European Union Aviation Safety Agency

This project has received funding from the European Union's Horizon Europe Programme

EMCO SIPO EASA.2022.C17

REPORT D-4 DURATION OF SLEEP INERTIA

eMCO-SiPO – Extended Minimum Crew Operations-Single Pilot Operations

An Agency of the European Union

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DELIVERABLE NUMBER AND TITLE:	D-4 Duration of sleep inertia
CONTRACT NUMBER:	EASA.2022.C17
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IPR OWNER:	European Union Aviation Safety Agency
DISTRIBUTION:	Public

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DATE: 15.12.2023

SUMMARY

Problem area

Two primary objectives were included in Task 4 of the research activity “Extended Minimum Crew Operations – Single Pilot Operations – Safety risk assessment framework” (EASA.2021.HVP.23): to assess the validity of the sleep-inertia duration assumption (30 minutes on average), and of the assumption that a pilot should not be expected to act or take decisions during this period. *Sleep inertia* refers to a transient state of ‘grogginess’ and disorientation immediately after waking up, during which cognitive performance is impaired. The Task 4 approach involved a systematic review of the literature, addressing the following questions as synthesized in this D-4 deliverable report:

(1) whether the average duration of 30 minutes for sleep inertia is a valid reference to be taken by EASA (**‘Duration’**); and
(2) whether, respectively, what tasks a pilot can be reasonably expected to perform during this period (**‘Type of task’**).
(3) whether effective countermeasures exist, including pro-active (i.e., before or during sleep) and reactive strategies (i.e., upon awakening) (**‘Countermeasures**); and
(4) whether there are individual factors that affect the duration and/or severity of sleep inertia (**‘Individual factors**).

Description of work

A systematic search was conducted in 3 online databases (i.e., PubMed, ScienceDirect, and PsychInfo), yielding 1,413 abstracts, each screened by 2 independent reviewers. Of these, 309 full texts were retrieved and again screened by 2 independent reviewers, resulting in a final set of 70 studies included in the literature review. Of these, 45 studies investigated the duration of sleep inertia; 43 studies investigated the effects of sleep inertia on different tasks/cognitive domains; 36 studies examined potential countermeasures for sleep inertia; and 4 studies examined inter-individual factors potentially associated with sleep inertia.

Application

“Duration”. Across different types of awakening (i.e., from a nighttime or daytime nap, or from nocturnal main sleep), sleep inertia was reported to last between 0 (no inertia) to 35 minutes.

“Type of task”. Findings were inconsistent as to whether and what cognitive domains/tasks were differentially impacted by inertia. Most studies found performance speed to be similarly or more impaired by inertia than performance accuracy, and observed that subjective ratings of cognitive impairment (e.g., self-reported alertness/sleepiness/fatigue) were not clearly correlated with impairments of objective performance (e.g., reaction speed).

“Countermeasures”. Nine countermeasures were identified, ranging from proactive strategies (i.e., applied before or during sleep) to reactive measures (i.e., applied upon awakening): nap timing; nap duration; light exposure; caffeine use; noise; exercise; anticipation of stress upon awakening; face-washing; and ‘self-

awakening'. Of these, the most promising countermeasures were short nap duration, exposure to light, and caffeine intake; yet, for all countermeasures, no studies testing their feasibility and implementation in an aircraft environment are available.

"Individual factors". Age, chronotype, and vulnerability to sleep inertia as a personality trait were identified as potential factors, that might affect the degree to which inertia impairs individual cognitive performance. However, due to the small number of studies, no firm conclusions could be drawn.

CONTENTS

ABBREVIATIONS

ACRONYM	DESCRIPTION
ADD	Addition task
ARROW	Cognitive functioning task
DF	Reviewer: Dorothee Fischer
DLR	German Aerospace Centre (German: Deutsches Zentrum für Luft- und Raumfahrt)
DST	Descending subtraction task
DSST	Digit Symbol Substitution Task
EASA	European Aviation Safety Agency
EE	Reviewer: Eva-Maria Elmenhorst
EEG	Electroencephalogram
ELOP	Equivalent Level of Performance
ELOS	Equivalent Level of Safety
eMCO	Extended Minimum Crew Operations
EU	European Union
FD	Forced-desynchrony protocol
FTT	Finger Tapping Task
ipRGCs	Intrinsically photosensitive retinal ganglion cells
KSS	Karolinska Sleepiness Scale
n-Back	Working memory task
NLR	Royal Netherlands Aerospace Centre (Dutch: Koninklijk Nederlands Lucht- en Ruimtevaartcentrum)
NREM	Non-Rapid Eye Movement sleep
PVT	Psychomotor Vigilance Test
SAS	Serial Addition and Subtraction Task
SB	Reviewer: Sibylle Benderoth
SPATIAL	Visual search task
SST	Serial subtraction task
STROOP	STROOP Color and Word Test
SWS	Slow wave sleep
TOC	Take-Over Controllability
UK	United Kingdom

1. Context

1.1 Main objective and scope of Task 4

The main objective in Task 4 of the research activity “Extended Minimum Crew Operations – Single Pilot Operations – Safety risk assessment framework” (EASA.2021.HVP.23) was two-fold: to assess the validity of the sleep-inertia duration assumption (30 minutes on average), and of the assumption that a pilot should not be expected to act or take decisions during this period. Sleep inertia refers to a transient state of ‘grogginess’ and disorientation immediately after waking up, during which cognitive performance is impaired. The Task 4 approach involved a systematic review of the literature, synthesizing the results of the review into a report, that considers endogenous and exogenous factors potentially affecting the duration of sleep inertia and performance of tasks during sleep inertia (i.e., inter-individual differences, use of countermeasures, contextual factors).

The approach in Task 4 sought to answer two primary questions:

(5) whether the average duration of 30 minutes for sleep inertia is a valid reference to be taken by EASA (**‘Duration’**); and
(6) whether, respectively, what tasks a pilot can be reasonably expected to perform during this period (**‘Type of task’**).

Beyond the two primary questions, we included two additional questions to be addressed by the literature review, namely:
(7) whether effective countermeasures exist, including pro-active (i.e., before or during sleep) and reactive strategies (i.e., upon awakening) (**‘Countermeasures**); and
(8) whether there are individual factors that affect the duration and/or severity of sleep inertia (**‘Individual factors**).

The Task 4 approach also included to balance the benefits of sleep periods of longer duration against the risk of more severe sleep inertia, and to evaluate *contextual/situational factors* that may influence the severity and dissipation of sleep inertia, such as sleep environment, timing of the flight in relation to the circadian sleep-wake cycle, duration of wakefulness prior to the allocated rest period, and the duration of the sleep period. These aspects will be addressed, as far as the literature permits, as part of the four main questions. In addition, the report includes a results synthesis regarding Equivalent Level of Performance (ELOP) findings.

The report is structured as follows: we begin by describing how the systematic literature review was conducted (Chapter 2). We then present the synthesized results of the included studies (Chapter 3), first for the two primary questions ‘Duration’ and ‘Type of Task’, followed by the two additional questions ‘Countermeasures’ and ‘Individual Factors’. Each result section is concluded with a summary paragraph. For each of the four questions, overall conclusions are drawn and presented in Chapter 4. These conclusions are then evaluated with a focus on eMCOs (Chapter 5), forming the basis for a set of conclusions regarding risk management of sleep inertia in eMCO settings (Chapter 6).

