**Supplementary Materials**

“From Learning to Remembering: How Memory Consolidation Differs in Term and Preterm Born Children from Young Adults”

Iryna Schommartz1, Philip F. Lembcke2, Henriette Schuetz2, Nina Wald de Chamorro3,4, Martin Bauer2, Angela M. Kaindl3,4,5, Claudia Buss2,7\*, and Yee Lee Shing1,8\*

\* Yee Lee Shing and Claudia Buss should be considered joint senior author.

1Department of Psychology, Goethe University Frankfurt, Frankfurt, Germany

2 Charité – Universitätsmedizin Berlin, corporate member of Freie Universität Berlin and Humboldt-Universität zu Berlin, Department of Medical Psychology, Berlin, Germany

3Charité – Universitätsmedizin Berlin, Department of Pediatric Neurology, Berlin, Germany

4Charité – Universitätsmedizin Berlin, Center for Chronically Sick Children, Berlin, Germany

5Charité – Universitätsmedizin Berlin, Institute of Cell- and Neurobiology, Berlin, Germany

6Charité – Universitätsmedizin Berlin, Department of Pediatric Surgery, Berlin, Germany

7Development, Health and Disease Research Program, Department of Pediatrics, University of California Irvine, USA

8Center for Individual Development and Adaptive Education of Children at Risk (IDeA), Frankfurt, Germany

**Supplementary Materials**

# Supplementary Methods

## Stimuli selection and randomization

The semantic themes were grouped based on six overarching topics (e.g., nature, school, home, etc). Then four sets with 60 unique object-location associations each were created. In each set 30 semantic themes belonging to all six overarching topics were represented with two unique object-location associations. In this way, each set consisted of a balanced combination of semantic themes. One of these sets was randomly assigned to each participant. For each scene, we identified one out of the six possible previously defined placement areas as plausible for positioning the object into the scene. Within each placement area, objects could be placed in one of three possible locations, resulting in a total of 18 possible locations.

## Assessment of demographic and cognitive covariates

In addition to the experimental paradigm, a sleep diary to assess the quality and duration of sleep was completed daily for the 14-day period between learning and long-delay. Other cognitive covariate tasks were also assessed, such as cognitive switching and object-location memory with immediate test but were not included in the current paper

## Structural Data Processing

The brain mask estimated previously was refined with a custom variation of the method to reconcile ANTs-derived and FreeSurfer-derived segmentations of the cortical gray-matter of Mindboggle (Klein et al., 2017). All data sets were transformed and organized according to the BIDS standard (Gorgolewski et al., 2016) using BIDSify (<https://github.com/MartinBa9210/BIDSify>). One T1-weighted (T1w) images was used within the input BIDS datasets. The T1-weighted (T1w) image was corrected for intensity non-uniformity (INU) with N4BiasFieldCorrection (Tustison et al., 2010), distributed with ANTs 2.3.3 (Avants et al., 2008; RRID:SCR\_004757), and used as T1w-reference throughout the workflow. The T1w-reference was then skull-stripped with a Nipype implementation of the antsBrainExtraction.sh workflow (from ANTs), using OASIS30ANTs as target template. The brain mask estimated previously was refined with a custom variation of the method to reconcile ANTs-derived and FreeSurfer-derived segmentations of the cortical gray-matter of Mindboggle (RRID:SCR\_002438, Klein et al., 2017). Volume-based spatial normalization to two standard spaces (MNI152NLin2009cAsym, MNI152NLin6Asym) was performed through nonlinear registration with antsRegistration (ANTs 2.3.3), using brain-extracted versions of both T1w reference and the T1w template. The following templates were selected for spatial normalization: ICBM 152 Nonlinear Asymmetrical template version 2009c (Fonov et al., 2009; RRID:SCR\_008796; TemplateFlow ID: MNI152NLin2009cAsym), FSL’s MNI ICBM 152 non-linear 6th Generation Asymmetric Average Brain Stereotaxic Registration Model (Evans et al., 2012; RRID:SCR\_002823; TemplateFlow ID: MNI152NLin6Asym).

