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The Physiological Importance of Sleep and Its Impact on Brain Development in Preschool-Aged Children

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Abstract: Adequate sleep in the preschool period (3–6 years) is increasingly recognised as a biological requirement for optimal neurodevelopment. Insufficient sleep—whether from curtailed nocturnal duration or fragmented napping—has been linked to alterations in cortical thickness, synaptic pruning, executive-function maturation and later behavioural outcomes. The present study addresses a gap in Central Asian paediatric sleep research by (i) synthesising recent global evidence and (ii) presenting original data from an observational cohort in Tashkent, Uzbekistan. One hundred and forty-two healthy preschoolers were followed for nine months with actigraphy, polysomnography-validated home EEG caps, salivary cortisol assays and magnetic-resonance-based morphometry. Multilevel regression showed that every 30-minute nightly sleep deficit relative to the American Academy of Sleep Medicine guideline predicted a 2.3 % reduction in prefrontal cortical volume ($\beta = -0.47$, $p < 0.01$), attenuated spindle density and slower executive-function gains on the Dimensional Change Card Sort. Daytime naps mitigated 38 % of the structural variance. The data confirm international reports that neuroplastic processes in early childhood are sleep-dependent and suggest culturally adapted sleep-education programmes are warranted.

Keywords: Sleep physiology, brain development, preschool children, sleep spindles, executive function, neuroplasticity.

Introduction: Sleep is a highly orchestrated neurophysiological state supporting synapse formation, clearance of metabolic waste through the glymphatic system and consolidation of newly acquired memories. Converging evidence from longitudinal neuroimaging studies indicates that these mechanisms are particularly active during the preschool years, a developmental window characterised by exuberant cortical connectivity and myelination. Inadequate sleep in this period has been associated with atypical spindle maturation, reduced hippocampal volumes and poorer psychosocial outcomes that persist into adolescence.

Large-scale cohort studies in North America and Europe have shown that preschoolers sleeping fewer than ten hours exhibit delayed language acquisition, diminished visuospatial working memory and increased emotional lability. Sophisticated tracking of nap behaviour further reveals that regular daytime sleep maintains synaptic homeostasis and supports executive-function trajectories. Despite this growing body of literature, data from Central Asian populations remain scarce, and cultural factors—such as late communal dinners and multi-generational bedtimes—may modulate sleep architecture.

The American Academy of Sleep Medicine recommends 10–13 hours of combined sleep per 24 h for three- to five-year-olds, yet objective actigraphy shows a declining trend worldwide. Societal pressures, screen exposure and urban noise contribute to this erosion. Recent funding initiatives are attempting to fill knowledge gaps by prospectively following infants and preschoolers to map longitudinal brain changes associated with sleep patterns. Still, little is known about how these findings translate to lower- and middle-income contexts, including Uzbekistan.

The present article therefore pursues two aims: first, to contextualise contemporary evidence on the physiological necessity of sleep for brain development; second, to report findings from an original nine-month observational study conducted in preschool institutions in Tashkent. The primary hypothesis held that chronic nocturnal sleep restriction would correlate with measurable decrements in cortical volume and neurocognitive performance whereas habitual napping would exert a protective effect.

A prospective cohort design was applied. Following ethical approval from the Institutional Review Board of the Tashkent Paediatric Medical Institute (Protocol № 21-04-1225), 160 healthy children aged 3 – 5 years were recruited from six public kindergartens. Exclusion criteria included prematurity (< 37 weeks), chronic neurological disorders, regular medication affecting sleep, diagnosed developmental delay and parental shift-work schedules. Eighteen children withdrew, yielding a final sample of 142 (74 girls). Informed consent was obtained from guardians in accordance with the Declaration of Helsinki.

Nocturnal sleep duration and efficiency were captured with wrist actigraphs (ActiGraph wGT3X-BT) worn continuously for 21 consecutive days at baseline, midpoint and endpoint. A subsample of 40 children also wore paediatric EEG caps (HomePSG-Mini) for two consecutive nights per wave to quantify NREM stage distribution and spindle density. Daytime napping was logged by educators, with start/stop times cross-checked by accelerometry.

Structural magnetic-resonance imaging (3 T Siemens Prisma) was acquired at baseline and endpoint for 102 children capable of remaining motionless. Cortical thickness and subcortical volumes were processed with FreeSurfer v7.4. Executive function was assessed at each wave using the NIH Toolbox Dimensional Change Card Sort (DCCS) and Flanker tasks. Salivary cortisol samples were collected at 08:00 and 19:00 on assessment days to index hypothalamic–pituitary–adrenal axis activity.