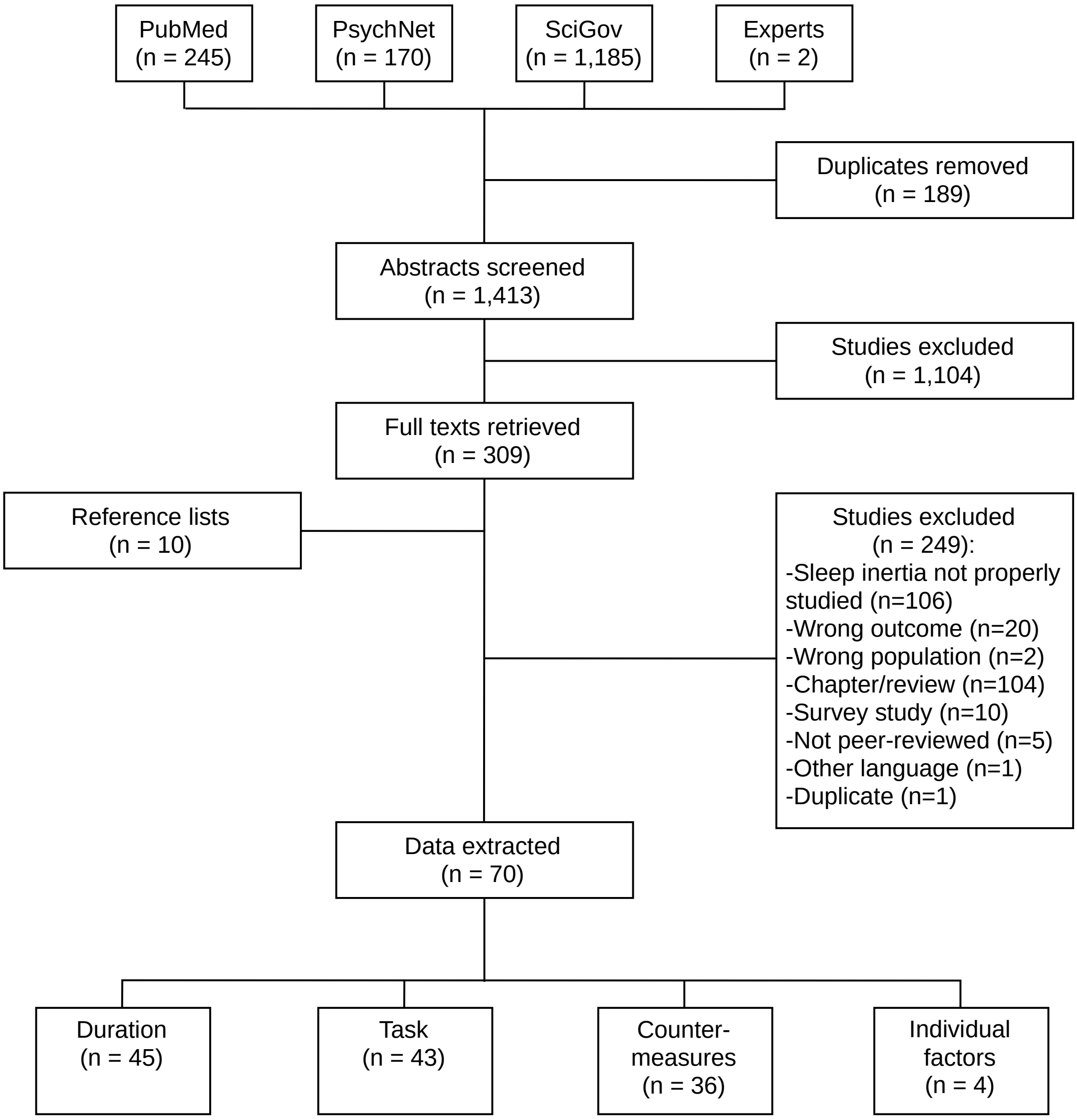
2. Methodology: Systematic review approach

A systematic search was conducted in 3 online databases: PubMed, PsychNet, and ScienceDirect. The originally proposed search strategy aimed to combine the outcome term (e.g., sleep inertia) with exposure terms describing the occupational nature (e.g., aviation, air crew). A PubMed search with ‘(“sleep inertia”) AND ("aviation" OR "airline" OR "aircrew" OR "flight")’ yielded 9 results. Additional exposure terms to include studies from driving, military, and medical settings added 26 studies. A similarly low number of search results were obtained in PsychNet and ScienceDirect. It was therefore decided to broaden the search such that occupational search terms were removed and the final search, conducted December 12, 2022, used the single outcome term “sleep inertia”.

2.1 Abstract screening

The systematic search yielded a total number of 1,600 potentially relevant abstracts (PubMed: 245; PsychNet: 170; ScienceDirect: 1,185), of which 189 duplicates were removed. In the process of abstract screening, 2 additional studies were identified by expert contacts as potentially relevant and included in the screening process, yielding a total of 1,413 screened abstracts. Figure 1 shows a PRISMA flow chart of the review process. Three independent reviewers at DLR (DF, EE, SB) performed the abstract screening, with each abstract evaluated by 2 of the 3 reviewers (i.e., DF-EE or DF-SB). Inclusion and exclusion criteria are shown in Table 1. Conflicts were resolved by consensus discussion, with both reviewers unanimously agreeing to include or exclude the abstract. Inter-rater reliability of the abstract screening, with a proportionate agreement of 86% (DF-EE) / 90% (DF-SB) and Cohen’s Kappa of 0.66 (DF-EE) / 0.67 (DF-SB), indicated substantial agreement between reviewers.

Figure 1: Overview of the screening process of the systematic review.



2.2 Full text review

Of 1,413 screened abstracts, 309 were included for full text retrieval (Figure 1). Full text screening was performed by the same 3 independent reviewers, again in pairs of two. Studies were included if they reported (i) information on at least one of the four review questions (i.e., duration, task, countermeasures, individual factors) and (ii) several measurements after awakening to determine sleep inertia. Studies with a single measurement after awakening were also included, if it was an immediate post-sleep measurement of sleepiness/performance (e.g., morning awakening after full-night sleep) vs. a baseline measurement, respectively, vs. a measurement after a nap/upon forced awakening during the night. Studies were excluded if sleep inertia itself was not studied but was used as a post-hoc explanation of the study’s findings; if inertia was self-reported (e.g., survey studies); or if the paper explicitly stated that a break was introduced between awakening and first test session to avoid sleep inertia. Full texts of reviews/chapters were retrieved to screen reference lists for additional studies but were not included for data extraction. Inter-rater reliability of the full text screening was at near-perfect agreement, with a proportionate agreement of 91% (DF-EE) / 99% (DF-SB) and Cohen's Kappa of 0.81 (DF-EE) / 0.98 (DF-SB).

Table 1: Inclusion and exclusion criteria of the systematic review.

Inclusion criteria	Exclusion criteria
Type of study: case-control studies, cohort studies, observational studies, laboratory studies, field studies.	**Type of study:** reviews, survey studies, case studies, clinical trials, pharmaceutical trials/pharmacotherapy studies, animal studies, modeling studies, general papers (e.g., overviews, reviews, chapters).
Outcome: cognitive performance (attention/reaction time, problem-solving, decision-making, logical reasoning, etc.), stress, fatigue, sleepiness, alertness. <ins>Comparison:</ins> nap vs. no-nap condition.	**Outcome:** physical performance (e.g., sprinting), recall/learning, dreaming/dream recall, emotion processing/fear/emotional responses, EEG measures only, mental disorders (e.g., depression, anxiety), sleep disorders (e.g., hypersomnia, narcolepsy, insomnia, excessive daytime sleepiness, somnolence), drugs/pharmaceuticals (e.g., alcohol, medication; unless specifically designated as a countermeasure for sleepiness/sleep inertia, such as caffeine). <ins>Comparison:</ins> pre-sleep vs. post-sleep comparison with single time points.
Population: pilots/cockpit crew, cabin crew, military, hospital staff, nursing home staff, emergency services personnel (e.g., helicopter pilots, firefighters, police), driving (e.g., truck drivers), shift workers; healthy adults in lab studies.	**Population:** children, adolescents, elderly (e.g., retired), patients/clinical populations, astronauts/space crew, athletes.
Exposure: sleep inertia, awakenings, sleep deprivation/restriction/loss, naps/napping.	
Language: English, German, Dutch	**Language:** all other languages

2.3 Data extraction

A final set of 70 studies was included for data extraction (Figure 1). Extracted data included: title, author, publication year, type of publication (e.g., peer-reviewed), country of data collection, study aim, type of study (e.g., lab study), study design (e.g., cross-sectional), occupation (e.g., non-occupational (healthy adults), civil aviation, military (incl. air force)), sample size, mean sample age, sex ratio (% male), study protocol, period over which inertia was studied, type of awakening (e.g., after a nighttime nap), time between awakening and first test session, number of time points after awakening, interval between time points, type of task (e.g., reaction time), name of task (e.g., PVT), main results and key messages. A list of all 70 studies is provided in Table S1 in Annex A.

