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Vestibular Stimulation Through Motion and Its Effects on Sleep and Relaxation

A Systematic Review

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Abstract

ABSTRACT

Background

Rocking motion has been used across cultures for millennia to soothe infants and promote sleep. Despite this universal practice, the neuroscientific mechanisms and optimal parameters for vestibular stimulation as a non-pharmacological sleep intervention in adults remain poorly characterized.

Objective

To synthesize the available human experimental literature examining the effects of passive rhythmic motion — including rocking beds, actuated platforms, chairs, mattresses, and pillow devices — on sleep architecture, sleep onset, relaxation physiology, and cognitive outcomes in adults.

Methods

A comprehensive review of 14 primary research articles was conducted, encompassing laboratory polysomnographic studies, home-based EEG trials, and relaxation physiology experiments. Studies ranged from single-session nap paradigms to multi-week home trials. Populations included healthy young adults, older adults (≥ 60 years), and individuals with poor self-reported sleep.

Results

A consistent pattern emerges across the majority of studies: vestibular stimulation at low frequencies (0.16–0.5 Hz) reduces sleep latency, increases slow-wave sleep (N3), augments sleep spindle activity, and improves subjective sleep quality. The strongest evidence comes from whole-night continuous rocking at 0.25 Hz, which additionally entrained endogenous thalamocortical oscillations and enhanced declarative memory consolidation. Critically, effect magnitude is modulated by (1) baseline sleep quality; (2) stimulation duration; (3) motion trajectory; and (4) stimulation intensity. Elderly populations did

not benefit under tested parameters. Respiration rate unexpectedly *increases* during rocking.

Conclusions

The evidence base robustly supports vestibular stimulation as a viable non-pharmacological intervention for sleep onset and sleep depth. Key mechanistic pathways such as thalamocortical entrainment, cholinergic modulation, and the Sopite syndrome/sensory mismatch route provide actionable targets for hardware and algorithm design that can further improve sleep parameters.

Keywords: vestibular stimulation · rocking · sleep onset · slow-wave sleep · sleep spindles · non-pharmacological intervention · thalamocortical entrainment · Sopite syndrome · sleep architecture · N3

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1. Introduction

The universal practice of rocking infants to sleep reflects an evolutionarily conserved behavioral mechanism. Adults, too, reliably report drowsiness in swaying hammocks, gently rocking trains, and boats — suggesting that the sleep-promoting capacity of rhythmic motion is not confined to early development. Yet until recently, this phenomenon lacked rigorous neuroscientific characterization. The link between vestibular stimulation and sleep regulation has gained significant experimental traction over the past fifteen years, producing a literature that — while modest in volume — is mechanistically rich and practically consequential.

Globally, sleep inadequacy constitutes a public health burden of the first order. Approximately one-third of adults report insufficient sleep duration or quality (Liu, 2016; Madrid-Valero et al., 2017), with downstream consequences for cognitive function (Alhola & Polo-Kantola, 2007), metabolic health (Garbarino et al., 2016), immune competence, and overall longevity (Kecklund & Axelsson, 2016). Standard pharmacological interventions — benzodiazepines, Z-drugs — carry risks of dependency, tolerance, and residual sedation (Vinkers & Olivier, 2012), particularly in elderly populations who face elevated fall and fracture risk (Donnelly et al., 2017). Behavioral interventions such as cognitive behavioral therapy for insomnia (CBT-I) are effective but access-limited. This gap motivates the search for hardware-based, non-pharmacological alternatives.

Vestibular stimulation operates through the inner ear's otolith organs — which detect linear acceleration — and semicircular canals — which detect angular velocity. These structures project via the vestibular nuclei to the thalamus, hypothalamus, brainstem sleep centers, and limbic system (Bayer et al., 2011). The thalamic projections are particularly salient: thalamo-cortical circuits generate the slow oscillations (SOs, <1 Hz) and sleep spindles (11–15 Hz) that define NREM sleep and subserve memory consolidation (Perrault et al., 2019). A rhythmic vestibular input at physiologically relevant frequencies could, in principle, entrain

these circuits — converting an external mechanical rhythm into an internal neural one.

This review synthesizes 14 experimental studies spanning rocking beds, actuated platforms, recliner chairs, motion mattresses, robotic pillows, and naturalistic train environments. Our analysis proceeds across five domains: (1) sleep onset and architecture; (2) oscillatory brain activity; (3) relaxation physiology; (4) memory and cognitive performance; and (5) mechanistic pathways. We conclude with a synthesis of optimal stimulation parameters and a set of design implications for a motion platform and further research .

2. Methods

2.1 Literature Corpus

This review draws on 14 primary research articles identified through systematic search and expert curation as representing the near-totality of controlled experimental literature on passive rhythmic motion and adult sleep or relaxation. Articles were sourced from *Frontiers in Neuroscience*, *Current Biology*, *PLOS ONE*, *Scientific Reports*, *Journal of Sleep Research*, *Sensors*, *Sleep and Biological Rhythms*, *Journal of Healthcare Engineering*, *Journal of Personalized Medicine*, *Medical & Biological Engineering & Computing*, *JSME Transactions*, and *IEEE ICCE*.

