Does Oral Breathing Disrupt Memory Consolidation During Waking Rest? A Registered Report

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Authors

Bethanie Richards https://orcid.org/0000-0002-7332-0393 B.Richards@hull.ac.uk

Henning Holle https://orcid.org/0000-0003-2455-1053 H.Holle@hull.ac.uk

Shane Lindsay https://orcid.org/0000-0002-0068-3468 S.Lindsay@hull.ac.uk

School of Psychology and Social Work, University of Hull, England, UK

Corresponding Author

Bethanie Richards

School of Psychology and Social Work

University of Hull, Cottingham Road, Hull, HU6 7RX

Email: B.Richards@hull.ac.uk

Bethanie Richards.

School of Psychology and Social Work, University of Hull,

Cottingham Road,

HU6 7RX

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Abstract

Studies of waking rest, whereby passive rest is compared with an active task, have shown a benefit for declarative memory during short waking rest periods, which has been argued to result from the active task disrupting slow oscillations that occur during rest. Arshamian et al. (2018) found that nasal breathing while resting for an hour led to an advantage for olfactory memory consolidation compared with oral breathing, which has been also argued to result from the disruption of slow oscillations during oral breathing. In the present pre-registered research, we looked to see whether this oral breathing disruption extended to impair declarative memory consolidation, and if it is modulated by the presence of an active task. We used a 2 x 2 within-participants counterbalanced design, of two sessions separated by a week where participants breathed either orally (induced by a nose clip) or nasally (induced through tape over the mouth). Each session involved learning two sets of pseudowords followed by either waking rest or an active task (N-back) for 15 minutes during the breathing manipulation. Memory performance was assessed by a recognition task. Our results show that the nasal advantage did not generalise to pseudowords, nor were we able to replicate the waking rest advantage or show an interaction between these factors. This study contributes to a growing body of evidence that challenges the consistency of the waking rest advantage and highlights the need for further exploration of the influence of breathing pathway on memory processes.

Keywords: breathing, respiration, consolidation, waking rest, oral breathing, nasal, memory, recognition memory

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With current lifestyles having an increasing demand on attention, periods of passive waking rest seem to be increasingly rare. While sometimes lamented as a waste of time, these periods of rest, characterised by less responsiveness to external distractions and the immediate environment, can allow for a range of benefits beyond that of mere rest. During resting states, parasympathetic activity dominates, reducing cardiac and respiratory rates, and facilitating the activation of the default mode network in the brain (see Raichle, 2015 for a review). This state features mind wandering and promotes the introspective processing of current and recent events. Recent research suggests this passive waking rest state, with the relative absence of the need to encode new information, is a preferential neurological state for the consolidation of new memories, allowing their stabilisation, strengthening and integration into long term memory networks (see for review Wamsley, 2019).

In a landmark study showing the benefits of waking rest on declarative memory performance, Dewar et al. (2012) presented participants with a story followed by either a 10-minute period of waking rest or an active task (spot-the-difference). Retention scores of story units were significantly higher following waking rest. Further studies have since shown the effects of waking rest on a variety of memory systems and processes, including enhanced performance in declarative (e.g., Brokaw et al., 2016; Martini et al., 2020; Mercer, 2015) and procedural memory tasks (Humiston & Wamsley, 2018; Wang et al., 2021), along with waking rest benefiting the processing of spatial and temporal memories (Craig et al., 2016), facilitating insight into complex problems (Craig et al., 2018), and enhancing auditory statistical learning (Gottselig et al., 2004).

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It could be argued that the active task in the waking rest paradigm could prevent explicit rehearsal, and therefore cause the waking rest effect. Dewar et al. (2012) argued against rehearsal as a mechanism for the waking rest advantage, as participants reported a lack of awareness of the memory requirement following a surprise recall test at the end of the study. Rehearsal has also been argued against by showing the waking rest effect still occurs where stimuli are non-rehearsable pseudowords (Dewar et al., 2014). Furthermore, Dewar et al. countered the idea that retrieval competition from stimuli processed during the active task is a potential explanation by employing a distractor task. Before the recall stage, all participants completed another task (spot-the-difference) that was the same as the active task, and therefore if retrieval competition explained why waking rest helped memory, it should have affected both conditions.

While there are several potential mechanisms that might help contribute to the waking rest advantage, such as temporal distinctiveness theory (Ecker et al., 2015), the most common argument has been that the waking rest effect primarily results from consolidation processes that occur during the waking rest state, which are disrupted during an active task (e.g., Brokaw et al., 2016; Dewar et al., 2012; Craig et al., 2018; Humiston et al., 2019; Wang et al., 2021). The consolidation account of the waking rest advantage follows the consolidation account of sleep-associated memory advantages, where similar active neurophysiological mechanisms that allow memory advantages following sleep (for reviews, see Diekelmann, Wilhelm & Born, 2009; Walker & Stickgold, 2004) may also occur in waking rest (Dastgheib et al., 2022; Dringenberg, 2019). This account differs from a more "passive" account where rest and sleep merely offers protection from forgetting caused by retroactive interference during wakefulness, without any active changes to memory traces as theorised by consolidation theories.

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In the dominant two-stage model of active declarative memory consolidation, new memories are thought to be initially reliant on storage through hippocampally dependent episodic memory systems in the Medial Temporal Lobes (Born & Wilhelm, 2012). During sleep, these engrams are reactivated, allowing stabilization, strengthening and integration of new memories into long term memory networks in the neocortex. Slow Wave Sleep (SWS) is thought to be crucial to this process, where the slow oscillations seen in SWS help to coordinate cortico-hippocampal communication allowing coordinated reactivation to occur (Wilson & McNaughton, 1994; Ji & Wilson, 2007). This reactivation is consistent with cross-frequency coupling observed in the hippocampus and cortex during sharp wave ripples (SWRs) seen in sleep (Siapas & Wilson, 1998, Sirota et al., 2003, Wierzynski et al., 2009), and the coordination of hippocampal and cortical sequences (Ji & Wilson, 2007).

Supporting an active account of consolidation during waking rest, similar reactivation processes underlying memory consolidation have been shown to occur in the waking state in rodents and in humans. For example, Karlsson and Frank (2009) showed that reactivation of place cells in the hippocampus during waking rest was related to subsequent spatial memory performance in rats, and Kudrimoti et al. (1999) found that cortical neurons in rats reactivated during a post-learning nap and that this reactivation correlated with memory retention. Similarly, evidence from fMRI studies shows reactivation processes in humans during waking rest. Hermans et al. (2017) found that resting-state functional connectivity in the hippocampus was associated with memory performance, and Tambini and Davachi (2013, 2019) showed that increased hippocampal activity during wakeful rest predicted better memory performance in subsequent memory tests. Similar effects have been found for spatial (Craig et al., 2016) and emotional memories (de Voogd et al., 2016). While memory reactivation processes take place during rest, the brain's responsiveness to external stimuli decreases, and endogenous processing becomes more dominant. In recent years, studies have

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suggested that endogenous rhythmic states may play a significant role in regulating brain dynamics, especially during restful states.

Of particular interest here is the role of respiration in influencing large-scale brain activity. It is well established that respiratory rhythms can entrain brain areas involved in olfaction. Work with animals has shown that during inhalation, airflow via the nasal passageway activates mammalian receptors of the olfactory sensory neurons generating a respiratory phase-locked rhythmic signal propagating to the olfactory bulb and onto the olfactory cortex (Adrian, 1942; Fontanini et al., 2003). However, a striking recent finding is that respiration can orchestrate activity outside of olfactory areas, where respiratory phase-locked oscillations in the olfactory bulb can propagate and drive respiration-locked oscillations in other brain areas, including memory associated networks such as the prefrontal cortex and hippocampus (for reviews see Heck et al., 2017 & Tort et al., 2018).