Type of awakening included: waking up from nighttime naps, after nocturnal awakenings (e.g., main sleep interruptions during the night), after daytime naps, and following nighttime or daytime main sleep episodes. The distinction was made since awakenings after naps were deemed more relevant to eMCO settings than waking up from main sleep episodes.

Studies were deemed as assessing performance at a **high resolution** if they fulfilled the following 3 criteria: first measurement immediately upon awakening (≤ 3 minutes between waking up and start of testing); repeated measurements at short intervals (≤ 10 minutes between test points); and a sufficiently long study period (≥ 20 minutes between first and last test point).

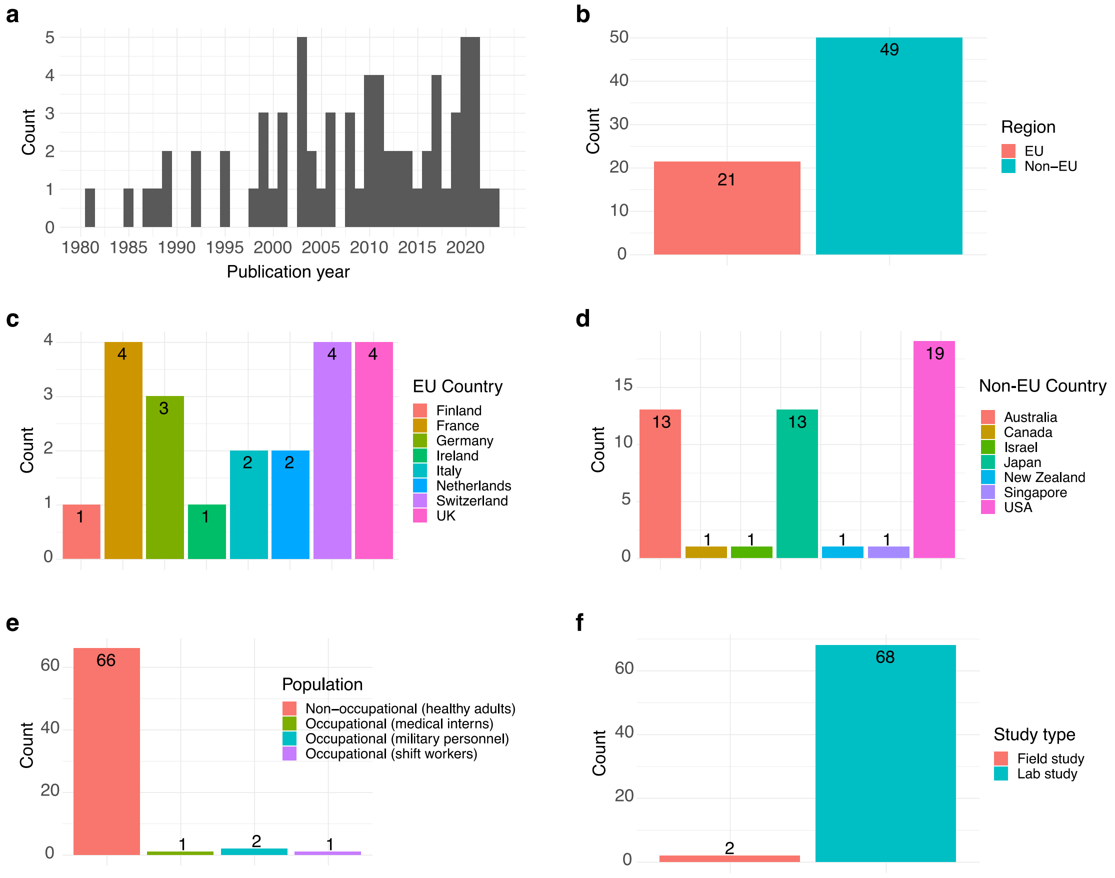
Studies were deemed **operationally relevant**, if they were conducted in an occupational population (e.g., pilots, military personnel, hospital staff); if they studied relevant work settings (e.g., on-call, night work, extended shifts); or if they assessed operationally relevant tasks/cognitive domains (e.g., decision-making, risk-assessment).

3. Synthesis of results

Study descriptives

Figure 2 shows an overview of study descriptives. The 70 studies included in the literature review were published between 1981 and 2023, with a median publication year of 2010. A majority of studies (49 out of 70 studies, 70%) were conducted in non-EU countries, with most of them being conducted in the US (n = 19 studies), followed by Japan and Australia (n = 13 studies each). Sixty-six of 70 studies (94%) included samples of healthy adults. The remaining 4 studies involved military staff (n = 2 studies), medical interns (n = 1 study), and shift workers (n = 1 study). An overwhelming majority of 68 of 70 studies (97%) were conducted in the laboratory, with only a single study conducted in the field.

Figure 2: Descriptives of included studies. *a) publication year, b) region (EU vs. Non-EU), c) EU countries (all included UK studies were conducted before Brexit; Switzerland was deemed more similar to EU than Non-EU countries with respect to regulations), d) Non-EU countries, e) study population, and f) study type (field vs. lab study).*

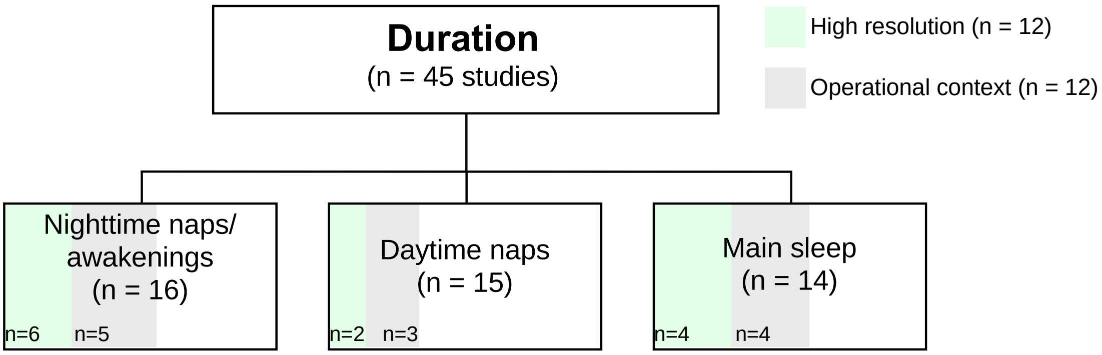


3.1 Primary results: Duration and Type of Task

3.1.1 Duration of sleep inertia

A total of 45 studies investigated the duration of sleep inertia. There was no standard approach to defining the duration of sleep inertia. Most studies used the absence of a significant difference between inertia-impaired performance and baseline performance to determine the end of sleep inertia, with baseline referring to performance in a well-rested state (e.g., during the daytime), in a wakefulness condition (e.g., participants not taking a nap), or before sleep/napping (i.e., pre/post comparisons). The studies were grouped according to the type of awakening after which sleep inertia was studied: after (i) nighttime naps/awakenings (n = 16), (ii) daytime naps (n = 15), (iii) nighttime main sleep (n = 12) and other types of main sleep (i.e., during the daytime or in a forced desynchrony protocol) (n = 2). Figure 3 shows an overview. Tables 2-4 list the included studies.

Figure 3: Overview of studies for sleep inertia duration, grouped by type of awakening. *Green shading shows the number of included high-resolution studies (criteria: ≤3 min since awakening, ≤ 10 min between tests, ≥20 study period). Patterned shading shows the number of studies deemed operationally relevant (criteria: occupational population (e.g., military staff), occupational work setting (e.g., on-call), or operationally relevant task (e.g., decision-making)).*



3.1.1.1 Duration of sleep inertia after nighttime naps/awakenings

Of the 16 studies investigating sleep inertia after a nighttime nap (n = 12) or upon nocturnal awakenings (n = 4), 6 studies measured performance at a very high resolution, i.e., immediately upon awakening (≤ 3 minutes), at short intervals (≤ 10 minutes), and over a sufficiently long period (≥ 20 minutes) (Bruck & Pisani, 1999; Figueiro et al., 2019; Newman et al., 2013; Salamé et al., 1995; Tassi et al., 1992, 2006). Five studies were deemed operationally relevant (Basner et al., 2017; Bruck & Pisani, 1999; Newman et al., 2013; Sallinen et al., 1998; Signal et al., 2012), with two studies having both high-resolution measurements and an operational context (Bruck & Pisani, 1999; Newman et al., 2013).