# Supplementary results

**Table S1.** *Descriptive statistics of IQ subscales as assessed by K-ABC II Test for preterm born and term born children.*

|  |  |  |  |
| --- | --- | --- | --- |
|  | Preterm born Children (PC; N = 15) | Term born Children (TC; N = 30) | PC vs. TC |
| ***IQ subscales*** | *M* | *SD* | *M* | *SD* | *p-value* |
| Simultaneous | 38.0 | 3.2 | 46.87 | 1.5 | \*\* |
| Sequential | 23.07 | 1.7 | 22.93 | .94 | ns |
| Learning | 23.93 | 1.6 | 23.73 | .02 | ns |
| Knowledge | 26.57 | 1.09 | 23.97 | .98 | ns |

*Notes.*  IQ = Intelligence Quotient based K-ABC (Kaufman & Kaufman, 2012) for term born and preterm born children. Simultaneous = processing scale of K-ABC for visual processing; Sequential = processing scale of K-ABC for short term memory; Learning = processing scale in K-ABC for long term storage and retrieval; Knowledge = scale in K-ABC for crystallised ability; PC = preterm born children; TC = term born children; N = number; M = mean; SD = standard deviation; ω2 = omega squared; \*p < .05; \*\* <.01, \*\*\*<.001 (significant difference); ns: non-significant difference.

**Table S2.** *Descriptive statistics of memory performance based on percentage of correct answers by age groups.*

|  |  |  |  |
| --- | --- | --- | --- |
| **Session** | Preterm born Children | Term born Children | Young Adults |
|  | *M* | *SD* | *M* | *SD* | *M* | *SD* |
| **Encoding** | .657 | .119 | .71 | .121 | .925 | .071 |
|  Day 0 |  |  |  |  |  |  |
| **Retrieval** |  |  |  |  |  |  |
|  Day 0 | .85 | .075 | .904 | .042 | .979 | .028 |
|  Day 1 | .76 | .125 | .818 | .123 | .936 | .071 |
|  Day 14 | .533 | .156 | .584 | .111 | .767 | .117 |

*Notes.*  M = mean; SD = standard deviation.

**Table S3.** *Statistical overview of the main and interaction effects of the linear mixed effects model with subjects as random intercept and the factors Group (term born children, preterm born children and young adults), Session (Day 0, Day 1, Day 14), IQ, Handedness, and Group x Session interaction on the memory retention rates.*

|  |  |
| --- | --- |
| **Factor** | **Memory Accuracy** |
| *F* statistic | *p*-value |
| Group | 44.32 | **<.0001** |
| Session | 269.53 | 0.35 |
| IQ | 4.28 | .042 |
| Sex | 1.19 | .28 |
| Handedness | .08 | .77 |
| Session x Group | 4.97 | **.0008** |

*Notes.* IQ = Intelligence Quotient based K-ABC (Kaufman & Kaufman, 2012) for term born and preterm born

children and WAIS-IV (Wechler, 2012) for young adults. Type III Analysis of Variance Table with Satterthwaite's

method. \*p < .05; \*\* <.01, \*\*\*<.001 (significant difference); ns: non-significant difference.

***Table S3a.*** *Detailed statistical overview of the main and interaction effects of the linear mixed effects models with subjects as random intercept and the factors Group (term born children, preterm born children and young adults), Session (Day 0, Day 1, Day 14), IQ, Sex, Handedness, and Group x Session interaction on the memory retention rates.*

|  |  |
| --- | --- |
|  | **Memory Accuracy** |
| *Predictors* | *Estimates* | *95% CI* | *p-value* |
| (Intercept) | .75 | .60 – .90 | **< .001** |
| PC vs TC | -.05 | -.11 – .01 | .08 |
| YA vs TC | .08 | .04 – .13 | **.001** |
| Short Delay | -.09 | -.12 – -.05 | **< .001** |
| Long Delay | -.32 | -.36 – -.28 | **< .001** |
| IQ\_new | .00 | .00 – .00 | **.04** |
| Sex | -.01 | -.02 – .01 | .28 |
| Handedness | .01 | -.06 – .07 | .78 |
| PC vs TC \* Short Delay | -.01 | -.07 – .06 | .88 |
| YA vs TC \* Short Delay | .04 | -.01 – .09 | .12 |
| PC vs TC \* Long Delay | .00 | -.06 – .07 | .93 |
| YA vs TC \* Long Delay | .11 | .06 – .16 | **< .001** |
| **Random Effect** |
| σ2 | .01 |
| τ00 subNo | .00 |
| ICC | .36 |
| N subNo | 78 |
| Observations | 234 |
| Marginal R2 / Conditional R2 | 0.697 / 0.806 |

*Notes.* IQ = Intelligence Quotient based K-ABC (Kaufman & Kaufman, 2012) for term born and preterm born

children and WAIS-IV (Wechler, 2012) for young adults. Type III Analysis of Variance Table with Satterthwaite's

method. CI = confidence intervals; PC = preterm born children; TC = term born children; YA = young adults;

\*p < .05; \*\* <.01, \*\*\*<.001 (significant difference); ns: non-significant difference.