In particular, nasal breathing has been shown to synchronise SWRs generated in the hippocampus in awake mice (Liu et al., 2017). As discussed above, SWRs are thought to be critical for declarative memory consolidation as seen in both sleep and wakeful rest (Jadhav et al., 2012; Zielinski et al., 2020). Given that slow oscillatory activity in waking rest appears to be linked with enhanced memory consolidation and that the respiratory cycle can modulate these oscillations (Karalis & Sirota, 2022) along with SWRs (Liu et al., 2017), one intriguing possibility is that respiration, and especially nasal respiration, may influence memory processing during waking rest in humans and help inform our understanding of the nature of active memory consolidation mechanisms during this state.

Following on from work done in rodents, neuronal entrainment of breathing has also been demonstrated in humans. Zelano et al. (2016) used intracranial EEG with patients with medically refractory epilepsy and found that respiratory entrainment was significantly

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stronger during inhalation compared with exhalation. Following observing respiratory synchrony in oscillatory power and breathing phase, Zelano et al. (2016) examined the interaction between breathing pathways. Breathing pathway was experimentally manipulated with airflow directed to the oral passageway by using a nasal clip obstructing airflow via the nose or to the nasal passageway using tape to cover the mouth. Zelano et al. found nasal breathing during inhalation led to significantly higher levels of synchronous oscillatory activity compared with oral breathing, with phase locked oscillations synchronized in the PC, amygdala and hippocampus.

The distinct reduction of respiration-locked synchronous oscillations during oral respiration could suggest impairment of cross-cortex communication, and consequently could lead to impaired behavioural performance in tasks that draw upon the piriform cortex and limbic networks including the hippocampus. Testing this prediction, Zelano et al. found significantly better recognition memory performance for pictures that were presented when participants were breathing nasally, as compared to orally. Nasal breathing was found to affect both the encoding as well as the retrieval stage. While Zelano et al. found nasal breathing enhanced memory processing during encoding and retrieval compared with oral breathing, Arshamian et al. (2018) extended this finding by testing if respiratory entrainment would influence consolidation processes during waking rest. They used a recognition memory paradigm where familiar and unfamiliar odours were initially encoded followed by a within-subjects consolidation period of oral or nasal breathing, prior to a recognition task. As in the previous study by Zelano et al., tape and a nasal clip were used to redirect airflow. Participants experienced a 1-hour awake rest period. While longer than the intervals typically used in the waking rest studies described above (e.g., 10 minutes in Dewar et al., 2014), the conditions were very similar, with participants seated facing a blank wall and told to not stand-up, sleep, talk or read during the resting consolidation phase, with compliance

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monitored by an experimenter. Arshamian et al. found that nasal breathing during this rest period resulted in significantly better odour recognition accuracy at the subsequent test compared to breathing through the mouth, with no effect of familiarity.

Arshamian et al.'s findings support the suggestion that nasal respiration-entrained infraslow oscillations in cortical structures support memory consolidation by enabling cross-cortex communication of critical memory networks, and that these oscillations are disrupted during oral breathing. They speculated that a potential cause for their findings was that oral breathing reduced the probability of SWRs, and hence disrupted their role in supporting memory reactivation during waking rest (Liu et al., 2017). Arshamian et al. suggested that the nasal effect may not be limited to olfactory memory, especially given they found no odour familiarity effect, and could potentially generalise to hippocampal-dependent consolidation of items across other modalities than olfaction. However, given that the motor activity of sniffing is critical for imagery ability (Bensafi et al., 2003), an alternative explanation could be that the oral condition disrupted the ability to rehearse odour stimuli. Consequently, showing that the nasal breathing memory advantage transfers to other non-odorous stimuli would be informative about the cause of the effect and help rule out alternative explanations for these findings.

As described earlier, while there is evidence supporting waking rest benefitting declarative memory consolidation, there are some studies where waking rest had equivocal results (Heim et al., 2017; Humiston et al., 2019; Martini et al., 2019; Tucker et al., 2020; Varma et al., 2017). For example, Martini et al. (2019) did not find that waking rest led to an advantage in the retention of words in younger adults. In a measure of retention of pseudowords, Heim et al. (2017) showed no waking rest memory benefits compared to an active task. Contrary to an earlier study by Brokaw et al. (2016), a follow-up study by

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Humiston et al. (2019) also found that waking rest did not lead to an advantage in retention scores of story units compared to an active task. In order to better assess the evidence for the waking rest advantage, Humiston et al. (2019) conducted a meta-analysis of 11 studies which examined the effect of brief waking rest periods on declarative memory in healthy participants. Their meta-analysis found a significant but moderate benefit of waking rest (d = .38). However, of the 11 studies reported, 6 had 95% confidence intervals overlapping with a zero effect, indicating considerable uncertainty on the reliability across studies of the waking rest advantage.

Given the uncertainties surrounding the waking rest advantage one method to provide clearer evidence would be the use of a pre-registered experimental investigation and analysis. To our knowledge, only Humiston et al. (2019) have conducted a pre-registered study of the waking rest advantage, in which they failed to find a waking rest benefit. Therefore, further pre-registered studies would be beneficial to better assess the reliability of this effect. Likewise, the use of a pre-registered study to test nasal breathing advantage during waking rest would be also beneficial for somewhat different reasons, as here benefits to consolidation during waking rest have only been shown in one published study and as highlighted above, has thus far only been demonstrated for olfactory memory (Arshamian et al., 2018). A study demonstrating the generalisability to non-odorous memory would be important, particularly if supported by a rigorous test using a pre-registered study design and analysis. Therefore, a pre-registered study that combined both paradigms could serve to establish both the reliability of the waking rest and nasal breathing consolidation advantage and assess the generalisability of the impact of the respiratory route on consolidation during waking rest.

Furthermore, in studies looking at the effect of respiration of cognition, there are open questions on the reliability of findings. Francis and Clarke (2017) have questioned the

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statistical analysis of Zelano et al. (2016), and Mizuhara and Nittono (2022) were unable to replicate Zelano et al.'s findings on breathing phase on visual discrimination accuracy. Johannknecht and Kayser (2022) also looked at the effect of breathing phase, and while they found it influenced behaviour in number of perceptual and cognitive tasks, they were not able to replicate the finding of Zelano et al. showing an influence of phase on visual recognition memory. Taken together, although the evidence mentioned here is focused on breathing phase rather than breathing pathway, we suggest that more pre-registered research is needed to help establish the validity and generalisability of the existing findings on respiration and cognition.

In the current study we combine the waking rest and respiratory pathway paradigms in a within-subjects 2 x 2 design testing verbal recognition memory. Our memory paradigm follows the design of Dewar et al., which involved remembering pseudowords (paired with faces at encoding) to limit the possibility of rehearsal. Following exposure of stimuli to be remembered, participants experienced a delay period of oral or nasal only respiration while resting passively or completing an active task. Given that nasal breathing should be the norm among resting participants (Swift et al., 1988), it is likely that participants in previous waking rest studies were predominantly breathing through their nose. Therefore, a conceptual replication of the waking rest advantage shown in previous studies (and in particular, Dewar et al., 2014) would be best represented by a conceptual replication of the waking rest effect: (Hypothesis 1a) *waking rest will lead to significantly higher memory recognition performance in comparison of an active task in the nasal condition.* A more general test of the power of the waking rest advantage across different breathing states would be a test of the overall main effect (Hypothesis 1b) *waking rest will lead to significantly higher memory recognition performance in comparison of an active task.*

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For testing the nasal advantage, the most direct test of a conceptual replication of nasal breathing improving memory consolidation would involve the waking rest condition, which is most similar to the previous study showing a nasal consolidation advantage (Arshamian et al.), where participants sat quietly in a delay period without any active task. Therefore, we test our conceptual replication hypothesis (Hypothesis 2a): *oral breathing will significantly reduce recognition performance in comparison to nasal breathing in the waking rest condition*. A more general test of the nasal breathing advantage would be a hypothesis of the main effect that (Hypothesis 2b) *oral breathing will overall significantly reduce recognition performance in comparison of nasal breathing.*

Along with these tests of the waking rest and nasal advantage, we will test whether these effects interact. While many interactions are possible, we consider the most likely interaction effect is to find a waking rest advantage in the nasal condition (Hypothesis 2a), but that oral breathing will attenuate or even entirely eradicate the consolidation benefits of waking rest. This leads to the hypothesis of a potential interaction that (Hypothesis 3) *memory performance will be higher for nasal compared with oral breathing in the waking rest condition, but this nasal advantage will be diminished or eradicated in the active task condition.* This would be demonstrated by a significant interaction, with the pattern described in hypothesis (2a), and in the active task the nasal benefit over oral breathing effect being smaller but still significant or showing as non-significant.