High-resolution studies

Two studies, Tassi et al. (1992) and Salamé et al. (1995), employed very similar study designs and tasks. They examined the effects of sleep inertia on spatial memory after a 1-h nap opportunity at two different times, an early-night nap (0:00 - 1:00) vs. a late-night nap (3:00 - 4:00). Inertia effects on response speed had dissipated after 9-15 minutes (Tassi et al., 1992), respectively, after 24 minutes (Salamé et al., 1995). Additionally, Salamé et al. found that inertia effects on logical reasoning had dissipated after 27 min. Another study by Figueiro et al. (2019) examined inertia effects on sustained alertness after a 1-h nap from 0:00 - 1:00, using two auditory reaction time tests. They observed that inertia had dissipated after approximately 15 minutes.

Tassi et al. (2006) examined sleep inertia effects on selective attention after a 2-h nap opportunity at the end of the night (5:00 - 7:00) and found that performance impairments in response speed had recovered after approximately 25 minutes and no more than 30 minutes.

Operationally relevant studies

A study by Bruck & Pisani (1999) investigated decision-making performance in a simulated, operationally relevant fire-fighter setting, waking participants up twice during the night. They observed the greatest impairments during the first 3 minutes, with performance at ~ 50% below the optimum. Performance stayed below the optimum until the end of the 30-min assessment period, yet most impairments were recovered after 20 minutes (≥ 80% of baseline level). Newman et al. (2013) assessed inertia in active-duty military personnel after a 1-h nap from 0:00 - 1:00, using a simple reaction time task. Response speed was at 79% of baseline performance immediately after awakening and continued to degrade to 73% at the last time point (e.g., 18 minutes post-awakening). The same trajectory was observed for attentional failures (i.e., lapses). The pattern of continuously degrading performance may indicate that circadian effects masked potential inertia effects, i.e., they outweighed the dissipation of inertia (i.e., improving performance with time since awakening). It may also mean that there were no detectable inertia effects on sustained alertness during the early night in a group of active-duty military personnel. A study by Signal et al. (2012) compared sleep inertia effects after naps during simulated night shifts vs. extended shifts (i.e., 30-h wakefulness). The naps had durations of 20/40/60 minutes and ended either at 2:00 (during the night shift at an adverse circadian time) or at 12:00 (after the extended shift at a more favorable circadian time but with increased sleep pressure). They observed that inertia effects on working memory did not last longer than 15 minutes and did not differ between the simulated night shift and extended shift. The third study with an operationally relevant context was conducted in a hospital and examined sleep inertia in medical interns and residents (Basner et al., 2017). After an on-call night, participants completed the PVT measuring sustained alertness once in the morning, with time since last awakening ranging from a few minutes to 2 hours. Interns obtained on average a total of ~ 2.2 hours of sleep during on-call nights. Basner et al. found that response speed after waking on-call was impaired for 60 minutes. A study by Sallinen et al. (1998) investigated sleep inertia in a sample of process operators from an oil refinery. Inviting participants to the lab, they studied naps of different lengths and timing: 30 vs. 50 minutes ending at 1:50 vs. 4:40, respectively, resulting in four combinations of ‘early-short’, ‘early-long’, ‘late-short’ and ‘late-long’ naps. Like Basner et al. (2017), they used a visual reaction time test to assess inertia effects on sustained alertness, but had a better measurement resolution, assessing performance twice in the same individual, once immediately upon awakening for 10 minutes, followed by a 5-min break, and again at 15 minutes post-awakening. They found inertia lasted for 10 - 15 minutes, having dissipated at the second testing, irrespective of nap length and timing.

Other studies

Hilditch et al. (2016) examined inertia after a 10-min vs. 30-min nap ending at 4:00 and found only minimal inertia effects after the 10-min nap. However, after the 30-min nap, PVT-measured sustained alertness was still worse at 47 minutes past awakening (i.e., the last measurement time point), whereas inertia effects on a general cognitive-functioning task (DSST, measuring various domains including processing speed and working memory) had dissipated between 2 and 15 minutes. Using the same tasks and a similar napping protocol, Tremaine et al. (2010) observed that sleep inertia after a 30-min nap ending at 3:00 lasted between 10 and 40 minutes (the wide range owing to the measurement interval of 30 minutes), and Centofanti et al. (2020) found that inertia effects on attentional failures (i.e., lapses) lasted less than 15 minutes after a 30-min nap ending at 4:00. Kovac et al. (2021) examined longer naps of 2 hours taken during the early night (0:00-2:00) and found that inertia effects on sustained alertness, selective attention, and cognitive throughput had dissipated after ≤ 30 minutes.

Two studies examined inertia effects after multiple awakenings during nighttime sleep, assessing performance at short, repeated intervals (2.5 - 6 min), yet over a brief period (10 - 13.5 min). Kolff et al. (2003) found that inertia effects on semantic memory (i.e., recognizing relations between words) dissipated very fast, lasting less than 5 minutes. Inertia effects on cognitive throughput as measured by a mathematical task (i.e., adding two-digit numbers) were still present at 13.5 minutes, i.e., the end of the measurement period (Balkin & Badia, 1988). Using the same task to examine sleep inertia upon awakening at different circadian phases, Scheer et al. (2008) found that the magnitude of sleep inertia showed a circadian modulation, being worse during an individual's biological night (i.e., when the body's physiology is prepared for sleep/rest), but that irrespective of the timing of awakening, inertia dissipated within 20 minutes.

Summary: Sleep inertia duration after nighttime naps/awakenings

Twelve out of 16 included studies, including 5 out of 6 high-resolution studies, indicated that the duration of sleep inertia after nighttime naps and awakenings lasted between 2.5 and 30 minutes. In one study of military personnel, the duration of inertia was unclear (Newman et al., 2013). Of the 3 studies reporting inertia durations of more than 30 minutes, one study observed a range of 10 - 40 minutes (owing to the study's wide 30-min measurement interval) (Tremaine et al., 2010); one study found a duration of ≥ 47 minutes for sustained alertness and ≤ 15 minutes for other cognitive functions (Hilditch et al., 2016a); and one field study conducted in medical interns observed a duration of 60 minutes for sustained alertness, based on a between-subject design with no repeated measurements (Basner et al., 2017).

Table 2: Overview of studies for sleep inertia duration after nighttime naps/awakenings (n = 16). *Studies are listed according to their appearance in the text. Period = time period over which inertia was tested. Interval = time between tests. Latency = time between awakening and first test. In yellow: high-resolution studies. *Operationally relevant studies.*

First author, Year	Period/Interval/ Latency	Nap duration (timing)	Inertia duration	Cognitive domain (*task*)
Tassi 1992	70min/3min/3min	60min (0:00-1:00 vs. 3:00-4:00)	9-15min	Spatial memory
Salame 1995	60min/3min/2min	60min (0:00-1:00 vs. 3:00-4:00)	24-27min	Spatial memory, logical reasoning
Figueiro 2019	30min/7min/0min	60min (0:00-1:00)	<15min	Selective attention (*auditory*), sustained alertness (*auditory*)
Tassi 2006	60min/5min/2min	120min (5:00-7:00)	25 to <30min	Selective attention/ cognitive inhibition (*STROOP*)
Bruck 1999*	30min/3-6min/0min	Nighttime awakenings	20min	Decision-making (*wildfire emergency*)
Newman 2013*	24min/6min/0min	60min (0:00-1:00)	Unclear	Sustained alertness (*visual PVT*)
Signal 2012*	60min/15min/0min	20/40/60min (ending at 2:00 vs. 12:00)	≤15min	Working memory (*n-Back*)
Basner 2017*	>120min/30min/1min	0 to 540min (unclear timing, average performance testing at ~8:00)	60min	Sustained alertness (*visual PVT*)
Sallinen 1998*	25min/15min/0min	30/50min (ending at 1:50 vs. 4:40)	10-15min	Sustained alertness (*visual*)
Hilditch 2016a	55min/15min/2min	10/30min (ending at 4:00)	2min to ≤15min (DSST), ≥47min (PVT)	Sustained alertness (*visual PVT*), cognitive functioning (*DSST*)
Tremaine 2010	250min/30min/5min	30min (2:30-3:00)	10-40min	Sustained alertness (visual, PVT), cognitive functioning (*DSST*)
Centofanti 2020	50min/15min/0min	30min (3:30-4:00)	<15min	Sustained alertness (*visual PVT with lapses only*)
Kovac 2021	120min/15min/ 5min	120min (0:00-2:00)	≤30 min	Sustained alertness (*visual PVT*), cognitive throughput (SAS), selective attention (*SPATIAL*)
Kolff 2003	10min/2.5/1min	Nighttime awakenings	2.5min to <5min	Semantic memory access
Balkin 1988	13.5min/6min/1.5min	Nighttime awakenings	>13.5min	Cognitive throughput (*ADD*)
Scheer 2008	20min/20min/2min	Nighttime awakenings	≤20min	Cognitive throughput (*ADD*)

STROOP = Stroop Color and Word Test. PVT = Psychomotor Vigilance Task. n-back = working memory task. DSST = Digit Symbol Substitution Test. SAS = Serial Addition and Subtraction Task. SPATIAL = visual search task. ADD = Addition task.

