that age influences how events are segmented (Friedman, 2013), it might also be interesting to do the same study with participants above the age of 50. It could be the case that the difference in memory score is more visible in their neural states than in the younger people.

Chapter 5

Conclusion

In conclusion, we did not find any evidence for our hypothesis that a higher score on the logical memory part of the WMS-III correlate with a higher strength in neural state boundaries at or around event boundaries when looking at a movie. We performed two analyses; one focused on the boundary strengths around event boundaries on group-level and the other on the fit between a subject's fMRI data and the neural states surrounding event boundaries. In both analyses we did not find a relation between someone's memory score and the strength and number of neural states around event boundaries.

It is still interesting to dive into this topic as it is based on previous literature and it would be really useful if we can help people remember certain events more easily. It might also be beneficial to do similar research with a different memory test, a test with a duration over a longer period of time and with more variance in the results. It might also be interesting to do the same research with older participants.

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Appendix A

TR x TR plots

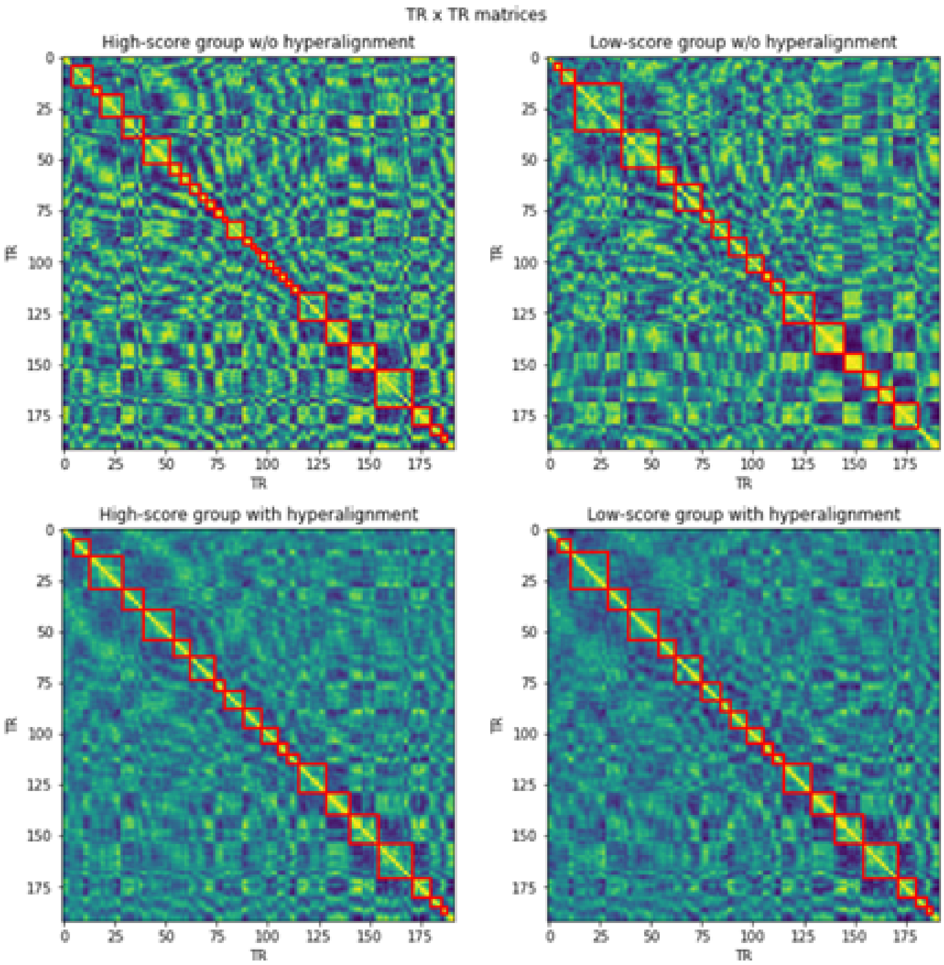

Figure A.1: The TR x TR plots from before and after hyperalignment of the high and low-score group. It is visible that the plots from after hyperalignment are less sharp. This was unexpected to see, as we interpret this as weaker boundaries.

Appendix B

ISC values

	ISC before hyperalignment	ISC after hyperalignment	Difference
High-score group	0.0130	0.02188	0.00888
Low-score group	0.2795	0.3358	0.0563

Table B.1: The Inter-Subject Correlation (ISC) of the high- and low-score group before and after hyperalignment. In both groups the ISC is higher after hyperalignment.