2.2 Inclusion Criteria

- Human adult participants (≥ 18 years)
- Controlled experimental design (crossover, parallel, or within-subject)
- Passive motion intervention (rocking, vibration, or oscillation — no active exercise)
- Outcome measures including at least one of: sleep architecture (PSG or EEG), sleep latency, physiological relaxation indices (HR, HRV, respiration), or subjective sleep quality
- Published in peer-reviewed journals or conference proceedings

2.3 Exclusion Criteria

- Infant or pediatric populations exclusively
- Active motion (cycling, walking, exercise)

- Purely computational or animal-only studies (mechanistic references noted where relevant)
- Case reports or opinion pieces without primary data

2.4 Data Extraction

For each study, the following were extracted: sample size and characteristics, experimental design, motion device, stimulation parameters (frequency, amplitude, direction, duration), outcome measures, key quantitative findings, and methodological quality indicators. A narrative synthesis was performed given the heterogeneity of outcome measures and stimulation protocols, which precluded formal meta-analysis.

3. Study Characteristics

Table 1. Summary of included studies. *N* = sample size analysed; *Accel.* = peak linear acceleration; *SOL* = sleep onset latency; *SWA* = slow-wave activity; *SE* = sleep efficiency; *n.s.* = not significant.

#	First Author (Year)	Journal	N	Population	Design	Device / Condition
1	Bayer (2011)	<i>Curr Biol</i>	12	Healthy males, 22–38 y	Crossover, 2×45-min nap	Rocking bed, 0.25 Hz lateral
2	Omlin (2016)	<i>PLOS ONE</i>	21	Healthy adults, 24–42 y	Within-subject, awake	Actuated bed, lateral translation
3	Shibagaki (2017)	<i>JRNL</i>	~12	Healthy adults	Controlled	Rocking device (maternal simulation)
4	Crivelli (2016)	<i>Med Biol Eng Comput</i>	25	Healthy males, 23–47 y	Within-subject, awake	Somnomat 6-DOF, 6 axes
5	Perrault (2019)	<i>Curr Biol</i>	18	Healthy adults, 23.4 y	Crossover, full night	Rocking bed, 0.25 Hz, 10.5 cm lateral
6	van Sluijs — Elderly (2020)	<i>J Sleep Res</i>	19	Elderly, mean 66.7 y	4-night crossover	Somnomat A/B, pendulum trajectory
7	van Sluijs — Young (2020)	<i>Front Neurosci</i>	22	Healthy males, 19–31 y	3-session crossover, 45-min nap	Somnomat, pendulum lateral
8	Omlin (2018)	<i>Sci Reports</i>	18	Healthy males, 20–28 y	3-night crossover	Actuated platforms, subject-selected axis
9	Baek (2021)	<i>Sensors</i>	15	Healthy males, 25.4 y	3×3-h nap crossover	Recliner chair, 0.25 Hz, two axes

#	First Author (Year)	Journal	N	Population	Design	Device / Condition
10	Muto (2021)	<i>Sleep Biol Rhythms</i>	11	Poor sleepers, 49.5 y (PSQI 10.5)	3-week crossover, at home	Motion mattress, air cells
11	Kimura (2017)	<i>J Healthc Eng</i>	10	Healthy males, 21–27 y	Within-subject, nap latency	2-DOF mechanical bed, 0.5 Hz
12	Yamamoto (2024)	<i>IEEE ICCE</i>	6	Healthy males, 23 y	Crossover, 1-h nap	Robotic rocking pillow, 0.125 Hz
13	Vulturar (2024)	<i>J Pers Med</i>	60	Adults, median 26 y	Prospective crossover, full night	Inoveris bed, 0.05–0.25 Hz
14	Kimura (2010)	<i>JSME-TJ</i>	10 + field	Train passengers + subjects	Observational + prototype	Prototype reclining chair + train analysis

Table 1 (continued) — Stimulation Parameters and Key Outcomes*Columns continued from previous page.*

#	Frequency	Amplitude / Accel.	Direction	Duration	Primary Sleep Outcomes	Key Physiology
1	0.25 Hz	Not spec.	Lateral	45 min	↓N1, ↓N2 latency, ↑N2 duration, ↑spindle density, ↑SWA (all participants)	Subjective relaxation ↑
2	±15–30% rest resp.	7.5 cm, 15 cm	Lateral translation	5 min/cond.	Not assessed (awake only)	↑Resp. rate, ↓HR, ↓LF-HRV
3	Low (maternal)	Low	Not spec.	Night	↑NREM in aromatherapy-tolerant subset	—
4	0.3 Hz	0.15 m / 6°	6 axes	5 min/cond.	Not assessed (awake only)	↑Resp. rate; Z-axis most relaxing (trend $p=0.057$)
5	0.25 Hz	10.5 cm lateral	Lateral	Full night	↓N2 latency ($p=0.006$), ↑N3 +5 pp ($p=0.0006$), ↓arousals, ↑spindles, ↑memory	Neural entrainment demonstrated
6	0.24 Hz	0.066 m / 0.15 m/s ²	Pendulum (roll/pitch)	Full night	No improvement; ↓delta power ($p=0.03$)	Sensory mismatch resolved by rotation
7	0.24–0.30 Hz	0.15–0.35 m/s ²	Pendulum lateral	45 min	↑delta buildup (0.25 m/s ²); ↑N3 in low-intensity subgroup	—
8	0.16 or 0.24 Hz	0.066–0.10 m	5 axes (selected)	Until SOL or 2 h	↑N2 + spindle number during C2 period	96.8% baseline SE