3.1.1.2 Duration of sleep inertia after daytime naps

Of the 15 studies investigating sleep inertia after a daytime nap, 2 studies measured performance at a high resolution (Kaida et al., 2003a,b; in the following summarized under ‘Studies on inertia after daytime naps of shorter duration (≤ 1 hour)’) and 3 studies were deemed operationally relevant, investigating take-over performance in simulated, automated driving (Wörle et al., 2020; Wörle et al., 2021a,b).

Operationally relevant studies

The 3 studies deemed operationally relevant were conducted quite recently by the same research group, Wörle et al. (2020, 2021a,b). Subjects participated in highly automated driving scenarios in a high-fidelity driving simulator. The inertia-driving sessions took place early in the morning (between 6:00 and 8:00) and participants were instructed to sleep no longer than 4 hours the night before to increase the likelihood of falling asleep in the simulator. During the drives, participants handled several takeover and/or driving scenarios. In takeover scenarios (e.g., construction vehicles block several lanes and participants must move to the unblocked lane), they were required to take back control of the vehicle within a given time frame of 60 seconds. In driving scenarios, participants were required to drive manually because of heavy rain, stay in their lane and continue driving under monotonous conditions. The scenarios were issued when participants experienced stable N2-stage sleep. Takeover performance was assessed using *Take-Over Controllability* (TOC) ratings, performed by trained raters, considering safety-criticality and quality/errors of the takeover. Additionally, reaction times were calculated for various components, e.g., first road glance, hands on the steering wheel, take back control (i.e., deactivate the automated system), change lanes. Driving performance was assessed as mean speed and standard deviations of speed and lane position. In all 3 studies, participants slept between 15 - 20 minutes before being woken up. Wörle et al. (2020) found that sleep inertia extended reaction times by 3 seconds on average, but all participants managed to take over manual driving within the given 60 seconds. In a subsequent study (Wörle et al., 2021a), the allotted time for takeover was reduced to 15 seconds, and again all participants managed to take back control within the time frame. Investigating driving performance, Wörle et al. (2021a,b) found that inertia negatively impacted lane keeping performance for 3 - 5 minutes and resulted in reduced speed for ≥ 10 minutes (i.e., for the entire manual driving period). Lane keeping performance recovered quickly but the magnitude of inertia was severe: during the 3 - 5 minutes of impairment, the observed lane deviations were as large as 0.25 m. In comparison, a study on driving performance with a blood alcohol level of 0.08% conducted in the same driving simulator observed a 0.05 m deviation for lane keeping performance (Kenntner-Mabiala et al., 2015).

Studies on inertia after daytime naps of longer duration (> 1 hour)

Kräuchi et al. (2003) observed an inertia duration of ≤ 60 minutes after a 2-h nap opportunity between 16:00 and 18:00; however, they only assessed subjective sleepiness and had no objective performance measures. Three studies investigated longer naps of 1.5 - 2 hours at different times of day: morning, 10:00-11:30 (Groeger et al., 2011) vs. afternoon, 14:00-16:00 (Hofer-Tinguely et al., 2005) / 15:00-16:30 (Groeger et al., 2011) / 15:00-17:00 (Lavie & Weler, 1989) vs. evening, 18:00-20:00 (Hofer-Tinguely et al., 2005) / 19:00-21:00 (Lavie & Weler, 1989). Two of the 3 studies observed different inertia effects depending on the timing of the nap; the findings were, however, inconsistent for afternoon naps: Groeger et al. (2011) found inertia effects on working memory with a duration of ≤ 25 minutes following the afternoon nap but no inertia effects for the morning nap, whereas Lavie and Weler (1989) found only minimal effects following the afternoon nap, but a duration of between > 20 and ≤ 40 minutes (owing to a measurement interval of 20 min) for the evening nap. In the study by Lavie and Weler (1989), inertia was measured as the inability to resist sleep during a period of 7 minutes. The third study by Hofer-Tinguely et al. (2005) found inertia effects on sustained alertness and cognitive throughput (mathematical addition task) for both the afternoon and evening nap, observing that the slowest reaction times had recovered significantly after ≤ 20 minutes. Yet, performance stayed below the baseline for 60 minutes (i.e., until the end of the measurement period).

Studies on inertia after daytime naps of shorter duration (≤ 1 hour)

Investigating inertia effects after short daytime naps (i.e., 5 - 60 min), 3 studies found no inertia effects on a task measuring selective attention after a 15- to 20-min nap ending at 14:20 (Kaida et al., 2003a,b) nor on short-term memory after a 20-min nap ending at 13:00 (Hayashi et al., 2003). After a 45-min nap ending at 14:15, Vallat et al. (2019) observed an inertia duration of ≤ 25 minutes for cognitive throughput (mathematical subtraction task). Dinges et al. (1981) examined inertia effects after a 60-minutes afternoon nap on cognitive throughput and the time it took participants to react to a phone bell ringing by picking up the receiver. Both measures were impaired upon awakening but had recovered at the second time point at 35 minutes post-nap. Three studies investigated the effects of different nap durations on inertia (all naps ending at approximately 15:00) using the same tasks to assess cognitive functioning and sustained alertness. All 3 studies (Tietzel & Lack, 2001; Brooks & Lack, 2006; Leong et al., 2023) observed no or minimal inertia after a 10-min nap; yet, after naps of 30-60min, inertia lasted between 5 minutes and no more than 30 - 35 minutes (the wide range owing to a measurement interval of 30 minutes in all 3 studies).

Summary: Sleep inertia after daytime naps

Based on 13 out of 15 studies with objective performance measures (excluding Lavie & Weler, 1989, measuring resistance to sleep, and Kräuchi et al., 2004, assessing subjective sleepiness only), inertia was reported to last between 0 (no inertia) and 35 minutes after daytime naps. There were shortcomings regarding the granularity of inertia assessments: only two studies (Kaida et al., 2003a,b) investigated inertia effects after daytime naps at a very high resolution, i.e., assessing performance immediately upon awakening (≤ 3 min), at short intervals (≤ 10 min), and over a sufficiently long period (≥ 20 min). Two other studies measured performance every 12 minutes between 5 - 60 minutes after awakening (Hofer-Tinguely et al., 2005), respectively, every 15 minutes between 2 - 60 minutes after awakening (Hayashi et al., 2003). The 3 operationally relevant studies assessed driving performance continuously, yet over very brief periods (≤ 10 min). The remaining 8 studies had measurement intervals of 20 to 30 minutes, from which the exact duration of inertia was difficult to determine.