**Table S4.** *Statistical overview of the main and interaction effects of the linear mixed effects model conducted separately for left and right hippocampal volume with subjects as random intercept and the factors Group (children and young adults), Session (Day 0, Day 1, Day 14), residualized hippocampal volume, Sex, and Group x Session x residualized hippocampal volume interaction on the memory retention rates.*

|  |  |  |
| --- | --- | --- |
| **Factor** | **Residualized Left HC volume** | **Residualized Right HC volume** |
| *F* statistic | *p*-value | *F* statistic | *p*-value |
| Session | 266.12 | **<.0001** | 271.76 | **<.0001** |
| HC | .89 | 0.35 | 5.98 |  **.016** |
| Group | 70.02 | **<.0001** | 76.40 | **<.0001** |
| Sex | .96 | .33 | .48 | .49 |
| Session x HC | .33 | .72 | 2.04 | .13 |
| Session x Group | 10.17 | **<.0001** | 10.39 | **<.0001** |
| HC x Group | .86 | .36 | 6.01 | **.016** |
| Session x HC x Group | 1.08 | .34 | 1.96 | .14 |

*Notes.* Type III Analysis of Variance Table with Satterthwaite's method. HC = hippocampal volume;

\*p < .05; \*\* <.01, \*\*\*<.001 (significant difference); ns: non-significant difference.

**Table S5.** *Statistical overview of the main and interaction effects of the linear mixed effects model conducted separately for left and right medial orbitofrontal cortical thickness with subjects as random intercept and the factors Group (children and young adults), Session (Day 0, Day 1, Day 14), medial orbitofrontal cortical thickness, Sex, and Group x Session x medial orbitofrontal cortical thickness interaction on the memory retention rates.*

|  |  |  |
| --- | --- | --- |
| **Factor** | **Left mOFC** | **Right mOFC** |
| *F* statistic | *p*-value | *F* statistic | *p*-value |
| Session | 267.48 | **<.0001** | 267.74 | **<.0001** |
| mOFC | .88 | 0.35 | 4.10 |  **.046** |
| Group | 73.55 | **<.0001** | 77.10 | **<.0001** |
| Sex | .48 | .49 | 1.44 | .23 |
| Session x mOFC | .34 | .71 | 1.16 | .31 |
| Session x Group | 10.22 | **<.0001** | 10.23 | **<.0001** |
| mOFC x Group | 1.64 | .20 | 3.21 | .076 |
| Session x mOFC x Group | 1.49 | .22 | .29 | .74 |

*Notes.* Type III Analysis of Variance Table with Satterthwaite's method. mOFC = medial orbitofrontal cortical thickness; \*p < .05; \*\* <.01, \*\*\*<.001 (significant difference); ns: non-significant difference.

**Table S6.** *Statistical overview of the main and interaction effects of the linear mixed effects models conducted separately for left and right inferior frontal gyrus (i.e., parsopercularis and parstriangularis) cortical thickness with subjects as random intercept and the factors Group (children and young adults), Session (Day 0, Day 1, Day 14), inferior frontal gyrus cortical thickness, Sex, and Group x Session x inferior frontal gyrus cortical thickness interaction on the memory retention rates.*

|  |  |  |
| --- | --- | --- |
| **Factor** | **Left IFG** | **Right IFG** |
| *F* statistic | *p*-value | *F* statistic | *p*-value |
| Session | 267.87 | **<.0001** | 267.45 | **<.0001** |
| IFG | 1.71 | .19 | .51 |  .47 |
| Group | 71.31 | **<.0001** | 69.44 | **<.0001** |
| Sex | .84 | .36 | .91 | .34 |
| Session x IFG | .39 | .67 | .35 | .70 |
| Session x Group | 10.24 | **<.0001** | 10.22 | **<.0001** |
| IFG x Group | .86 | .35 | .002 | .96 |
| Session x IFG x Group | 1.25 | .29 | 1.07 | .35 |

*Notes.* Type III Analysis of Variance Table with Satterthwaite's method. IFG = *inferior frontal gyrus (i.e.,*

*parsopercularis and parstriangularis) cortical thickness;* \*p < .05; \*\* <.01, \*\*\*<.001 (significant difference); ns:

non-significant difference.