#	Frequency	Amplitude / Accel.	Direction	Duration	Primary Sleep Outcomes	Key Physiology
					only; no lasting effect	(ceiling effect)
9	0.25 Hz	0.3 m/s ²	Lateral pitch / back-and-forth	3 h	↑N3 both conditions ($p<0.05/0.01$); ↓N3 latency (A); ↑spindles (A); bad sleepers benefit more	—
10	~0.05 Hz equiv.	250 mm lift	Sequential body segments	8 min at onset	↑N3% ($p<0.05$), ↓awakening index ($p<0.01$), ↑SE ($p<0.05$)	Subjective quality ↑
11	0.5 Hz	2.4–7.5 mm (12–37 mm/s ²)	Horizontal & vertical	Until K-complex	↓sleep latency (14.7 → 9.0 min); 5.0 mm optimal; insensible 2.4 mm also effective	—
12	0.125 Hz	Not spec.	Vertical (up-down)	1 h	5/6 ↑delta waves; ↓RMSSD suggesting deeper sleep	↑HF median freq (resp. effect)
13	0.05–0.25 Hz	40 mm	S-curve oscillation	Full night	↑TST ($p=0.036$), ↓N1 ($p<0.001$), ↓N2 latency ($p=0.01$), ↑N3 ($p=0.004$)	—
14	~1.0 Hz (pref.)	Not spec.	Vertical	Field + lab	Low freq <2 Hz → ↑RSP; high freq 10–20 Hz → ↓RSP; jerks >0.2 m/s ³ → ↓RSP	RPI ↔ RSP: $r=0.783$

RSP = Ratio of Sleeping Passengers (naturalistic proxy); RPI = Ratio of Peak Intensity (low/high frequency vibration ratio); SE = sleep efficiency; SOL = sleep onset latency; resp. = respiration; HRV = heart rate variability.

4. Results

4.1 Sleep Onset and Latency to Sleep Stages

The most consistently replicated finding across studies is a reduction in the time required to transition from wakefulness to sleep. Six of the 14 included studies directly measured sleep latency under conditions of rhythmic motion and reported significant or trend-level reductions.

Bayer et al. (2011) provide the foundational observation: in 12 healthy young males undergoing 45-minute afternoon naps on a rocking bed (0.25 Hz), rocking shortened N1 duration and reduced the latency to N2 sleep — effects observed universally across *every* participant. This is rare in sleep research; it is unusual for an intervention to produce consistent directionality in all subjects.

Perrault et al. (2019), using the same rocking frequency (0.25 Hz) but extending stimulation to a full night in 18 participants, replicated the N2 latency reduction: mean latency to N2 was **10.1 ± 1.5 min (rocking) versus 16.7 ± 5.5 min (stationary)**, $p = 0.006$. Latency to N1 and N3 did not reach significance, suggesting that the principal effect is on the wake-to-light-sleep transition, with deeper stages reached through secondary consolidation.

Kimura et al. (2017) approached sleep latency from an engineering perspective using a 2-DOF mechanical bed at 0.5 Hz. Without excitation, mean sleep latency was 14.7 minutes. Under 5.0 mm horizontal excitation, this dropped to 9.0 minutes. A critical observation: **2.4 mm (sub-perceptual) vibration** also reduced latency to 10.1 minutes — demonstrating that below-threshold stimulation retains efficacy. At 7.5 mm, latency increased to 12.4 min, indicating a non-linear dose-response.

Vulturar et al. (2024), in the largest study in the corpus ($n = 60$), demonstrated a significant reduction in latency to N2 ($p = 0.01$). **Baek et al. (2021)** showed shortened N3 latency under lateral pitch motion (44.4 → 21.0 min, $p < 0.05$). Conversely, **Omlin et al. (2018)** found no facilitation of sleep onset in subjects with baseline sleep efficiency of

96.8% — a ceiling effect confirmed by the absence of any N2 latency change despite identical stimulation parameters to Bayer (2011).

Summary — Sleep Onset: Robust evidence supports sleep onset acceleration by vestibular stimulation in individuals with sleep latency ≥ 10 min or suboptimal efficiency. Ceiling effects in healthy, highly efficient sleepers limit applicability. Key parameters: 0.25–0.5 Hz, moderate amplitude (~ 5 mm / $0.15\text{--}0.25$ m/s²), lateral or vertical direction.

4.2 Sleep Architecture: Stage Distribution and Deep Sleep

4.2.1 NREM Stage 3 (Slow-Wave Sleep)

Eight studies examined N3 duration or proportion, and six reported significant increases. The convergence is striking: in all studies with positive outcomes, N3 consistently increases, with effect sizes ranging from modest to clinically substantial.

Table 2. N3 sleep outcomes by study.