Table 3: Overview of studies for sleep inertia duration after daytime naps (n = 15). *Studies are listed according to their appearance in the text. Period = time period over which inertia was tested. Interval = time between tests. Latency = time between awakening and first test. In yellow: high-resolution studies. *Operationally relevant studies. #Studies with subjective or non-performance measures only.*

First author, Year	Period/Interval/ Latency	Nap duration (timing)	Inertia duration	Cognitive domain (*task*)
Kaida 2003a	25min/2min /5min	15-20min (14:00-14:20)	No inertia	Selective attention (*Oddball task*)
Kaida 2003b	30min/1min /5min	15-20min (14:00-14:20)	No inertia	Selective attention (*Oddball task*)
Wörle 2020*	5min/continuously/ 0min	15-20min (between 6:00-8:00)	≤60s, +3s for takeover when inertia vs. awake	Driver performance (*take-over*)
Wörle 2021a*	2-10min/ continuously/0min	15-20min (between 6:00-7:30)	≤15s (takeover); 3min (lane keeping), ≥10min driving speed	Driver performance (*take-over & driving*)
Wörle 2021b*	10min/ continuously/0min	15-20min (between 6:00-7:30)	5min (lane keeping), ≥10min driving speed	Driver performance (*driving*)
Kräuchi 2004#	120min/30min/0min	120min (16:00-18:00)	≤60min	Subjective only (*KSS*)
Lavie 1989#	>120min/20min/13min	120min (15:00-17:00 vs. 19:00-21:00)	>20-≤40min (only after early nap)	Resisting sleep
Groeger 2011	25min/20min/5min	90min (10:00-11:30 vs. 15:00-16:30)	≤25min (only after late nap, no inertia after early nap)	Working memory (*n-back*)
Hofer-Tinguely 2005	60min/12min/5min	120min (14:00-16:00 vs. 18:00-20:00)	≤20min	Sustained alertness (*auditory*), cognitive throughput (*ADD*)
Hayashi 2003	60min/15min/2min	20min (ending at 13:00)	No inertia	Short-term memory (*search task*)
Vallat 2019	25min/20min/5min	45min (13:30-14:15)	≤25min	Cognitive throughput (*DST*)
Dinges 1981	35min/35min/0min	60min (afternoon, not specified)	<35min	Cognitive throughput (*DST*), reaction time to a phone bell/alarm
Tietzel 2001	75min/30min/5min	10/30min (ending at 15:10)	≤35min (after 30min nap only)	Cognitive functioning (*DSST*)
Brooks 2006	180min/30-60min/5min	5/10/20/30min (ending at 15:00)	≤35min (after 30min nap only)	Cognitive functioning (*DSST*), selective attention, sustained alertness (*visual*)
Leong 2023	240min/30min/5min	10/30/60min (ending at 14:30)	≤30min (DSST, 30/60min naps only), no inertia (PVT)	Cognitive functioning (*DSST*), sustained alertness (*visual PVT*)

KSS = Karolinska Sleepiness Scale. n-back = working memory task. ADD = Addition task. DST = Digit Subtraction Task. DSST = Digit Symbol Substitution Test. PVT = Psychomotor Vigilance Task.

3.1.1.3 Duration of sleep inertia after main sleep

The majority of the 14 included studies investigating sleep inertia after a main sleep episode examined inertia after nighttime main sleep (n = 12), while 2 studies examined inertia either after daytime main sleep (Balkin et al., 1989) or within a forced-desynchrony protocol, used to separate circadian effects from the sleep-wake cycle (McHill et al., 2019). Four studies had a high resolution (Balkin et al., 1989; Jewett et al., 1999; Ritchie et al., 2017; McHill et al., 2019) and 4 studies were deemed operationally relevant (Paul et al., 2001; Hilditch et al., 2016b; Jay et al., 2019; Kovac et al., 2020a). Four studies quantified a *time-constant* for the dissipation of inertia after main sleep (Folkard & Åkerstedt, 1992; Achermann et al., 1995; Jewett et al., 1999; Lundholm et al., 2021).

Time-constant studies

Four studies determined a time constant for the dissipation of inertia by fitting exponential functions to the first few hours of data (i.e., 1 - 4 h) after awakening from a full night's sleep of 8-12 h. A time constant defines the period in which a signal is reduced to 1/e (i.e., about 37%) of the output signal, e.g., the time it takes to dissipate approximately 63% of inertia effects. Folkard & Åkerstedt (1992) expanded the two-process model of sleep-wake regulation, including a circadian component (Process C) and a sleep-homeostatic component (Process S), by a third component, Process W, that described the time course of sleep inertia dissipation. They determined a time constant of 0.66 h (i.e., 40 min) for inertia, based on subjective alertness levels (no objective performance data were used). The other three studies determined similar or shorter time constants for inertia effects on subjective alertness/sleepiness: 0.67 h (40 min; Jewett et al., 1999), 0.45 h (27 min; Achermann et al., 1995), and 0.34 h (20 min; Lundholm et al., 2021). Two of the 4 studies also determined time constants for inertia dissipation based on objective performance data and found very different values: 0.30 h (18 min) for short-term memory (Achermann et al., 1995) vs. 1.17 h (70 min) for cognitive throughput (mathematical addition task) (Jewett et al., 1999). Methodological explanations for the almost 4-fold difference have been offered, including the absence of tests between 1 h and 3 h and no verification that the scheduled waketimes corresponded with the subjects' actual waketimes in the study by Achermann et al. (1995). However, similar time constants of inertia dissipation have been reported across studies for subjective alertness levels, despite these methodological differences. Another explanation might be that inertia may last longer for cognitive throughput (e.g., 70 min) than for short-term memory (e.g., 18 min); yet, all included studies that examined inertia effects on cognitive throughput using mathematical addition/subtraction tasks observed inertia durations that were shorter (i.e., ≤ 30 min) than the 70 minutes reported by Jewett et al. (1999) (see Tables 2-4).

Operationally relevant studies

The 4 studies deemed operationally relevant included using a flight simulator task (Paul et al., 2001), simulating on-call nights (Jay et al., 2019; Kovac et al., 2020a), and simulating a 6-h on/6-h off split-duty schedule offered as an alternative strategy to running 24-h operations (Hilditch et al., 2016b). Paul et al. (2001) aimed to determine whether certain medications could facilitate sleep at an early circadian time (17:00-23:45), as often required in transport aircrew, but would negatively affect subsequent performance upon awakening. They applied an extensive cognitive test battery including tasks on sustained alertness, logical reasoning, cognitive throughput (mathematical subtraction task), and a complex multi-task, designed to simulate the information processing characteristics of flight performance. The task simulated flying an aircraft, with a computer screen showing four separate displays representing four, interacting sub-tasks to be performed simultaneously. Unfortunately, the test battery started 15 minutes after awakening and the flight simulator task was applied last, i.e., at 25 minutes post-awakening. No performance decrements were observed, and the authors concluded that inertia effects had dissipated by the time the task started. Two studies examined inertia during simulated on-call nights. Kovac et al. (2020a) simulated two on-call nights in the laboratory, with participants expecting to be woken to a high- or low-stress task. Participants were, however, not woken during the night but tested in the morning after a full night's sleep from 23:00 - 7:00. Inertia effects on response speed lasted ≤ 17 minutes for sustained alertness and between 17 - 32 minutes for selective attention. Jay et al. (2019) used the same reaction time task as Kovac et al. (2020a) to investigate inertia effects on sustained alertness during two simulated on-call nights. On both nights, participants were woken up at 4:00 after a 5-h sleep period, either gently by study staff or by an alarm followed by a mobilization procedure, involving putting on a firefighter jacket and shoes and walking quickly to the testing room. No inertia effects were detected at the first time point 7 minutes past awakening, suggesting inertia, if any, lasted less than 7 minutes. Hilditch et al. (2016b) tested inertia effects on cognitive functioning and sustained alertness in a simulated split-duty schedule, that allows two 5-h sleep opportunities per 24 hours, in an attempt to limit performance deterioration by extended wakefulness and time-on-task. They found that performance in both domains was still impaired at 47 minutes (i.e., the last time of testing).

Other studies

Three studies examined inertia duration after habitual morning awakenings (i.e., no sleep restriction or forced wakeup). Ikeda et al. (2008) assessed the same cognitive domains as Hilditch et al. (2016b) (i.e., cognitive functioning and sustained alertness) and found that response speed was impaired for ≤ 15 minutes (sustained alertness), respectively, for 15 minutes to ≤ 30 minutes (cognitive functioning). Out of a total of 8 different measures derived from the two tasks, 6 showed no inertia effects. Ritchie et al. (2017) observed impairments that lasted between 10-30 min for selective visual attention, and Wertz et al. (2006) found inertia durations of ≤ 20 minutes for cognitive throughput (mathematical addition task), with cognitive performance ranging from 83 - 86 % of peak performance between 21 - 61 minutes after awakening. However, Wertz and colleagues subsequently exposed participants to 26-h of total sleep deprivation and assessed the same performance measures. They compared performance under sleep inertia vs. following sleep deprivation, showing that cognitive throughput was significantly worse immediately upon awakening from an 8-h sleep opportunity than after 26 hours of continued wakefulness.