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Methods

Participants

Participants (N = 75, M_{age} = 21.5, SD = 6.8, Male = 17, Left-handed = 12) were recruited from a pool of psychology undergraduates from the University of Hull studying in their 1st or 2nd year. Participants (n = 30) who did not complete both sessions were removed and replaced. Participants were compensated with course credits or monetary incentive. Participants were literate in English with normal or corrected to normal vision, with no reason preventing them from breathing via their mouth or nose for the duration of the study (e.g., blocked sinuses making nasal breathing difficult).

Ethics approval for this study was granted by the University of Hull Faculty of Health Sciences Ethics Committee (Reference FHS/353).

Power Analysis

The planned sample size for this study (N = 75) was based on practical constraints on the number of participants that can be recruited for a two-session study within a single academic semester and is informed by Brysbaert's (2019) recommendations. For the interaction effect (Hypothesis 3) we considered a hypothetical interaction between Breathing Pathway and Delay, and corresponding simple contrasts. This included a test of Hypothesis 2a – an extension of the pathway effect for non-olfactory memory –where nasal breathing leads to higher memory performance than oral breathing following wakeful rest with a Cohen's dz = 0.5, in conjunction with no effect of Breathing Pathway during the active task (dz = 0). These values were influenced by Arshamian et al. (2018), who reported a dz of 0.59 for the effect of breathing pathway on olfactory recognition memory under wakeful rest conditions. As shown in simulations by Brysbaert (2019), a sample size of 75 participants would provide 80% power to detect an interaction in a 2 x 2 repeated-measures ANOVA, with Bonferroni adjustment for familywise multiple comparisons.

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Our test of the conceptual replication of the waking rest effect (Hypothesis 1a) was to observe significantly higher memory in the wakeful rest condition compared with an active task under conditions of nasal breathing. Our design is most similar to Dewar et al. (2014) who found a rest benefit on recognition memory of pseudowords of $d = .89$. However, Humiston et al.'s meta-analytic estimate across more varied designs was $d = .38$, which is closer to the recommended default minimal effect size for psychology (Brysbaert, 2019) of $d = .4$. With this more conservative value of d = .4, according to Brysbaert (2019), when comparing two levels of a variable within a group, 52 participants are required to have 80% power. Therefore, our design with N = 75 is well powered to detect an effect of this size.

Our principal research questions informing our design are on the conceptual replications of the waking rest effect and the breathing pathway effect extension to non-olfactory memory, which are tested in simple planned contrasts (Hypotheses 1a/2a). However, we additionally check for main effects of Delay and Breathing Pathway (Hypotheses 1b/2b), respectively, in the previously mentioned 2x2 ANOVA. These effects are of primary interest in the absence of an interaction, but could have the highest power, given that only 27 participants are needed to achieve at least 80% power in detecting a main effect of size $dz = .4$ in a 2 x 2 repeated measures design (Brysbaert, 2019). Therefore, our study with N = 75 is very well powered for the main effects of Breathing Pathway and Delay for effect sizes of this magnitude and have good sensitivity to even smaller effect sizes.

Design

Participants took part in two sessions separated by a week apart. In each session participants experienced either oral or nasal breathing during the delay period, with the order of both experimental factors counterbalanced across subjects. In each session, participants experienced the experimental procedure with both delay periods during which they rested while awake or completed an active task for 15 minutes, separated by a short break. Within

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each session, the process of exposure, delay period, distractor task, and recognition was repeated resulting in two 23-minute sections with a 5-minute break. While we aimed for a 7-day interval between sessions, to facilitate recruitment and completion of both sessions, we allowed a minimum of 4-day and a maximum 11-day gap between sessions. The experimental design is illustrated in Figure 1.

--- Figure 1 here ---

Materials

A total of 240 pseudowords were used within the experiment; half of the words were encoded and half were foils for the recognition task. The words were formed using a similar procedure as Dewar et al. (2014), by selecting real words from the MRC Psycholinguistic database matched for number of letters, syllables, familiarity, concreteness, imaginability and British National Corpus frequency. Each word was then scrambled to form phonotactically legal two or three syllable pseudowords (e.g., "*catapult*" > "*paltacut*") and designed to make each word as phonologically distinct as possible. Words were recorded by a British native English speaker.

Following the design and rationale of Dewar et al. (2014), the words to be remembered during encoding were paired with faces. Participants were asked to learn to associate the novel word with the face, based on Dewar's rationale to simulate a real situation. The images were taken from the FACES database (Ebener et al., 2010) and showed a neutral facial expression (see Figure 2 top left for an example).

The total stimulus set of 240 pseudowords were divided into 4 lists of 60 words each. Within each list, half (30) of the pseudowords served as distractors and were only presented as a foil in the recognition task. The other half of the pseudowords in each set were presented in combination with a face (15 with a female face, 15 with a male face) during the encoding

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phase and served as targets during the recognition phase (see https://osf.io/xqdtw/ for a full list of stimuli and scripts).

During the interval period participants were asked to breathe either via the mouth or nose; breathing redirection was aided by the apparatus shown in Figure 2. For oral conditions, a nasal clip was used to restrict airflow via the nose and redirect airflow to the oral passageway. For nasal conditions tape over the mouth aided in obstructing airflow through the mouth and direct airflow towards the nasal passageway.

--- Figure 2 here ---

Procedure

To prevent demand characteristics, participants were told at the start that the study "aims to examine the effect of oxygenation levels on memory performance". This cover story was aided by the attachment of an oximeter (MeasuPro digital fingertip oximeter) that participants were told would measure blood oxygenation, which was attached to the participant's index finger of their non-dominant hand. In each session there were between one to six participants tested in the same room separated by division boards, but visible to the experimenter in the same room who were monitoring participants throughout the study.

Encoding

Similar to Dewar et al. (2014), participants in the encoding task observed faces paired with the pseudowords which were described as foreign names, and they were provided with a real-life context for learning them: "Imagine you have moved to a new country where they speak a language unfamiliar to you and are joining a new society, such as the chess society. You're meeting the other members for the first time. They will have names that sound foreign and unfamiliar to you. When you hear each name, you will see that person's face on the screen. You should try to remember the names. Later on, you will be presented with these names again one by one intermixed with a new set of words. Your task will be to respond

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whether you've met that person at the society and recognise that name, or whether the word you hear is entirely novel. You probably won't be able to recognise all of the names but do your best".

During each of the four encoding phases, participants were presented with one of four sets of 30 pseudoword and face pairs in the centre of the screen with a grey background, each of the list were equally present within each condition and breathing route and delay period with the order randomised per participant. The order of the face-pseudoword pairs were also presented randomly per participant. Stimuli were presented on a 21" 1920x1080 computer monitor using Open Sesame (Mathôt et al., 2012). Participants heard the novel word over headphones concurrent with the presentation of the face. Each trial started with the playback of a pseudoword (variable duration between 600 – 800ms), accompanied by a face presented on the screen for a fixed period of 3000ms. This ensured a gap between successive pseudoword presentations and provided participants with additional time to encode the association between the face and the pseudoword.

Due to the use of a within-participant design, where participants would have become aware of the recognition tests as they proceed through the study, participants were made aware from the beginning that their memory of the words would be tested.

