Sleep Inspires Insight: a Preregistered Study

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Abstract

Humans sometimes have insights, which is expressed in a sudden and drastic performance improvement on the task they are working on. While the origins of insights are unknown, previous work has suggested that insights require a form of memory restructuring that often occurs during sleep. In addition, computational work has suggested that neural variability could increase the likelihood of an insight. Although previous work has investigated sleep as a potentially enhancing factor of insights, the evidence for this idea has so far been mixed. One reason for this unclear picture could be that different sleep stages have differential effects on insights. To investigate the link of different sleep stages and variability to insight, we conducted a preregistered study in which N = 90 participants performed an insight task before and after a 20 minute daytime nap. We find that N2 sleep, but not N1 sleep increases the likelihood of insight moments after the nap, suggesting the need for deeper sleep in order to gain insight. Further, analyses of EEG power spectra showed that 1/f slopes could predict insight above and beyond sleep stages. Our findings thus point towards a role of N2 sleep and aperiodic, but not oscillatory, neural activity for insight.

Keywords: Insight; Sleep; Learning; Aperiodic neural activity

Introduction

Insights, or aha-moments, describe a discrete learning mechanism (Stuyck, Aben, Cleeremans, & Van den Bussche, 2021; Weisberg, 2015) that evokes non-linear improvements in task performance or problem solving (Köhler, 1925; Durstewitz, Vittoz, Floresco, & Seamans, 2010). Insight behaviour can be defined based on three characteristics: an abrupt, non-linear increase in task performance; a variable delay before the insight occurs 'spontaneously' (Ohlsson, 1992) and a selectivity of the improvement, which typically happens in some, but not in all participants (Schuck et al., 2015; Löwe et al., 2023). While it is undisputed that insights usually have above mentioned characteristics, it is not fully understood which factors trigger insights.

One such potential factor is sleep. Sleep has been shown to consolidate and further, restructure existing task representations, deeming it to be a possible candidate for the incubation of insight (Cowan et al., 2020). The evidence for sleep supporting insight, however, is inconclusive, and particular uncertainty surrounds the question which effect different sleep stages may have. Work by Wagner et al. (Wagner, Gais, Haider, Verleger, & Born, 2004) suggests a beneficial effect of a night's sleep on insight, finding more than twice as many subjects gaining insight into a hidden task rule after sleep compared to wakefulness. Contrary, other studies did not find any benefits of sleep on insight, or no difference between sleep and awake rest (Cordi & Rasch, 2021; Schönauer et al., 2018; Brodt, Pöhlchen, Täumer, Gais, & Schönauer, 2018). In a study in which participants performed an insight task before and after a daytime nap, Lacaux et al. recently reported an effect of the light sleep stage N1 on insight, while no effect was found for the deeper sleep stage N2 (Lacaux et al., 2021).

To follow up on this finding, we preregistered a conceptual replication study, using a different task but otherwise identical procedures (pregregistration link: https://osf.io/z5rxg/resources). This allowed us to test whether N1 sleep compared to wakefulness or N2 sleep after task exposure would lead to a higher number of insights during a post-nap behavioural measurement. Our own computational work (Löwe et al., 2023) has suggested that neural variability or noise can have beneficial effects for insights. Hence, we also asked which neural variability-related aspects of the EEG signal might have additional effects on insight besides sleep.

Results

To study the effect of different sleep stages on insight, 90 participants performed a previously developed perceptual decision task (Löwe et al., 2023) intermitted by a nap period. Subjects were presented with dots that were characterised by two features (1) colour (orange or purple) and (2) motion direction (four possible orthogonal directions: NW, NE, SW, SE). Dot motion had a varying degree of noise across trials (5%, 23%, 41%, 59% or 76% coherent motion), making motion judgement relatively harder or easier. Participants were provided with two buttons and instructed at the start of the experiment that only one button was correct for each trial, which they could learn from trial-wise binary feedback. While only motion direction was related to the correct response for the first 3 blocks, stimulus colour began predicting the correct button in the middle of the 4th block (Fig 1A, grey blocks). This unannounced change in task structure provided a hidden opportunity to improve the decision strategy that could be discovered through insight (Schuck et al., 2015).

After block 4, participants were given a 20-minute opportunity to nap in a reclining arm chair. To monitor brain activity and sleep, a 64-channel electroencephalography (EEG) was recorded during this period. After the nap, participants completed 5 more blocks during which insight about the colour strategy was measured (Fig. 1A) by assessing behaviour in trials with the highest amount of motion noise, where high accuracy could only be achieved by using the colour information.

To identify different sleep stages during the nap period, sleep was scored according to the guidelines from the American Academy of Sleep Medicine (Berry et al., 2016) based on 30 sec EEG (O2, O1, Pz, Cz, C3, C4, F3 and F4), EOG and EMG epochs. Using these criteria, participants were categorised as having had either no sleep, N1 sleep, or N2 sleep.

Insight-like Strategy Switches

Because 15 subjects had an insight before the nap, and in 7 cases EEG data quality prevented sleep classification, we analysed the post nap data of 68 subjects. 70.6% (48/68) of participants showed abrupt, non-linear performance improvements and were thus classified as "insight participants", following previous work (Löwe et al., 2023). This percentage is larger than our “baseline” of 48.5% (48/99) insight which we observed in our previous study without a nap period (Löwe et al., 2023), suggesting a potential effect of the sleep modification ($p = .007$, Fisher’s exact test). While the frequency of insight was increased, insights had the same characteristics we observed before, occurring with a highly variable delay across subjects and non-linearly increasing accuracy around each participant’s individually identified switch point ($M = 62.4 \pm 16.9\%$ vs $M = 87.6 \pm 15.1\%$ $t(92.8) = -11.16$, $p < .001$).