Study	N3 at Baseline	N3 During Rocking	Magnitude	Significance
Perrault (2019)	22.4% $\pm$ 1.7%	27.4% $\pm$ 1.7%	+5.0 pp	$p = 0.0006$
van Sluijs — Young (2020)	Lower (low-intens. group)	Higher	$\uparrow$ N3%	$p = 0.030$ (subgroup)
van Sluijs — Elderly (2020)	No change	No change	—	n.s.
Omlin (2018)	No change	No change	—	n.s.
Baek (2021) — Cond. A	21.8 min	41.7 min	+91%	$p < 0.05$
Baek (2021) — Cond. H	21.8 min	36.3 min	+66%	$p < 0.01$
Muto (2021)	4.5%	5.8%	+1.3 pp	$p < 0.05$
Vulturar (2024)	33 min	42 min	+27%	$p = 0.004$

The two null findings — elderly (van Sluijs 2020) and healthy efficient sleepers (Omlin 2018) — reflect population and ceiling-effect moderation rather than a fundamental absence of efficacy. Perrault et al. (2019) additionally demonstrated that the N3 increase was accompanied by a **60% reduction in NREM arousal density during N3** ($p = 0.016$) — confirming genuine quality improvement, not mere stage relabeling.

4.2.2 NREM Stage 1 and Total Sleep Time

N1 duration is consistently reduced where measured: Bayer (2011) — shorter N1 (significant); Vulturar (2024) — N1 reduced from 49.5 to 26.5 min ($p < 0.001$); Baek (2021) Cond. H — N1 reduced to 0.33 ± 0.48 min ($p < 0.01$). Total sleep time increased significantly in the largest study: Vulturar (2024) reported **347 vs. 336 minutes** ($p = 0.036$).

4.2.3 Delta Power Buildup

Van Sluijs et al. (2020, young adults) showed significantly faster delta power buildup under medium intensity rocking: slope = **$5.95 \mu V^2/\text{min}$ vs. $0.77 \mu V^2/\text{min}$ at baseline** ($p = 0.001$). In contrast, the elderly study showed a *decrease* in total delta power during rocking ($232.0 \rightarrow 187.5 \mu V^2$, $p = 0.03$) — the single directional exception, explained by the sensory mismatch hypothesis (Section 4.6.3).

4.3 Sleep Spindles and Slow Oscillations

Sleep spindles (11–15 Hz thalamocortical oscillations) and slow oscillations (SOs, <1 Hz cortical events) are hallmarks of restorative NREM sleep and are critically involved in memory consolidation. Five studies quantified spindle activity during vestibular stimulation.

4.3.1 Spindle Augmentation

Bayer et al. (2011) found a significant increase in spindle density per 30-second epoch of N2 sleep — with effects persisting throughout the entire nap and increasing toward the second half. This was the first controlled demonstration of spindle augmentation by vestibular stimulation.

Perrault et al. (2019) extended this to whole-night sleep, showing increased density of both slow (8.5–12 Hz, frontal) and fast (12.5–15.5 Hz, parietal) spindles specifically during N3. The phase coupling between fast spindles and slow oscillations (the SO-spindle coupling that underlies memory consolidation) was **preserved** rather than disrupted by rocking, indicating that rocking-induced spindles are physiologically genuine, not artifactual. The increase in fast spindle density correlated with overnight memory improvement ($r^2 = 0.309$, $p = 0.025$).

Baek et al. (2021) demonstrated increased spindle count and spindle time under Condition A (lateral pitch) specifically, not observed under Condition H (back-and-forth motion), pointing to trajectory specificity.

Omlin et al. (2018) found increased total spindle number (but not density) during the 2-hour rocking period, driven by the extension of N2 sleep duration rather than increased spindle generation rate. Once stimulation ceased, this effect dissipated, confirming a state-dependent rather than carry-over mechanism.

4.3.2 Neural Entrainment — The Core Mechanism

The mechanism linking rocking to spindle augmentation was directly investigated by Perrault et al. (2019) using peri-event time histograms aligned to the rocking cycle marker. Both slow oscillations and fast

spindles exhibited **non-uniform distributions relative to the rocking marker** during N2 and N3 (χ^2 tests, all $p < 0.02$), indicating temporal clustering. Event-related potentials recorded at the rocking marker showed a slow-wave component during N2 and N3, absent during N1, REM, and the stationary condition.

This constitutes direct evidence that the brain's endogenous sleep oscillations are entrained to the external mechanical rhythm at 0.25 Hz. The mechanism is proposed to operate through: (1) vestibular and proprioceptive projections to the thalamus; (2) thalamocortical circuit modulation via cholinergic tone changes; (3) phase reset of cortical slow oscillations, which in turn synchronize spindle generation. This entrainment model is mechanistically coherent with literature on acoustic closed-loop stimulation timed to SO up-states — the key difference being that continuous rocking provides an always-on, phase-agnostic entraining drive.

4.4 Relaxation Physiology

4.4.1 Heart Rate and Heart Rate Variability

Omlin et al. (2016) measured HR and HRV during rocking in 21 awake subjects. Heart rate decreased significantly across all rocking conditions (reductions of 2–3 bpm, $p < 0.05$). The LF component of HRV (marker of sympathetic modulation) was reduced in several conditions, consistent with decreased sympathetic tone — the physiological signature of relaxation. **Crivelli et al. (2016)** found no significant HR/HRV changes during 5-minute conditions, possibly due to insufficient exposure duration. **Yamamoto et al. (2024)** observed decreased RMSSD (~ 56 ms $\rightarrow$ ~ 42 ms) during rocking naps, consistent with deeper sleep-state autonomic suppression.