Respiratory Manipulation

At the start of both sessions a familiarity period occurred during which participants experienced the nasal clip and tape and were asked to administer the apparatus as shown when instructed. Participants were asked to adjust the pressure of the nasal clip until it was perceived to be equal to the tape by adjusting the shape of the nasal clip, ensuring any intrusiveness perceived by the apparatus is approximately equal across conditions. The experiment continued when all participants were confident in administering the apparatus. The order in which the participants experienced the apparatus was counterbalanced.

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Following the encoding period, participants were given a fixed 60 second period to administer the apparatus and make adjustments where necessary. Participants were then asked to breathe either via their nose or mouth and if airflow was able to penetrate the obstructed pathway additional tape or repositioning of the clip occurred. The apparatus used to limit the breathing pathway (nasal clip or tape) were applied along with the pulse oximeter on the index finger of the non-dominant hand for the 15-minute delay period. At the end of the delay period participants were asked to remove the tape or clip.

Delay period

After the equipment was attached participants started the 15-minute delay period. The delay period was also counterbalanced, with half experiencing the nasal condition first and half the rest condition first. For the waking rest condition, participants were instructed that following the application of the respiratory apparatus they should close their eyes and rest quietly while the next part of the study is being prepared. Participants were observed for signs they were falling asleep, including head nodding and snoring. It was planned that if this was observed participants would be removed from the study. No participants were removed. The experimenter also noted the number of adjustments participants made to the breathing apparatus during the session and no repeated adjusting or removing of the apparatus was observed.

For the active condition, participants spent the delay period carrying out a Toulouse N-back task (TNT; Causse et al., 2017), which is a variant of the N-back reliant on mental arithmetic as well as working memory. The TNT was chosen for two reasons. Firstly, it is a numerically based task that can be presented visually, and therefore dissimilar to the verbal pseudoword-face learning task, which should reduce any effects of retroactive interference. Secondly, it is a more challenging task than the standard N-back task, therefore we would expect it to be more difficult and better able to engage participants' full attention.

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The TNT trials consisted of sums of addition or subtraction of numbers that were multiples of 5, ranging between 5 and 95. Each trial involved the presentation of a number on the left, an equal or minus sign in the middle, and a number on the right, for example, "5 + 40" (see Figure 3 for illustration). Participants were instructed to calculate the answer and whether it matched the answer n-trials previously, responding by pressing the space bar for a match. Each trial was presented for 4s in blocks of 35 trials, and instructions for the block were presented at the start for 10 seconds. Approximately one third of the trials were targets. Each block lasted a total of 150 seconds including instructions, leading to a total of 15 minutes.

--- Figure 3 here ---

At the start of each session there was a practice block of 10 trials for each of the 1-back and 2-back tasks to familiarise participants with the task.

Distractor Task

Regardless of condition, all participants then completed a 5-minute distractor task of the TNT, with the purpose of eliminating retrieval competition, such as retroactive interference (Dewar et al., 2007), as a potential cause for the wakeful rest advantage. Though we expected retrieval competition interference to be minimal due to the nature of the active task being dissimilar to the target stimuli of pseudowords, if interference was present from the TNT then by having all participants regardless of the active or waking rest condition complete the distractor task should result in the interference being similar across both conditions (Dewar et al., 2012). The distractor task contained a block of the 1-back, followed by a block of the 2-back, with a total of 70 trials in each session. Including instructions at the start and in between blocks, the duration was approximately 5 minutes to complete.

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Recognition Task

After the 5-minute distractor task, participants were presented with 60 pseudowords (without accompanying face presentation) comprised of the pseudowords presented during the previous encoding task and 30 novel pseudowords acting as foils. For the recognition task, the lists were pseudo-randomised separately for each participant, with the constraint that no more than 3 foils or targets appear in succession. Each trial began with the presentation of a pseudoword. Participants were asked to use the keyboard ("m" or "z" key) to respond as to whether they heard that name presented in the previous encoding phase ("Old" responses) or whether it has not been previously heard ("New" responses), with these words showing on the right and left of middle of a grey screen as a reminder. Once a participant gave a response, an intertrial interval of 1500ms was presented before the next recognition trial began.

After recognition, participants then repeated the procedure with the same respiratory pathway but the remaining delay condition and then returned a week later where the procedure was repeated for the remaining breathing pathway. At the end of the second session participants completed an exit questionnaire (partially adapted from Humiston et al., 2019), which asked what participants thought about during the rest periods, including whether they engaged in rehearsal of the stimuli and to what extent. The questionnaire also examined how well they felt they followed instructions in the rest period (see the OSF questionnaire folder for the wordings used in this questionnaire).

Planned Analysis

The TNT during the active and distractor task and recognition performance of the pseudowords were analysed using Signal Detection Theory (SDT) giving a measure of *d'* (*d prime)* for memory discrimination performance. This measure of sensitivity was defined as the difference between z-transformed hit (H) and false alarm rate (FA) $d' = z(H) - z(FA)$

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(Macmillan and Creelman, 2005). Hit and false alarm rates of 1 and 0 were adjusted to 1 - 1/(2N) and 1/(2N), respectively, where N is the number of trials (Macmillan & Creelman, 2005).

To control for task engagement and following of instructions, it was planned that participants would be removed if *d'* was three SDs below the mean for performance in the active task, distractor task or recognition performance.

The *d'* data from the recognition task was subjected to a repeated measures 2 x 2 ANOVA using the factors of Delay (Active Task vs. Waking Rest) and Breathing Pathway (Nasal vs. Oral), with an alpha of .05 allowed assessing the statistical significance of the main effects (Hypothesis 1b/2b) and interaction (Hypothesis 3). Our focal tests rely on two planned pairwise comparisons to test Hypotheses 1a/2a.

Results

Registered analysis

In accordance with the pre-registered analysis, participants were planned to be removed if the individual scored below 3 SD *d'* on the active task ($M = 1.64$, $SD = .79$), distractor task ($M = 1.76$, $SD = .74$) or recognition task ($M = .72$, $SD = .31$) to control for task engagement. However, no participants met this exclusion criterion. All data and experimental scripts can be found on the OSF (https://osf.io/xqdtw/) along with the approved Stage 1 protocol. A deviation from protocol is a reduced participant number of ($N = 74$) due to discovering late in the analysis stage one that participant had no recording of their recognition performance for one of the four iterations (oral breathing during a delay rest period).

Descriptive statistics for condition means are shown in Figure 4. Wakeful rest ($M = .72$, $SD = .57$) did not lead to significantly higher *d*' values in comparison to the active task

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(*M* = .72, *SD* = .53), as indicated by a non-significant main effect of Delay [$F(1, 73) < .001$, $p = .98$, $\eta p^2 < .001$]. Thus, Hypothesis 1b was not supported and no evidence was found for a general waking rest advantage. Hypothesis 2b was also not supported, as the main effect of Breathing Pathway was not significant [$F(1, 73) = 1.1$, $p = .297$, $\eta p^2 = .01$], indicating that Nasal breathing (*M* = .76 , *SD* = .51) did not lead to significantly higher overall *d*' values in comparison to Oral breathing (*M* = .68, *SD* = .59). Hence, no evidence was found for a general nasal breathing advantage. Finally, Hypothesis 3 was also not supported as the interaction between Breathing Pathway and Delay was not significant [$F(1, 73) = 2.06$, $p = .155$, $\eta p^2 = .03$].

--- Figure 4 here ---

To test Hypothesis 1a, which tested if waking rest would significantly improve recognition performance compared to an active task in the nasal breathing condition, we conducted a paired samples t-test. Contrary to the hypothesis, waking rest during nasal breathing resulted in lower d' scores (*M* = .73, *SD* = .54) compared to the active task (*M* = .79, *SD* = .48). This difference was not statistically significant [$t(73) = 1.03$, $p = .306$, $dz = .12$].

Hypothesis 2a tested whether nasal breathing could significantly enhance recognition performance in comparison to oral breathing during waking rest. Nasal breathing during Waking Rest led to slightly higher scores of *d*' (*M* = .73, *SD* = .54) in comparison to Oral breathing (*M* = .71, *SD* = .6). However, this difference was also not significant [$t(73) = .21$ $p = .835$, $dz = .02$].