**Table S7.** *Statistical overview of the main and interaction effects of the regression model conducted for left and right \*structural brain measures with the factors Group (children and young adults), and \*structural brain measure, and Group x \*structural brain measure interaction on the final learning performance on Day 0. \*Structural brain measures were: residualized hippocampal volumes, medial orbitofrontal cortical thickness and inferior frontal gyrus cortical thickness.*

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Factor** |  | **Left residualized HC** |  | **Right residualized HC** |
|  | **Final Learning Accuracy** |
| *F statistic* | *p*-value | F statistic | *p*-value |
| Group | 87.34 | **<.001** | 73.74 | **<.001** |
| HC | .00 | .92 | 1.28 | **.26** |
| Group x HC | .08 | .77 | 2.80 | 0.098 |
| R2 / R2 adjusted |  .505 / .484 | .523 / .503 |
|  |  | **Left mOFC** |  | **Right mOFC** |
| Group | 81.36 | **<.001** | 77.29 | **<.001** |
| mOFC | 9.30 | **.003** | 3.44 | **.06** |
| Sex | .34 | .55 | .06 | .80 |
| Group x mOFC | 3.20 | .078 | 5.19 | **.026** |
| R2 / R2 adjusted |  .574 / .549 | .551 / .526 |
|  |  | **Left IFG** |  | **Right IFG** |
| Group | 69.80 | **<.001** | 68.94 | **<.001** |
| IFG | .83 | .36 | .06 | .79 |
| Sex | .24 | .62 | .12 | .72 |
| Group x IFG | .01 | .90 | .01 | .91 |
| R2 / R2 adjusted | .503 / .475 | .497 / .468 |

*Notes.* CI = confidence interval; HC = hippocampal volume; mOFC = medial orbitofrontal cortical thickness; IFG = inferior frontal gyrus cortical thickness; \*p < .05; \*\* <.01, \*\*\*<.001 (significant difference);

ns: non-significant difference.

# References

Avants, B., Epstein, C., Grossman, M., & Gee, J. (2008). Symmetric diffeomorphic image registration with cross-correlation: Evaluating automated labeling of elderly and neurodegenerative brain. *Medical Image Analysis*, *12*(1), 26–41. https://doi.org/10.1016/j.media.2007.06.004

Evans, A. C., Janke, A. L., Collins, D. L., & Baillet, S. (2012). Brain templates and atlases. *NeuroImage*, *62*(2), 911–922. https://doi.org/10.1016/j.neuroimage.2012.01.024

Fonov, V., Evans, A., McKinstry, R., Almli, C., & Collins, D. (2009). Unbiased nonlinear average age-appropriate brain templates from birth to adulthood. *NeuroImage*, *47*, S102. https://doi.org/10.1016/S1053-8119(09)70884-5

Gorgolewski, K. J., Auer, T., Calhoun, V. D., Craddock, R. C., Das, S., Duff, E. P., Flandin, G., Ghosh, S. S., Glatard, T., Halchenko, Y. O., Handwerker, D. A., Hanke, M., Keator, D., Li, X., Michael, Z., Maumet, C., Nichols, B. N., Nichols, T. E., Pellman, J., … Poldrack, R. A. (2016). The brain imaging data structure, a format for organizing and describing outputs of neuroimaging experiments. *Scientific Data*, *3*(1), 160044. https://doi.org/10.1038/sdata.2016.44

Klein, A., Ghosh, S. S., Bao, F. S., Giard, J., Häme, Y., Stavsky, E., Lee, N., Rossa, B., Reuter, M., Chaibub Neto, E., & Keshavan, A. (2017). Mindboggling morphometry of human brains. *PLOS Computational Biology*, *13*(2), e1005350. https://doi.org/10.1371/journal.pcbi.1005350

Tustison, N. J., Avants, B. B., Cook, P. A., Yuanjie Zheng, Egan, A., Yushkevich, P. A., & Gee, J. C. (2010). N4ITK: Improved N3 Bias Correction. *IEEE Transactions on Medical Imaging*, *29*(6), 1310–1320. https://doi.org/10.1109/TMI.2010.2046908