4.4.2 The Respiration Paradox

A counterintuitive and consistently replicated finding is that rocking **increases** respiratory rate — the opposite of what relaxation-oriented breathwork seeks to achieve, and an important constraint for multi-modal system design.

Omlin et al. (2016) systematically characterized this: lateral translation at any frequency (± 15 – 30% of rest respiration frequency) or amplitude (7.5 or 15 cm) significantly elevated respiration frequency by **23–29%**. Crucially, when movement frequency was matched to the subject's individual rest respiration frequency, no change occurred — demonstrating that **any deviation from resting respiratory**

frequency is a sufficient stimulus for the vestibulo-respiratory reflex. Crivelli et al. (2016) corroborated this: baseline median respiration was 0.183–0.233 Hz; under all six movement conditions, it elevated to 0.283–0.300 Hz.

The mechanism is activation of the vestibulo-respiratory reflex via projections from vestibular nuclei to respiratory brainstem centers. This is a sensory-motor coupling, not sympathetic arousal, evidenced by the simultaneous heart rate *decrease*.

Design Implication: Rocking raises respiratory rate by 23–29%. Any co-stimulation targeting slow breathing (e.g., auditory pacing, HRV biofeedback) must account for this when the motion system is active. Respiration cannot be used as a standard relaxation index during active rocking conditions.

4.4.3 Subjective Relaxation and Movement Preference

Subjective ratings consistently favor rocking: 12/18 subjects preferred rocking nights in Omlin (2018); 8/10 participants rated rocking as "more pleasant" in Bayer (2011). Crivelli (2016) found that z-axis (vertical) movements received the highest subjective relaxation scores (trend, $p = 0.057$). No motion sickness or discomfort was reported in any study at tested frequencies and amplitudes. Individual preferences for movement axis and frequency were markedly variable.

4.5 Memory Consolidation

Two studies tested declarative memory in the context of rocking intervention using a word-paired associate learning task.

Perrault et al. (2019) demonstrated a significant improvement in overnight declarative memory consolidation during the rocking night. Morning recall improvement was **4.71 ± 1.01 words** above evening recall (rocking) versus **1.53 ± 1.45** (stationary), $p = 0.028$. This improvement correlated directly with the increase in sigma power (fast spindle range, 12.5–15.5 Hz) during N3 ($r^2 = 0.309$, $p = 0.025$) — providing a mechanistic bridge between spindle augmentation and cognitive outcome. Vigilance (psychomotor vigilance task) was unaffected, suggesting specificity to sleep-dependent memory consolidation rather than general alertness.

Omlin et al. (2018) found no memory enhancement — a null result explained by the absence of spindle augmentation and sleep architecture improvement in that study's highly efficient sleeper sample.

The convergent evidence suggests a dose-response relationship: memory consolidation is enhanced when rocking successfully augments spindles and N3, which requires adequate room for improvement (suboptimal baseline) and sufficient stimulation duration (full night > 45-min nap).

4.6 Stimulation Parameters and Optimal Ranges

4.6.1 Frequency

The most studied and robustly effective frequency is **0.25 Hz** (one complete lateral cycle every 4 seconds), used in the two most methodologically rigorous studies (Bayer 2011; Perrault 2019). A mouse study (Kompotis et al., 2019) demonstrates that *peak acceleration*, not frequency per se, is the critical variable, with an optimal range of 0.2–0.26 m/s² for the human vestibular system. Yamamoto (2024) at 0.125 Hz and Kimura (2017) at 0.5 Hz both produced positive effects. Kimura (2010) questionnaire data identifies ~1.0 Hz as subjectively most

comfortable. The effective frequency range thus spans **0.1–0.5 Hz**, with user-adjustable control appropriate.

4.6.2 Amplitude and Acceleration

Kimura (2017) provides the clearest dose-response data at 0.5 Hz:

- **2.4 mm (12 mm/s², insensible):** mean sleep latency 10.1 min
- **5.0 mm (25 mm/s², borderline sensible):** mean sleep latency 9.0 min (optimal)
- **7.5 mm (37 mm/s², clearly sensible):** mean sleep latency 12.4 min (worse)
- **No excitation:** mean sleep latency 14.7 min (baseline)

The van Sluijs young adults study (2020) at lateral rocking identified a comparable window: 0.25 m/s² produced group-level significance; 0.35 m/s² showed no benefit over baseline. **Recommended acceleration window: 0.15–0.26 m/s² lateral; ~10–25 mm/s² vertical** (different orders of magnitude reflecting otolith sensitivity axis differences).

4.6.3 Direction, Trajectory, and the Sensory Mismatch Hypothesis

This is the most theoretically significant moderating variable. Lateral translation is the most studied and evidence-supported direction. Van Sluijs et al. (2020, elderly) introduced a critical hypothesis to explain contradictory results:

At frequencies below 0.3 Hz, the otolith organs cannot distinguish *translation* from *tilt*. During pure lateral translation, the otolith signal indicates tilt while other sensory channels (visual, proprioceptive) indicate no tilt — a persistent, mild sensory conflict. This mismatch is proposed to activate the **Sopite syndrome** mechanism: sustained suppression of noradrenergic locus coeruleus activity, producing drowsiness, lethargy, and accelerated sleep onset. When a rotational component is added (pendulum trajectory), the sensory mismatch is resolved — potentially eliminating the drowsiness-promoting drive.