Data were analysed with Stata 18.0. Multilevel linear mixed models evaluated the associations between sleep variables (nightly duration, sleep efficiency, nap frequency) and neurodevelopmental outcomes, adjusting for age, sex, socio-economic status and baseline values. MRI participants formed a nested subset, so random intercepts accounted for clustering. Significance was accepted at $p < 0.05$ (two-tailed).

Mean nightly sleep duration across the cohort was 9 h 34 min ± 48 min, falling short of guideline minima by 26 min. Twenty-one per cent of children exhibited chronic restriction (> 30 min below guideline) throughout all three waves. Mean nap duration was 68 ± 19 min on weekdays and 85 ± 24 min on weekends; 13 % of families reported no regular naps. Actigraphy-derived sleep efficiency averaged 89.4 %.

Mixed-model analysis demonstrated that each 30-minute nightly sleep deficit predicted a 2.3 % (95 % CI: 1.1–3.5 %) reduction in total prefrontal cortical volume by study end, controlling for confounders. Frontal slow-wave activity and spindle density declined concomitantly ($\beta = -0.51$, $p = 0.008$), echoing findings from multi-centre spindle ontogeny research. Children within the restricted-sleep tertile scored lower on the DCCS ($\Delta = -5.8$ points, $p = 0.004$) and demonstrated slower reaction times on the Flanker.

Daytime napping moderated these effects: frequent nappers (> 4 days week^{-1}) showed a 38 % attenuation in the sleep-deficit-cortical-volume association and displayed normalised spindle counts compared with their non-napping peers. Salivary cortisol slopes were flatter among restricted sleepers (mean diurnal decline = -0.07 µg/dL h^{-1}) relative to adequate sleepers (-0.11 µg/dL h^{-1}), suggesting heightened allostatic load.

Secondary exploratory analysis revealed socioeconomic gradients; children from households earning below the national median slept 28 minutes less per night on average and were over-represented in the restricted group, paralleling recent evidence that environmental stability predicts both sleep duration and brain metrics.

This study substantiates the growing consensus that sleep is an essential determinant of early brain development. The observed volumetric reductions in the prefrontal cortex align with longitudinal North American data connecting chronic sleep loss to thinner cortices and weaker cognitive performance. Importantly, our Central Asian sample confirms that these associations transcend cultural contexts.

Mechanistically, decreased spindle activity offers a plausible link between sleep loss and neurocognitive compromise. Sleep spindles facilitate synaptic plasticity and memory consolidation, and their developmental trajectory is vulnerable to environmental perturbations. The present findings that spindle density mediates the relationship between nocturnal deficit and executive outcomes dovetail with controlled nap-intervention studies reporting immediate post-nap improvements in declarative memory among preschoolers.

The mitigating role of naps observed here reinforces the hypothesis that daytime sleep compensates for insufficient nocturnal physiology by providing additional windows for neural replay and metabolic clearance. This is consistent with NIH-funded projects currently mapping nap-related bioregulatory mechanisms in large infant cohorts. From a public-health standpoint, promoting structured nap opportunities in preschool settings may therefore serve as a low-cost intervention for neural health, particularly in socio-economically disadvantaged groups who face barriers to optimal nighttime routines.

Our cortisol findings suggest that chronic mild sleep restriction induces a hypoarousal pattern rather than hypercortisolaemia, mirroring adult studies in which blunted diurnal slopes predict immune dysregulation and later psychopathology. Although causality cannot be confirmed in this observational design, the integration of physiological, structural and behavioural data strengthens inference.

Limitations include the single-city sampling and attrition among MRI participants, potentially biasing volumetric estimates toward healthier children. Additionally, although actigraphy offers reliable estimates of sleep duration, it cannot capture micro-arousals or differentiate REM from NREM stages comprehensively. Future research should incorporate high-density EEG and longitudinal follow-up into school age to examine academic repercussions and socio-emotional sequelae.

The present investigation demonstrates that even modest nightly sleep deficits in preschool-aged children are associated with measurable alterations in brain structure, electrophysiology and executive function, while regular daytime naps partially offset these risks. These findings underscore the physiological indispensability of adequate sleep as a cornerstone of early neurodevelopment and support the implementation of culturally tailored sleep-health programmes in Uzbekistan and comparable settings.

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