Two studies looked at the impact of sleep deprivation (both, total and slow-wave sleep deprivation) on inertia. Ferrara et al. (2000) investigated inertia after 7.5-h nighttime sleep, including two baseline nights without disturbances, two nights with slow-wave sleep (SWS) deprivation, and one recovery night. There was no clear difference in inertia between the baseline and SWS-deprivation nights, but inertia was significantly increased following recovery night. It had dissipated after ~ 30 minutes for cognitive throughput (mathematical subtraction task) and sustained alertness, but lasted ≥ 75 minutes for motor performance, measured by a finger tapping task. Balkin et al. (1989) investigated inertia following 6-h recovery sleep during the daytime (8:00 - 14:00) after 24-h sleep deprivation. Inertia effects lasted between 15 minutes and < 20 minutes for cognitive throughput (mathematical addition task).

McHill et al. (2019) examined the impact of chronic sleep restriction on inertia, using a forced-desynchrony (FD) protocol, in which sleep takes place at all circadian phases, allowing to assess independent circadian influences on performance. Before the start of the FD protocol, baseline performance was assessed during 3 days of 10-h nocturnal sleep opportunities at participants' habitual sleep times. Within the FD protocol, sleep per 24 hours was restricted to 5.6 hours (sleep-restricted) vs. 8 hours (control condition). They found that in the control condition, inertia lasted at least 10 min but no longer than 20 minutes (= performance returned to baseline values), whereas in a chronically sleep-restricted state, inertia was prolonged to more than 70 minutes for cognitive functioning. As in the study by Scheer et al. (2008), inertia effects were further exacerbated when awakenings occurred during the individual's biological night. Importantly, circadian misalignment and chronic sleep restriction worsened the severity of inertia but did not affect dissipation rate (e.g., if performance is more strongly impaired upon awakening, it takes longer to recover back to baseline).

Summary: Sleep inertia after main sleep

Based on 12 out of 14 studies with objective performance measures (excluding Folkard & Åkerstedt, 1992, measuring subjective alertness, and Lundholm et al., 2021, assessing subjective sleepiness), 10 studies reported inertia to last between < 7 minutes (possibly no inertia) and 32 minutes after a main sleep episode. Overall, however, results for the duration of inertia after main sleep were more heterogeneous than for inertia after waking from nighttime or daytime naps. Inertia durations across all 14 included studies ranged from < 7 minutes to > 70 minutes. Four studies specified time-constants (i.e., the time it takes to dissipate 63% of inertia effects) for the dissipation of sleep inertia after main sleep, with relatively consistent values for subjective sleepiness/alertness (e.g., 20 - 40 min), but highly inconsistent values for objective performance (e.g., 18 - 70 min). Inertia duration in the four studies deemed operationally relevant (involving a flight simulator task, simulated on-call shifts, and a simulated split-duty schedule) ranged from < 7 minutes to ≥ 47 minutes. Three studies assessed performance upon habitual awakening in the morning (i.e., no sleep deprivation, no forced wake-up) and found relatively consistent inertia durations between 10 - 30 minutes, whereas 3 studies involving sleep loss (either total deprivation, selective slow-wave sleep deprivation, or chronic sleep restriction) before assessing performance observed longer and more variable inertia durations, ranging from < 20 minutes to > 70 minutes. In general, prior sleep loss seemed to exacerbate and/or prolong inertia effects, but the duration of inertia after waking from main sleep appeared quite variable.

Table 4. Overview of studies for sleep inertia duration after main sleep (n = 14). *Studies are listed according to their appearance in the text. Period = time period over which inertia was tested. Interval = time between tests. Latency = time between awakening and first test. In yellow: high-resolution studies. *Operationally relevant studies. #Studies with subjective measures only. Time constant = time required to dissipate ~ 63% of inertia effects.*

First author, Year	**Period/Interval/ Latency**	**Nap duration (timing)**	**Inertia duration**	**Cognitive domain (*task*)**
Jewett 1999	210min/10,20, 60min/1min	8h (habitual awakening)	70min (time constant)	Cognitive throughput (*ADD*)
Folkard 1992#	240min/5,60, 120min/0min	8h (23:00-7:00)	40 min (time constant)	Subjective only (*alertness*)
Achermann 1995	180min/20, 120min/0min	8h (23:00-7:00)	18min (time constant)	Short-term memory (*search task*)
Lundholm 2021#	60min/40-60min/ 0min	6h (4:00-10:00)/ 12h (22:00-10:00)	20min (time constant)	Subjective only (*KSS*)
Paul 2001*	60min/60min/15min	6.75h (17:00-23:45)	25min	Cognitive throughput (*SST*), sustained alertness (*visual*), logical reasoning, flight simulation task
Kovac 2020a*	60min/15min/2min	7.5h (23:00-7:00)	≤17min (PVT, SPATIAL accuracy), 17min to ≤32min (SPATIAL speed)	Selective attention (*SPATIAL*), sustained attention (*visual PVT*)
Jay 2019*	120min/15min/7min	5h (23:00-4:00)	No inertia to <7min	Sustained alertness (*visual PVT*)
Hilditch 2016b*	55min/15min/2min	2x5h (split-duty)	≥47min	Cognitive functioning (*DSST*); sustained alertness (*visual, PVT*)
Ikeda 2008	60min/15min/1min	6-8h (habitual awakening)	No inertia to ≤15min (sustained alertness), 15min to ≤30min (one measure on ST)	Cognitive functioning (*ST*), sustained alertness (auditory)
Ritchie 2017	60min/10min/1min	8h (habitual awakening)	10-30min	Selective attention (*SPATIAL*)
Wertz 2006	120min/20-60min/1min	8h (habitual awakening)	≤20min	Cognitive throughput (*ADD*)
Ferrara 2000	75min/15min/0min	7.5h (23:30-7:00)	30min (DST, sust. alert.), ≥75min (FTT)	Cognitive throughput (*DST*), sustained alertness (*auditory*), motor performance (*FTT*)
Balkin 1989	25min/5min/0min	6h (8:00-14:00; daytime main sleep)	15min to <20min	Cognitive throughput (*ADD*)
McHill 2019	70min/10min/2min	5.6h vs. 8h per 24-h (FD protocol)	10min to <20min (rested) vs. >70min (sleep restricted)	Cognitive functioning (*DSST*)

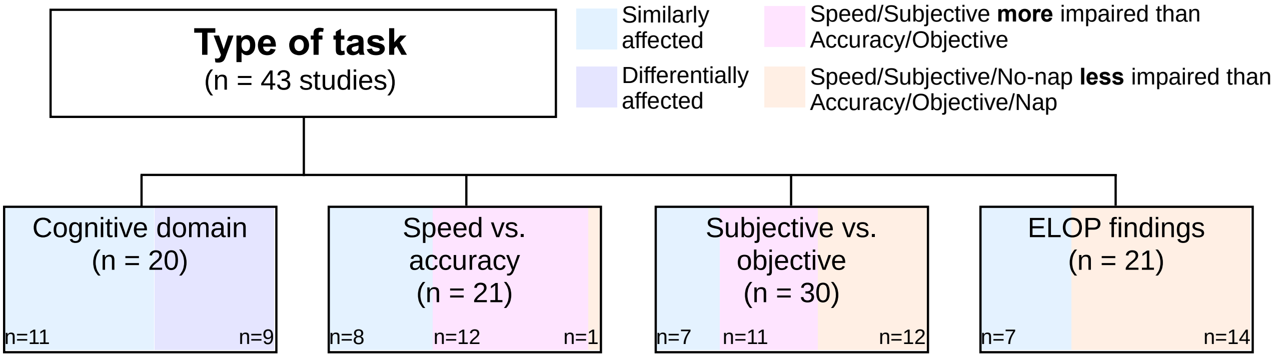
ADD = Addition task. KSS = Karolinska Sleepiness Scale. SST = Serial Subtraction Task. SPATIAL = visual search task. PVT = Psychomotor Vigilance Task. DSST = Digit Symbol Substitution Test. ST = switch task. DST = Digit Subtraction Task. FTT = Finger Tapping Task.