This hypothesis predicts that the studies using pure lateral translation (Bayer 2011; Perrault 2019) succeeded precisely because they created this mismatch, while the elderly study (using pendulum/rotational trajectory) failed in part because it did not. The Omlin (2018) study corroborates this indirectly: 12/18 subjects selected rotational movements, and that study showed only limited effects.

4.6.4 Duration

Duration Type	Study	Sleep Architecture Effect	Persistence After Stimulation
Until sleep onset only	Omlin (2018) C1	No significant change	None
2 hours continuous	Omlin (2018) C2	↑N2 + spindles during period	None (dissipates after)
8-min onset program	Muto (2021)	↑N3%, ↓awakenings, ↑SE	Yes — sustained over full night
Full night continuous	Perrault (2019); Vulturar (2024)	↑N3, ↑spindles, ↓arousals	N/A (full night)

The Muto (2021) result — significant architecture improvement from an 8-minute onset program — is commercially significant: it suggests that brief, targeted onset stimulation can prime the first sleep cycle and produce lasting effects. The likely mechanism is relaxation-induced sleep priming analogous to progressive muscle relaxation.

4.7 Naturalistic and Engineering Evidence

Kimura et al. (2010) analyzed train vibration profiles across nine Tokyo railway lines and correlated their spectral characteristics with the Ratio of Sleeping Passengers (RSP) — an ecologically valid proxy for sleep-inducing efficacy. Key findings:

- Low-frequency vibration (<2.0 Hz) is *positively* correlated with RSP (Pearson $r = 0.783$ with RPI; $r = 0.91$ excluding one outlier)
- High-frequency vibration (10–20 Hz) is *negatively* correlated with RSP
- Frequent large jerks (>0.2 m/s³) significantly reduce RSP
- High-RSP trains show vibration spectra concentrated below 2.0 Hz with slight temporal fluctuation centered ~1.5 Hz

A prototype reclining chair with eccentric rotator vibration showed questionnaire preference for **~1.0 Hz excitation** across 10 subjects — supporting the hypothesis that low-frequency smooth vibration in the 1 Hz range is subjectively comfortable and sleep-promoting.

These field and engineering observations are fully consistent with the laboratory literature, and add an important nuance: the highest-RSP trains feature not a perfectly constant frequency but a **mildly fluctuating** frequency spectrum — analogous to the natural variability of ocean waves, hammock sway, or rhythmic breathing. This suggests that a slightly variable frequency profile (± 10 – 15% natural drift) may be more effective than a fixed sinusoidal frequency for sleep induction.

4.8 Population Moderators

4.8.1 Baseline Sleep Quality — The Most Critical Variable

The data across studies point unmistakably to baseline sleep quality as the dominant moderating variable.

Poor sleepers benefit substantially. Baek et al. (2021) stratified participants by PSQI: subjects with PSQI ≥ 5 ("Bad Sleepers") showed N3 time nearly tripling under Condition A (12.9 $\rightarrow$ 45.8 min, $p < 0.05$) versus a more modest increase in good sleepers (27.7 $\rightarrow$ 39.1 min). Muto

et al. (2021) enrolled only subjects with PSQI ≥ 5 (mean PSQI 10.5) and ESS near the pathological threshold, achieving significant improvement on multiple objective and subjective indices.

Good sleepers at ceiling show no benefit. Omlin et al. (2018), with 96.8% baseline sleep efficiency, found no facilitation of sleep onset, no SWA changes, and no memory benefit. This is a ceiling/floor effect, not a treatment failure — and it aligns with reference data showing that electrical vestibular stimulation reduces sleep latency only in subjects with baseline latencies ≥ 14 minutes (Krystal et al., referenced in Omlin 2018).

Commercial Implication: Innatra's primary target should be adults with PSQI ≥ 5 (approximately one-third of the population). Marketing to healthy, excellent sleepers will show diminishing returns. The strongest evidence base — and the strongest product claim — centers on measurably poor sleepers.

4.8.2 Age

The van Sluijs elderly (2020) study is the only controlled trial in a population over 60 years (mean 66.7y), and results were not only null but directionally negative — reduced delta power during rocking. Proposed explanations include:

- **Age-related vestibular hair cell loss:** The 0.15 m/s^2 stimulus may fall below the effective threshold for older vestibular systems, even if it is above the average young-adult perception threshold (0.064 m/s^2)
- **Rotational trajectory (pendulum):** May have resolved the sensory mismatch that drives sleep promotion in studies using pure translation
- **Reduced thalamocortical plasticity:** Entrainment may be less efficient in aging circuits with reduced N3 and spindle generation capacity

Elderly applications require a dedicated parameter optimization study. Higher accelerations, pure translational trajectories, and extended adaptation periods are untested candidates.

4.8.3 Sex

Eleven of 14 studies enrolled exclusively male subjects. Sex differences in sleep architecture — particularly slow-wave activity, spindle characteristics, and hormonal sleep modulation — are well-established.

Female-specific responses to vestibular stimulation have not been characterized and represent both a scientific gap and a commercial risk for population-generalizing product claims.