Exploratory Analysis

Hit and False Alarm Rate

While the primary analysis focused on *d'* as an overall measure of recognition performance, examining its components—Hit rate and False Alarm rate—can offer insights

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into underlying processes. For example, in the study by Dewar et al. (2014), it was found that differences in *d'* were driven by an increase in false alarms following the active condition. However, in our study we found no evidence that our experimental factors differentially affected Hit Rate and False Alarms. An ANOVA using Hit rate as the outcome variable indicated no significant main effects of Breathing Pathway [$F(1, 73) = .63$, $p = .429$, $\eta p^2 < .001$] or Delay Period [$F(1, 73) = 1.26$, $p = .265$, $\eta p^2 = .02$] and also no significant interaction [$F(1, 73) = 1.48$, $p = .228$, $\eta p^2 = .02$]. The same pattern was observed when the False Alarm Rate was used as the outcome variable, with non-significant main effects of Breathing Pathway [$F(1, 73) = 1.54$, $p = .219$, $\eta p^2 = .02$] and Delay Period [$F(1, 73) = .85$, $p = .361$, $\eta p^2 = .01$] as well as a non-significant interaction [$F(1, 73) = .78$, $p = .379$, $\eta p^2 = .01$].

Session performance

To assess changes in performance across the repeated iterations of the procedure, we conducted a within-subjects 2 x 2 ANOVA, with factors for Session (1st vs 2nd session) and the Half of each session (1st vs 2nd half). As can be seen in Figure 5, there was a general trend towards worse recognition performance across successive iterations. Our analysis revealed a significant main effect of Session [$F(1, 73) = 90.79$ $p < .001$, $\eta p^2 = .55$], with a substantial decrease in performance from the first session ($M = .98$, $SD = .45$) to the second session ($M = .47$, $SD = .53$). There was also a significant main effect of Half [$F(1, 73) = 17.1$, $p < .001$, $\eta p^2 = .19$], with a decline in recognition performance within sessions, with better performance in the first half ($M = .82$, $SD = .46$) compared to the second half ($M = .64$, $SD = .52$) across sessions. There was no significant interaction [$F(1, 73) = .91$, $p = .342$, $\eta p^2 = .01$].

--- Figure 5 here ---

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To provide further insight into this decrease in recognition performance, we examined both Hit and False Alarm Rate using similar 2 x 2 ANOVAs. As can be seen from Figure 6, the general trend was for Hit Rate to reduce across iterations of the recognition memory test, and for False Alarm Rate to increase.

--- Figure 6 here ---

There was a significant decrease in Hit Rate from Session 1 [$F(1, 73) = 53.18$, $p < .001$, $\eta p^2 = .42$], and from the first half [$F(1, 73) = 4.57$, $p = .036$, $\eta p^2 = .06$] and there was no significant interaction [$F(1, 73) = .85$, $p = .361$, $\eta p^2 = .01$].

Consistent with worse discrimination overall and the linked fall in Hit Rate, there was a significant increase in False Alarm Rate from Session 1 to Session 2 [$F(1, 73) = 44.97$, $p < .001$, $\eta p^2 = .38$], and the False Alarms also increased within sessions [$F(1, 73) = 14.05$, $p < .001$, $\eta p^2 = .16$], with no significant interaction [$F(1, 73) = .27$, $p = .61$, $\eta p^2 < .01$].

One possible explanation for these notable drops in recognition performance across the study could be reduced task engagement and fatigue due to the repetition of the procedure. If this were true, we may expect to also see a decline in performance across the Toulouse N-back task used in the active delay period and distractor task before completing the recognition memory test. However, *d'* performance was very similar in the N-back active task in Session 1 ($M = 1.54$, $SD = .76$) compared with Session 2 ($M = 1.55$, $SD = .77$) [$t(73) = 2.598$, $p = .112$, $dz = .03$].

Similar results were shown in the distractor task data. A repeated measures 2 x 2 showed no significant main effect of session, with similar values for Session 1 ($M = 1.72$, $SD = 1.09$) and Sesson 2 ($M = 1.82$, $SD = 1.1$) [$F(1, 73) = 2.58$, $p = .11$, $\eta p^2 = .03$]. There was also no significant difference [$F(1, 73) = .26$, $p = .61$, $\eta p^2 < .001$] between performance in the first half ($M = 1.75$, $SD = 1.14$) of the sessions in comparison to the second half ($M = 1.78$,

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SD = 1.06). This suggests that the drop in performance across the recognition tasks was unlikely to be due to fatigue and disengagement.

Memory performance dependent on session

To control for the differences in recognition performance across iterations of the recognition task, with a decline in performance observed in the second session, we carried out two mixed 2 x 2 ANOVAs, one for Session 1 where performance was strongest, and one for Session 2 where performance was weakest. Here Breathing Pathway was a between-subjects variable and Delay Period remained as a within-subjects variable, which meant these exploratory analyses will have less statistical power than our pre-registered main analysis (which were entirely within-subjects).

The results for Session 1 again showed no significant main effect of Breathing Pathway on *d'* [$F(1, 73) = .01$, $p = .93$, $\eta p^2 = < .001$], with Oral breathing ($M = .98$, $SD = .46$) showing nearly identical *d'* scores as Nasal Breathing ($M = .98$, $SD = .41$). There was no significant main effect of Delay Period [$F(1, 73) = .22$, $p = .64$, $\eta p^2 < .001$] with active rest ($M = .97$, $SD = .43$) leading to similar recognition performance to wakeful rest ($M = .99$, $SD = .44$). There was also no significant interaction effect between Breathing Pathway and Delay Period [$F(1, 73) = .07$, $p = .79$, $\eta p^2 < .001$].

When looking just at the second session, the results showed oral breathing ($M = .42$, $SD = .57$) was slightly worse than nasal breathing ($M = .52$, $SD = .49$), but this was not significant [$F(1, 73) = 1.3$, $p = .26$, $\eta p^2 = .03$]. There was also no main effect of Delay Period [$F(1, 73) = .24$, $p = .63$, $\eta p^2 < .001$], where the active task ($M = .49$, $SD = .51$) led to slightly higher performance to wakeful rest ($M = .44$, $SD = .56$). There was no significant interaction between Breathing Pathway and Delay Period in the second session [$F(1, 73) = 2.48$, $p = .12$, $\eta p^2 = .31$].

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N-back Performance

A further area of exploratory analysis was performance in the Toulouse N-back task. Some studies of breathing pathway have found a nasal advantage in the performance of tasks requiring sustained attention. Yoshimura et al. (2019) found a nasal breathing advantage for the visual search of targets with difficult discriminability. In studies looking at individual difference in natural breathing styles it was found that those that breathe nasally scored significantly higher in a sustained auditory attention ability test (Braga Junior et al., 2020) and were shown to have higher performance on phonological working memory tasks (Kuroishi et al., 2014). Lee et al. (2019) also found that nasal breathing resulted in higher (but not significant) performance in oral breathing during a 2-back task and significant decreases of power in slow oscillatory activity. We therefore looked to see whether the nasal breathing led to higher performance in both the active and distractor task compared with oral breathing.

A 2 x 2 ANOVA of Breathing Pathway and N-back Level (1 or 2) on *d'* data from the active task revealed a significant main effect of N-back level [$F(1, 73) = 33.25$ $p < .001$ $\eta p^2 = .31$] with performance being highest in the 1-Back condition ($M = 1.85$, $SD = .94$) in comparison to the 2-Back condition ($M = 1.44$, $SD = .89$) confirming the 2-back was more difficult than the 1-back condition, as would be expected. Regarding breathing pathway, there was slightly lower performance in the Oral breathing condition ($M = 1.62$, $SD = .89$) comparison to the Nasal breathing condition ($M = 1.67$, $SD = .97$), but the ANOVA found no significant main effect of Breathing Pathway [$F(1, 73) = .56$, $p = .456$ $\eta p^2 < .001$], and there was no significant interaction with N-back level [$F(1, 73) = .13$, $p = .721$, $\eta p^2 < .001$].