No Evidence For N1 but for N2 Sleep Promoting Insight

28 subjects reached N2 sleep during the 20-minute nap period, 22 were classified as N1 sleep and the remaining 18 subjects as Wake. Of those sleep groups, 85.7% (24/28) of the N2 group gained insight into the hidden strategy, while only 63.6% (14/22) of the N1 and 55.5% (10/18) of the Wake group gained this insight (Fig. 1B). Based on the paper by Lacaux et al. (Lacaux et al., 2021), our first preregistered hypothesis proposed that N1 sleep would lead to an increased number of insight compared to the Wake and N2 sleep groups, respectively. We find no support for either the first (Fisher’s exact test N1 vs. Wake: $p = 0.75$) or second (Fisher’s exact test N1 vs. N2: $p = 0.1$) hypothesis. Interestingly, we observed a significantly higher number of insight after N2 sleep compared to Wake (Fisher’s exact test, $p = 0.038$). In line with these analyses, we find that a generalised linear model (GLM) with sleep as a predictor fits the data better than a model with just a random effect (AIC 82.5 vs. 84.4). Post-hoc tests showed a significant N2 sleep coefficient in this model ($p = 0.03$), while N1 sleep and Wake remain non significant (Wake: $p = 0.64$, N1: $p = 0.6$). We thus find no evidence for N1, but for N2 sleep promoting insight.

Aperiodic Neural Activity Predicts Insight

To test for physiological predictors of insight going beyond sleep stages, we extracted power and the 1/f slope as proxies for oscillatory and aperiodic activity, respectively. In a data driven fashion, we compared 1/f-corrected power spectra (1-20Hz, 0.2Hz frequency resolution, 50% overlap) between Wake, N1 and N2. As expected, oscillatory power in the alpha (7-10Hz) and sleep spindle frequency range (11-16Hz) significantly differed between sleep stages (post-hoc cluster-based permutation test, t-statistics, Wake > N2: positive cluster, $p = 0.025$ over central areas, 7-10Hz; negative cluster, $p = 0.052$ over fronto-central areas, 11-16Hz). But neither power in the alpha nor in the spindle frequency range predicted insight beyond sleep stages (nested model comparison; AIC for both models > 82.5 AIC found for the model containing only sleep stages).

We then estimated the 1/f slope (FOOOF algorithm (Donoghue et al., 2020), 1-30Hz, 0.2Hz frequency resolution, 50% overlap) and compared it between Wake, N1 and N2 (across the whole nap period). Again, as expected, the 1/f slope became significantly steeper from Wake to N2 (cluster-based permutation test, F-statistics, positive cluster, $p = 0.001$). To ask whether 1/f slopes explained insights above and beyond sleep stages, we again compared a baseline model in which insight was predicted from sleep stage, to a model of interest which included the 1/f slope (averaged across all significant channels obtained from the cluster-based permutation test) as an additional predictor. 1/f slopes indeed explained additional variance in insights (AIC: 81.15 vs. 82.5): the steeper the slope, the higher the insight likelihood ($\beta = 2.02$). When comparing both models channel-wise, we observe a decrease in AIC score (i.e., better fit of the model including both, sleep and slope as predictors) over frontal-central areas (Fig. 1C).

Conclusion

We investigated the effect of sleep on insight. In our preregistered study we set out to conceptually replicate findings of Lacaux et al. (Lacaux et al., 2021) that suggested a beneficial effect of N1 sleep on insight. We find no evidence for an effect of N1 sleep: the insight ratio of N1 subjects did not differ from subjects of the Wake group. However, we do find a beneficial effect of N2 sleep on post-nap insight likelihood, suggesting a need for deeper sleep for insight. An exploratory analysis showed that the 1/f slope of the power spectrum did explain additional variance in insight probability above and beyond sleep stages. In contrast, neither power in the alpha nor in the spindle frequency range could predict insight. Hence, aperiodic but not oscillatory neural activity emerged as an additional factor that promotes insight.

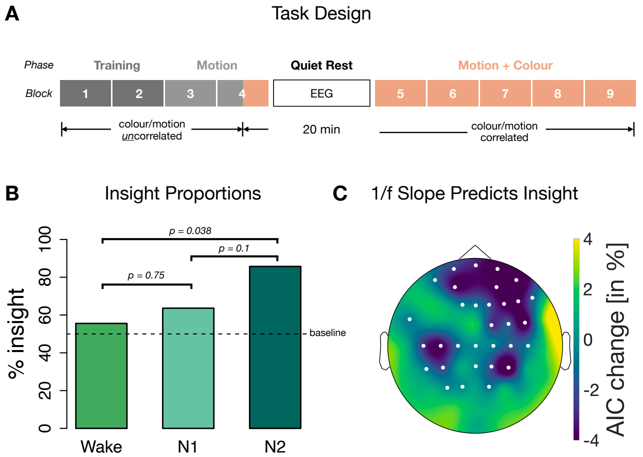

Figure 1: **A:** Insight task design of the perceptual decision making task including a nap period. Initially randomly changing stimulus colour becomes predictive of correct choices before the nap in block 4 and allows for easier solving of the task. This unannounced hidden strategy can only be discovered through insight. **B:** Proportions of insight about the hidden strategy (Wake: 55.5%, N1: 63.6%, N2: 85.7%, $N = 68$). **C:** AIC change from model containing sleep as the sole predictor (AIC set to 100%) to the model containing sleep and the 1/f slope as predictors. White dots = AIC becomes smaller.

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