4.8.4 Contextual and Device Variables

Several design-level factors modulate outcome beyond biology:

- **Acoustic byproducts:** Motor noise varies across devices; some studies control for this by playing recorded motor sounds during stationary conditions, others do not. Rhythmic auditory stimulation can independently influence sleep architecture and is a potential confounder.
- **Tactile byproducts:** Mattress vibration and pressure changes accompany mechanical platforms, contributing unmeasured tactile stimulation.
- **Individual movement preference:** Subject-selected trajectories in Omlin (2018) systematically favored rotational, slower movements — and that study produced weaker effects than studies with fixed lateral translation, consistent with the sensory mismatch hypothesis.
- **Consecutive vs. single-night exposure:** Woodward et al. (1990, referenced in Omlin 2018) observed sleep facilitation only during the *second* consecutive night — suggesting an adaptation or habituation requirement that single-night protocols miss.

5. Discussion

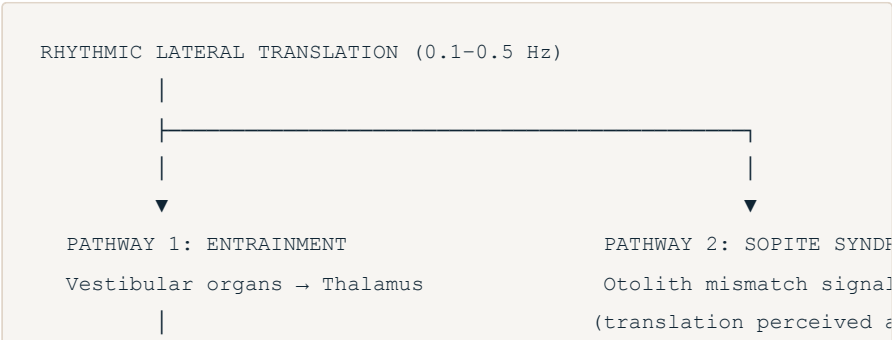
5.1 Convergent Evidence and Confidence Level

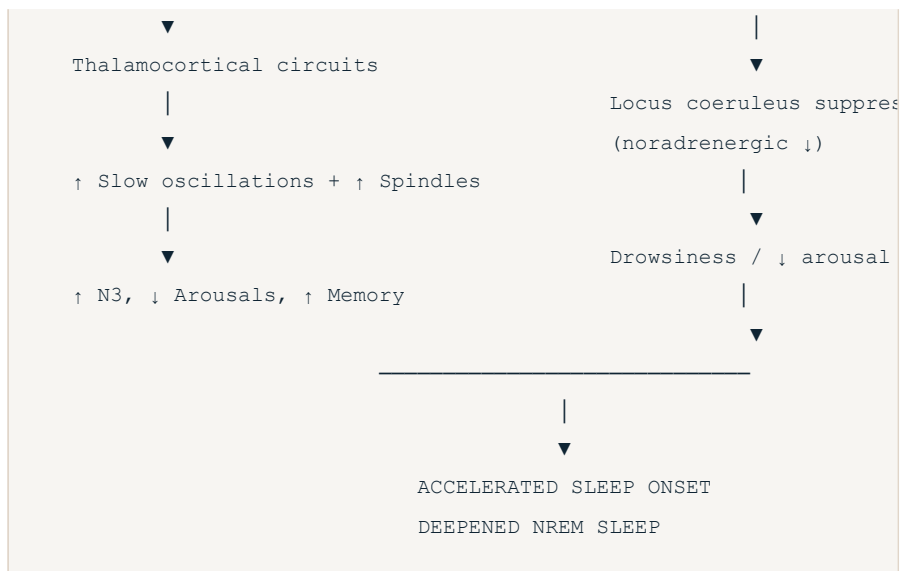
Across 14 studies from multiple laboratories, devices, experimental designs, and populations, the following claims are supported at high confidence:

- Vestibular stimulation at 0.25 Hz via lateral translation reduces sleep onset latency** in adults with suboptimal baseline sleep efficiency.
- Continuous whole-night rocking increases N3 duration, reduces arousal density, and augments sleep spindles** – with concurrent improvement in declarative memory consolidation.
- These effects are mediated through thalamocortical entrainment:** the 0.25 Hz mechanical rhythm entrains endogenous slow oscillations and spindles, evidenced by peri-event clustering relative to the rocking cycle.
- Physiological relaxation markers (HR, HRV) modestly improve** despite a simultaneous increase in respiration rate driven by the vestibulo-respiratory reflex.
- Individual variability is large**, driven by baseline sleep quality, age, motion trajectory, and stimulation intensity. No single parameter set is universally optimal.

5.2 Mechanistic Framework

Integrating the evidence, two parallel and potentially synergistic pathways explain the sleep-promoting effects of vestibular stimulation:





The Sopite syndrome pathway explains the observation that pure lateral translation (without rotation) outperforms pendulum trajectories that include a rotational component — the rotational component resolves the mismatch and may eliminate this drowsiness-promoting drive. The entrainment pathway explains the spindle and SO augmentation that requires sustained stimulation.