For the shorter distractor task (2 blocks vs. 6 blocks in the delay version), we used a 2 x 2 ANOVA with levels of Breathing Pathway and Delay Period (collapsing the N-back level) in the distractor task, and found that there was no main effect of Breathing Pathway on

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N-back performance [$F(1, 73) = .85$, $p = .359$, $\eta p^2 = .01$] or Delay Period activity [$F(1, 73) = .93$, $p = .337$, $\eta p^2 = .01$] and no significant interaction [$F(1, 73) = .69$, $p = .41$, $\eta p^2 = .01$].

--- Figure 7 here ---

Bayesian Analysis

Given the null results of the pre-registered analysis, we conducted a Bayesian analysis to assess the strength of evidence for the null hypotheses. We employed the *bayesfactor* package by Morey et al. (2015), using Bayesian ANOVA and Bayesian within-subjects t-tests with default priors. The default priors are Cauchy distributions centred at 0 with a scale parameter of r = .707 for fixed effects. These priors are chosen as a compromise between being sufficiently wide to include reasonable effect sizes while not being so wide as to place undue prior mass on implausibly large effects.

The Bayesian ANOVA results indicated moderate evidence supporting the absence of an effect for the Respiratory Pathway ($BF = .35$, ±4.28%), suggesting that the data are approximately three times more likely under the null hypothesis. For the Delay factor, there was substantial evidence favouring the null hypothesis ($BF = .13$, ±2.36%), implying the data are about eight times more likely under the null hypothesis. The interaction effect showed strong evidence for the null hypothesis ($BF = .01$, ±4.25%), indicating that the data are overwhelmingly more likely under the null model compared to the alternative.

For the Bayesian t-tests, the analysis of active rest during nasal breathing showed moderate evidence in favour of the null hypothesis ($BF = .23$). Similarly, the t-test comparing oral and nasal breathing during rest indicated strong evidence supporting the null hypothesis ($BF = .18$).

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Discussion

The current study was a high-powered, pre-registered study that is the first to combine the waking rest advantage and the nasal advantage paradigms. The study consisted of three main aims: to determine the replicability of the waking rest advantage; to assess the generalisability of the nasal advantage; and to determine whether the breathing pathway modulated the waking rest advantage.

By comparing recognition performance following periods of active or wakeful rest, we found no significant evidence to support the general waking rest advantage, as recognition performance was not significantly higher following periods of wakeful rest. Similarly, the specific comparison of waking rest and an active task conducted during nasal breathing - which is the most frequently observed pathway in natural breathing and likely featured in conventional waking rest studies - also failed to provide evidence for a meaningful distinction in wakeful rest. By comparing recognition performance following periods of oral or nasal-only breathing, we found no significant evidence to suggest that the nasal advantage for consolidation extends to pseudowords. Similarly, the more specific comparison of comparing oral and nasal breathing during wakeful rest which more closely replicates the previous literature resulted in no evidence for a nasal advantage for consolidation. Finally, the results showed no significant modulation of breathing pathway on the waking rest advantage. An exploratory Bayesian analyses showed moderate to substantial evidence for the null for these hypotheses.

To examine the wakeful rest advantage, the methodology of the current study involved a conceptual replication of Dewar et al. (2014) by including adapted stimuli of face-name (pseudowords) pairings. We also used the same instructions and a similar recognition memory task used by Dewar et al. However, our findings diverge from those of Dewar et al.,

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who reported a significant improvement in delayed recognition performance following a period of wakeful rest.

In considering how the differences in design may have led to different results, Dewar et al. used a between-subjects design allowing for a surprise test after learning. The current study was a within-subjects design and thus participants were aware they would be tested. However, a within-subjects design may be thought to make it more likely to find a waking rest effect, as it could allow greater opportunities for facilitating rehearsal in the waking rest condition and boosting a waking rest effect, and hence unlikely to be the driver of the null effect seen within the current study. Other studies (Dewar et al., 2012; King & Nicosia, 2022; Martini et al., 2019) have also managed to replicate the waking rest advantage using a within-subjects design.

The null result also does not appear to be due to the discrepancy in active tasks. Various tasks have been used in previous studies which found a waking rest effect including a more standard N-back task (King & Nicosia, 2022), spot-the difference (Dewar et al., 2012), and an active task that matched the learning task (English-Icelandic word pair learning; Mercer, 2015). Similarly, a variety of active tasks have been used in other studies where a wakeful rest advantage was not found, including a puzzle game (Humiston et al., 2019), progressive matrices (Martini et al., 2019) as well as the N-back task (Varma et al., 2017). It is therefore currently not clear what characteristics of an active task facilitates the likelihood of observing a waking rest advantage.

We chose the Toulouse N-back Task (TNT) for its visual and numerical focus, contrasting with our verbal pseudoword-face learning task to reduce retroactive interference. The TNT's challenging nature minimises default mode network activity and rehearsal chances, while taxing cognitive domains not associated with pseudoword processing. This design should rule out rehearsal and retroactive interference from the active task. One

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interpretation is that our lack of effect could imply that for the waking rest advantage to occur, the active task may need to tax cognitive domains associated with the learned stimuli, preventing spontaneous activations during the active task though potentially inducing retroactive interference (though see Mercer, 2015).

However, it should be noted that the reliability and specificity of the waking rest advantage are subjects of ongoing debate. Recent studies have cast doubt on the robustness of this effect. In the only other pre-registered study to date that we are aware of, Humiston et al. (2019) failed to replicate the waking rest advantage found in Brokaw et al. (2016). Similarly, Varma et al. (2017) did not find a waking rest advantage across six experiments. Furthermore, the meta-analysis included with Humiston et al.'s study revealed that 6 of the 11 reviewed studies showed 95% confidence intervals overlapping with zero effect, suggesting considerable uncertainty about the reliability of the waking rest advantage with existing paradigms.

This variability in findings has led researchers to propose that the waking rest advantage may be sensitive to specific experimental conditions (Martini & Sachse, 2019). Several factors have been suggested to influence the effect, including the nature of the memory task (Gonsalez et al., 2024), the rehearsability of materials (Millar & Balota, 2018), and individual differences among participants (Martini et al., 2020). These potential moderating factors, combined with our null results and those of other recent studies, underscore the need to better delineate the conditions under which the waking rest advantage may occur.

The second aim of the study was to assess the generalisability of the nasal advantage observed during wakeful rest and to determine whether nasal breathing enhances recognition memory performance of previously learned pseudowords, as compared to oral breathing. This investigation incorporated aspects of Arshamian et al.'s (2018) study, where participants

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exposed to odours exhibited significantly better performance on a recognition task following a period of nasal breathing rather than oral breathing. Arshamian et al. suggested that the nasal advantage might transfer to other modalities. However, the current study did not find evidence that the breathing pathway influenced recognition memory for pseudowords, suggesting limited generalisability.

Odour processing differs from other sensory stimuli in that it bypasses the thalamus and directly activates the olfactory bulb (Smith & Bhatnagar, 2019). The neural synchrony thought to underlie the nasal breathing advantage also originates in the olfactory bulb (for reviews, see Heck et al., 2017; Tort et al., 2018). Our study's negative result might suggest that the nasal advantage reported by Arshamian et al. is specific to olfaction.

However, the failure to extend this effect to pseudowords could be attributed to methodological differences between our study and Arshamian et al.'s, such as the duration of the delay period (15 minutes in our study versus 60 minutes in theirs). Given that evidence for this nasal effect on memory is currently limited to a single study, it remains unclear what duration of nasal or oral breathing is necessary to produce the neurological effects potentially underlying consolidation during wakeful rest, such as the hypothesised disruption of sharp-wave ripples during oral breathing (Zelano et al., 2016; Liu et al., 2017). Future research should systematically vary this time period to identify optimal conditions for enhancing consolidation during waking rest, including any potential nasal breathing advantage.