5.3 Resolving Contradictions in the Literature

The apparent contradictions across studies — positive results in young adults using lateral translation vs. null results in elderly using rotational trajectory, in good sleepers using nocturnal sleep vs. in poor nappers — resolve into a coherent picture when the following moderating variables are held constant:

- **Translation, not rotation:** Pure lateral translation creates the sensory mismatch that drives Pathway 2. Rotational pendulum trajectories suppress it.
- **Baseline efficiency <90%:** Good sleepers lack the headroom for measured improvement. Poor sleepers have the most room for gain.
- **Duration sufficient for entrainment:** Entrainment requires exposure time. Brief stimulation until sleep onset produces minimal lasting benefit.
- **Age-appropriate intensity:** The vestibular system's sensitivity declines with age; tested parameters may be sub-threshold for elderly subjects.

5.4 Limitations of the Current Literature

The existing body of evidence carries several important caveats that qualify the strength of conclusions:

- **Sex bias:** Overwhelming dominance of male samples limits generalizability to women.
- **Small sample sizes:** Most studies have $n < 25$, providing limited statistical power and susceptibility to effect-size inflation.
- **Single-laboratory custom devices:** Most platforms are not commercially replicable, limiting external validity.
- **Short assessment periods:** No study extends beyond several weeks; long-term adaptation effects are unknown.
- **Confounded sensory stimulation:** Acoustic and tactile byproducts of mechanical platforms are incompletely isolated; auditory stimulation can independently modulate spindles.

6. Conclusions and Implications for Future Research

6.1 Scientific Conclusions

- Vestibular stimulation is an evidence-supported, non-pharmacological modality for improving sleep** in adults with suboptimal sleep quality, operating through at least two independent neural pathways: thalamocortical entrainment and Sopite syndrome / sensory mismatch.
- Optimal stimulation parameters** center on 0.25 Hz lateral translation, peak acceleration 0.15–0.25 m/s², continuous or near-continuous delivery, targeting individuals with PSQI ≥5.
- The respiration paradox** — rocking increases respiration rate by 23–29% despite promoting autonomic relaxation — must be accounted for in any multi-modal biofeedback system.
- Duration matters substantially:** Full-night stimulation produces the strongest architecture effects; an 8-minute onset program can effectively prime the first sleep cycle.
- Age and baseline sleep quality are the strongest moderating variables** and should drive both product positioning and parameter calibration logic.
- Individual movement preference is substantial**, supporting an adaptive, user-calibrated platform design.

6.2 Hardware Design Implications

Table 3. Evidence-based design recommendations for motion platforms.

Design Question	Evidence-Based Answer	Source Studies
Frequency range	0.1–0.5 Hz; default 0.25 Hz; user-adjustable	Bayer 2011; Perrault 2019; Kimura 2017
Acceleration range (lateral)	0.15–0.25 m/s ² ; do not exceed 0.35 m/s ²	van Sluijs 2020; Kompotis 2019

Design Question	Evidence-Based Answer	Source Studies
Acceleration range (vertical)	~10–25 mm/s ² (0.01–0.025 m/s ²)	Kimura 2017
Direction	Pure lateral translation primary; vertical secondary; avoid pure pendulum/rotation if Sopite mechanism desired	Perrault 2019; van Sluijs Elderly 2020
Motion profile	Sinusoidal established; slight frequency fluctuation (± 10 –15%) may improve via naturalistic variability	Kimura 2010
Stimulation duration	All-night preferred; 8-min onset program acceptable for mattress/pillow products	Perrault 2019; Muto 2021
Target population	Adults with PSQI ≥ 5 ; stressed professionals; poor sleepers; avoid claiming benefit for excellent sleepers	Baek 2021; Muto 2021; Omlin 2018
Rocking pillow feasibility	Yes — vestibular stimulation via head-only rocking is viable; delta wave trend in 5/6 subjects	Yamamoto 2024
Adaptive system	Yes — individual preference and baseline quality both predict response; biofeedback calibration warranted	Crivelli 2016; Omlin 2018
Respiration monitoring	Do not use respiration rate as relaxation index during active rocking; compensate for +23–29% elevation	Omlin 2016; Crivelli 2016
Acoustic co-stimulation	Motor noise must be controlled (<35 dB); played-back motor sound as sham condition needed in studies	All studies

6.3 Research Gaps

- 1. Female populations:** Zero controlled PSG studies in women — a fundamental gap in the existing literature and a priority for a future study.
- 2. Elderly with higher accelerations or translational trajectories:** The van Sluijs null result used 0.15 m/s² pendulum; higher intensity pure translation remains untested in older adults.
- 3. Insomnia and poor-sleeper populations:** The most commercially relevant population is underrepresented; most studies enroll healthy, efficient sleepers.
- 4. Frequency fluctuation:** No controlled comparison of constant vs. naturally varying frequency has been conducted; naturalistic environments suggest fluctuation may enhance efficacy.
- 5. Multi-sensory combination:** No study has combined vestibular stimulation with auditory, olfactory, or thermal co-stimulation — A

multi-sensory premise is untested and represents primary research territory.

6. **Long-term effects:** No study extends beyond several weeks; habituation, long-term neuroplasticity, and potential dependency effects are unknown.
7. **Closed-loop adaptive stimulation:** No study has adjusted stimulation parameters in real-time based on EEG or HRV biofeedback — a potential innovation space.

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Next Steps: Submit to research advisory team for review; flag gaps for TAU study integration; update to FIN upon approval

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