Another objective of our study was to examine how the nasal advantage might interact with the waking rest advantage. However, our inability to replicate the waking rest advantage prevented us from assessing this potential interaction. In considering our null results, it is worth noting that the mean recognition performance in our study ($d' = .72$) was notably lower than that reported by Arshamian et al. ($d' = 1.4$). This disparity could suggest that our task conditions were too challenging to detect a nasal breathing advantage. The same

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argument might apply to the null effects of waking rest, although our recognition performance falls within the lower range observed by Dewar et al. (2012) for rest (M = 1.2) and active task (M = .7) conditions.

Our exploratory analysis revealed a decline in discrimination performance across the four task iterations, with a particularly notable drop when participants returned for the second session a week later. This decline seems unlikely due to fatigue, disengagement, or decreased motivation, as performance in the active task and distractor remained stable.

The pattern we observed has similarities to a "mirror effect", observed across different conditions in recognition memory paradigms (Glanzer & Adams, 1985; Stretch & Wixted, 1998), where in this case earlier tasks lead to stronger memories than later tasks, shown in decreasing hit rates accompanied by increasing false alarm rates occur as participants are repeatedly assessed. This observed decline in performance can be attributed to the increasing cumulative familiarity of distractors as participants progress through task repetitions with new stimuli. As familiarity builds, it becomes progressively more challenging for participants to distinguish between studied items and new distractors. This difficulty is likely exacerbated by proactive interference from previously learned lists, potentially resulting in poorer encoding of new items and increased familiarity for distractors. Consequently, participants exhibit lower hit rates and higher false alarm rates in later tasks, leading to reduced overall discriminability.

The use of pseudowords as stimuli may have amplified the effects of proactive interference in our study. Pseudowords, lacking semantic and phonological structures that aid in rehearsal and retrieval (Hulme et al., 1991), present unique challenges for encoding and remembering. The absence of semantic associations forces greater reliance on perceptual and phonological processing (Gathercole & Baddeley, 1990), increasing the likelihood of

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interference during recognition tasks. In contrast, real words have distinct semantic features that facilitate differentiation and reduce interference (Roodenrys & Quinlan, 2000).

Due to the decline in recognition performance found within the second session, we analysed the data in exploratory analyses to consider performance in the first and second session separately. However, when restricting data analysis to Session 1, where performance was best (mean *d'* = .98), and when influences of interference should be lessened, our between-subject analysis did not show evidence that breathing pathways influenced memory, nor did it support the existence of a waking rest advantage or a significant interaction effect. Similar results were found with Session 2 where performance was weaker (mean *d*' = .47). Although these exploratory analyses had less statistical power than our pre-registered main analysis (which were entirely within-subjects).

Despite the unexpected decline in discrimination performance and the potential impact of proactive interference, we might still have anticipated observing a waking rest effect and/or a nasal breathing advantage. If these effects are indeed robust, they should theoretically withstand the influence of different levels of performance. Although research on the influence of memory strength on waking rest-based memory processing is limited, recent studies on sleep-dependent memory consolidation provide a relevant parallel. For example, Petzka et al. (2021) found that the benefits of sleep on memory consolidation can be masked by ceiling effects for stronger memories under standard testing conditions. They demonstrated that by increasing retrieval demands, sleep-dependent consolidation effects became apparent for both weak and strong memories. Applying this principle to our study, it is possible that the overall decline in performance we observed could have obscured these effects, particularly if they preferentially benefit weaker memories. Alternatively, the strength of the initial memory traces in our study, influenced by the use of pseudowords as stimuli, might have affected the potential for consolidation during waking rest or the impact of nasal breathing. These considerations

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underscore the importance of carefully designed testing conditions in future studies, potentially incorporating varying levels of retrieval difficulty or manipulating initial memory strength, to understand the nature and extent of waking rest and nasal breathing effects on memory consolidation across different levels of memory strength.

In conclusion, the current well-powered pre-registered study was the first to investigate waking rest and nasal breathing advantage in a single study. Our results did not support the generalisation of the nasal advantage to pseudowords, nor did we replicate the previously reported waking rest advantage or detect an interaction between these factors. Bayesian analysis supported the null hypotheses. We thus conclude that this research adds to a growing body of evidence that challenges the consistency of the waking rest advantage, and further exploration is needed to better understand the influence of breathing pathway on memory processes as well as potential moderating factors that may explain the variability in findings across studies.

Data Accessibility Statement

The data and materials from the present experiment are publicly available at the Open Science Framework website:https://osf.io/xqdtw/

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Figure Captions

Figure 1. *Illustration of the Experimental Procedure*

Note. The order of the respiratory manipulation and delay period of active or waking rest were both counterbalanced across participants.

Figure 2. *Respiratory Apparatus used to Manipulate Breathing Pathway*

Note. Left: Tape used to direct airflow towards the nasal passageway. *Right*: Clip used to direct airflow towards the oral passageway

Figure 3. *Visual illustration of the Toulouse N-back Task*

Note. Calculations highlighted in circles are trials where participants should indicate a "match" via a space button press.

Figure 4. *Mean d' scores for Waking and Active Rest During Oral and Nasal Only Breathing*

Note. Error bars represent standard error.

Figure 5. *Mean d' Across the Iterations of the Recognition Task*

Note. Error bars represent standard error.

Figure 6. *Mean Hit Rate (A) and False Alarm Rate (B) Across the Iterations of the Recognition Task*

Note. Error bars represent standard error.

Figure 7. *Mean d' for N-Back Level in the Active Task (A) and Distractor Task (B) during Oral or Nasal Breathing*

Note. Error bars represent standard error.

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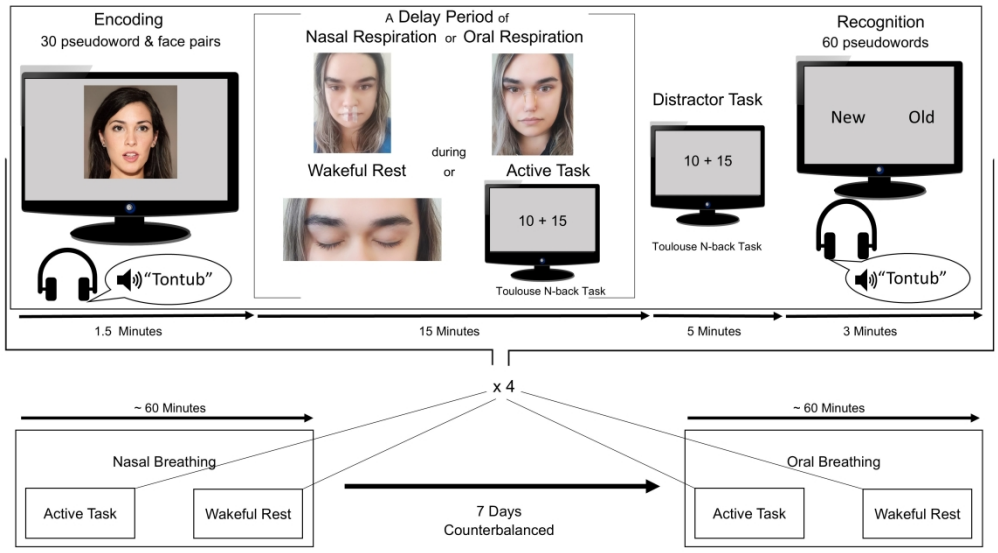

Figure 1. Illustration of the Experimental Procedure
Note. The order of the respiratory manipulation and delay period of active or waking rest were both counterbalanced across participants.

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Figure 2. Respiratory Apparatus used to Manipulate Breathing Pathway
Note. Left: Tape used to direct airflow towards the nasal passageway. Right: Clip used to direct airflow towards the oral passageway

338x190mm (300 x 300 DPI)

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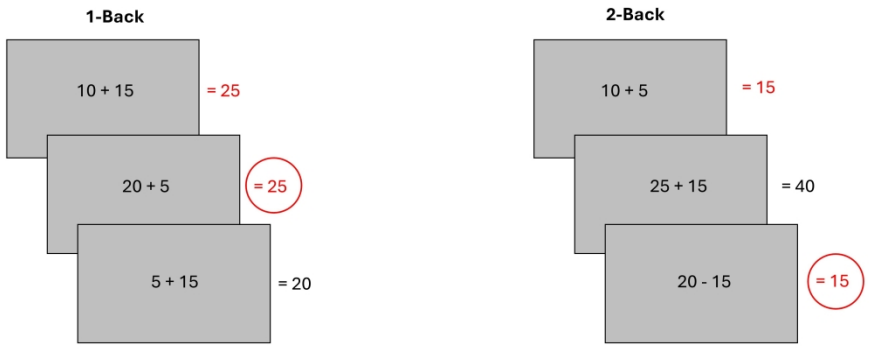

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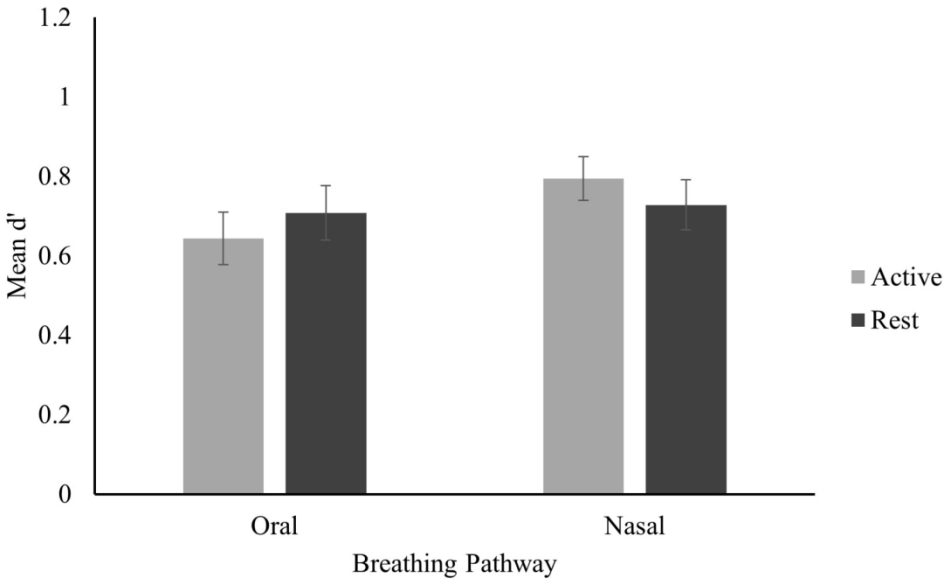

Figure 4. Mean d' scores for Waking and Active Rest During Oral and Nasal Only Breathing
Note. Error bars represent standard error.

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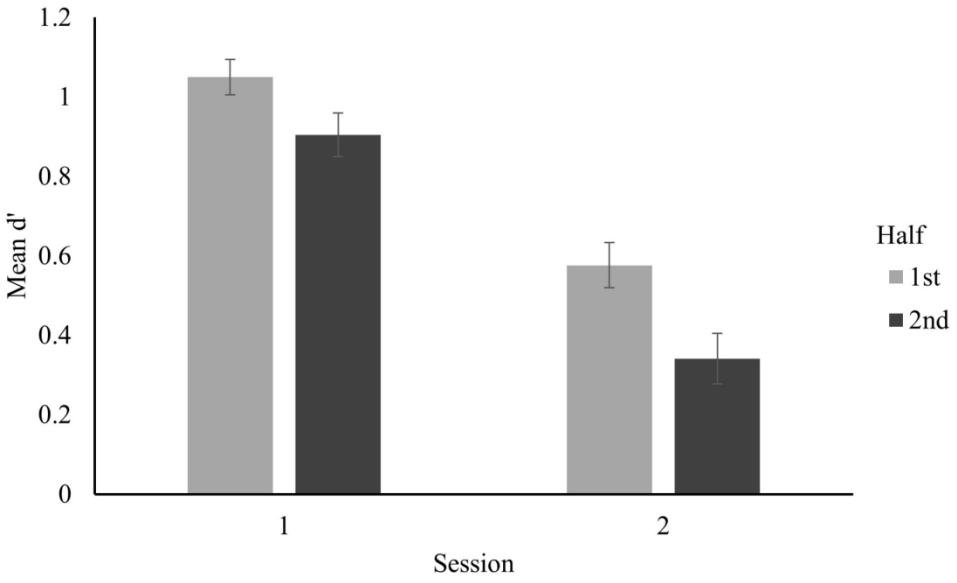

Figure 5. Mean d' Across the Iterations of the Recognition Task
Note. Error bars represent standard error.

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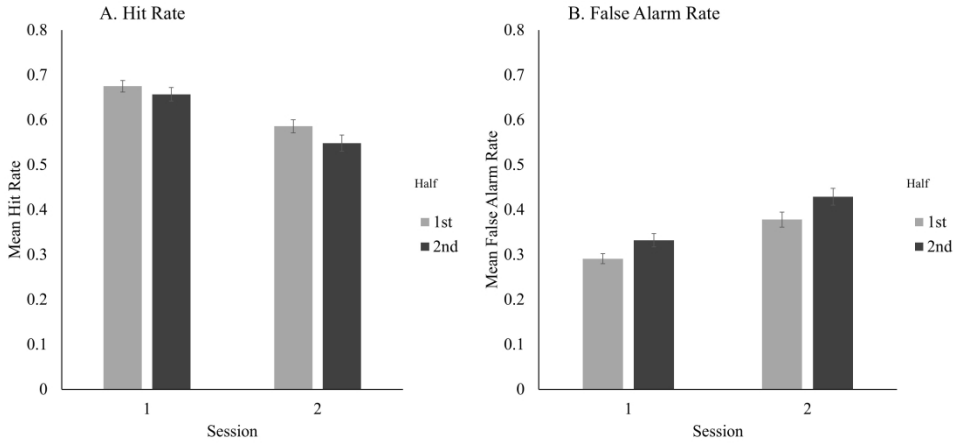

Figure 6. Mean Hit Rate (A) and False Alarm Rate (B) Across the Iterations of the Recognition Task
Note. Error bars represent standard error.

338x190mm (300 x 300 DPI)

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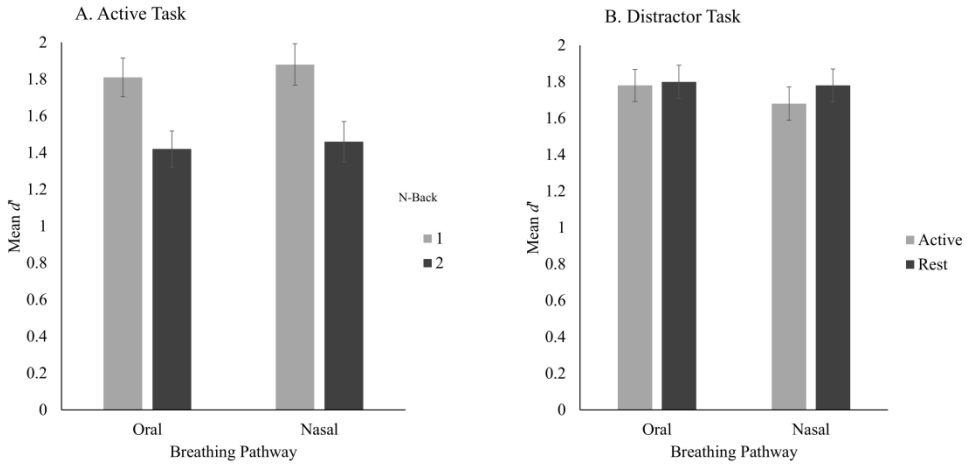

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Note. Error bars represent standard error.

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