3.1.2 Type of task

A total of 43 studies investigated the effects of sleep inertia on different tasks, respectively, cognitive domains. The studies were assigned to the following 4 aspects of interest (multiple assignments per study possible): (i) comparison of different tasks/cognitive domains and task complexity (n = 20 studies); (ii) comparison of performance speed vs. accuracy (n = 21 studies); (iii) comparison of subjective sleepiness vs. objective measures (n = 30 studies); and (iv) equivalent level of performance findings (ELOP, n = 21 studies). Figure 4 shows an overview.

Of the included 43 studies, the most studied cognitive domain was sustained alertness (n = 22 studies), followed by working memory/cognitive throughput (n = 14 studies), selective attention (n = 11 studies), and general cognitive functioning (n = 8 studies). Few studies examined effects of sleep inertia on logical reasoning (n = 3 studies) and decision-making (n = 1 study). Figure 5 shows an overview of the included domains. The cognitive domains and their corresponding tasks are briefly described, before summarizing the results.

Figure 4: Overview of studies for sleep inertia and type of task, grouped by aspect of interest.
Blue shading = compared aspects (e.g., cognitive domains) are similarly affected by inertia. Purple shading = compared aspects are differentially affected by inertia. Pink shading = speed or subjective measures are more impaired by inertia than accuracy or objective measures, respectively. Orange shading = speed or subjective measures are less impaired by inertia than accuracy or objective measures, respectively.



3.1.2.1 Description of cognitive domains and tasks

Sustained alertness. *Most commonly used task: PVT*. The cognitive domain 'sustained alertness' is almost exclusively assessed by reaction time tasks. Reaction time tasks require participants to react as fast as possible to a presented visual or auditory stimulus. The most widely used test is the Psychomotor Vigilance Test (PVT), of which 3-min, 5-min, and 10-min versions exist. Common outcomes are reaction time (RT), reaction speed (the inverse of RT), and lapses (failure to respond, i.e., RTs > 500 - 850 ms).

Working memory / cognitive throughput. *Most commonly used tasks: n-back, ADD, DST.* Working memory is often assessed using the n-back task, which requires participants to continuously memorize a sequence of stimuli (e.g., letters) and to indicate whether the current stimulus matches the one from n steps earlier. The factor n typically varies between 1 and 3, to make the task more or less difficult. Outcome measures include both speed and accuracy. Other commonly used tasks include mathematical addition (ADD) or subtraction (i.e., descending subtraction task, DST) tasks. These tasks require participants to add or subtract 1-, 2- or 3-

digit numbers, either presented randomly (e.g., ’57 – 38 = ?’) or in a systematic way (e.g., from the number ‘789’, subtract 9, then 8, then 7, and so on). The output metric typically calculated for these mathematical tasks is *cognitive throughput*, which represents the number of correct responses within a certain amount of time. While the tasks itself involve working memory, we use the term cognitive throughput to report findings of the ADD and DST tasks to be consistent with how the studies reported their results.

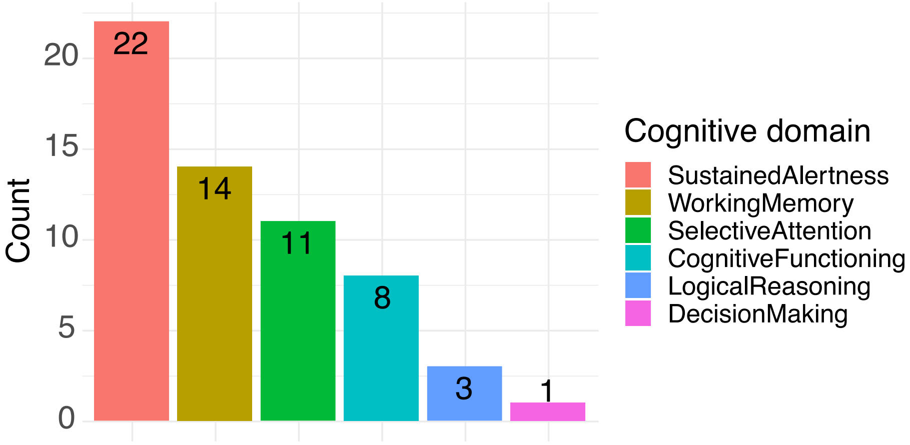
Selective attention/spatial memory. *Most commonly used task: SPATIAL*. The cognitive domain ‘selective attention’ is usually assessed via visual search tasks. A widely used task is the spatial-configuration visual search task (SPATIAL), in which participants are required to determine whether a target (the number 5) is present among distractor stimuli (the number 2). Outcome measures are calculated for both, speed (e.g., RT) and accuracy (e.g., number of correct responses).
Other tasks: STROOP. The Stroop Color and Word Test is a popular psychological task that measures multiple cognitive domains, including cognitive inhibition, processing speed, and selective attention. Participants are required to react as fast and as accurately as possible to matching (the word ‘blue’ written in blue) and non-matching stimuli (the word ‘blue’ written in red). Another STROOP-like task is the ARROW task, in which a white arrow pointing up or down is presented above or below the fixation cross and participants are required to respond to the pointing direction of the arrow (up or down) but not to the location (above or below).

Cognitive functioning. *Most commonly used task: DSST*. Studies referring to this domain usually employ the Digit Symbol Substitution Task (DSST; sometimes Symbol Digit Substitution Task, SDST). The task requires participants to match the numbers 1 to 9 to a series of random symbols (e.g., #,*,=), based on a code that is displayed at the top of the computer screen. It measures a range of cognitive operations, involving associative learning, motor speed, attention, and working memory. Both speed and accuracy measures (number of correct matches) are used as outputs.

Logical reasoning. *Most commonly used task: none*. Logical reasoning tasks usually involve several statements and/or symbol sequences, that are evaluated regarding their coherence/correctness, e.g., participants rate whether a pair of letters (e.g., ‘AB’) corresponds to a textual statement (e.g., ‘A follows B’).

Decision-making. *Most commonly used task: none*. Decision-making is a multi-level construct and challenging to assess. Participants are usually presented with a simulated scenario, in which they are required to solve a difficult situation or achieve a certain outcome, based on a limited set of information and/or resources. For instance, in the ‘Fire Chief’ decision-making task, participants assume the role of a chief fire officer, responsible for controlling fires in a specified area with various types of landscapes and fire appliances (trucks, helicopters). They are required to control the spread of wildfires by dispatching firefighting vehicles, dropping water. Performance is scored as the percentage of houses and trees still unburned at the end of each trial.

Figure 5: Overview of included cognitive domains.



3.1.2.2 Effects of sleep inertia on different cognitive domains and task complexity

Twenty of 43 included studies (47%) had two or more objective performance measures to examine inertia effects. The majority did not have the explicit aim to compare inertia effects on different tasks. Eleven of the 20 studies observed no major differences among the studied domains. Sustained alertness was found to be similarly impacted by sleep inertia as cognitive functioning (Tremaine et al., 2010; Hilditch et al., 2016b), cognitive throughput (Hayashi et al., 1999; Hofer-Tinguely et al., 2005; Oriyama et al., 2018; Kovac et al., 2021), logical reasoning (Hayashi et al., 1999), and selective attention (Kovac et al., 2020a; Kovac et al., 2021). Salamé et al. (1995) observed a similar inertia duration for spatial memory (e.g., mentally rotating a four-bar histogram) and logical reasoning (24 min vs. 27 min). Dinges et al. (1981) found similar impairments of cognitive throughput, measured by a mathematical subtraction task, and reacting to a phone bell ringing loudly, by picking up the receiver as fast as possible. Two studies by Tietzel & Lack (2001) and Brooks & Lack (2006) found similar inertia effects on selective attention and general cognitive functioning.

The remaining 9 studies observed inertia to differ by cognitive domain, yet their findings were inconsistent as to how the domains were impacted by inertia. Hilditch et al. (2016a) found sustained alertness to be much longer impaired than cognitive functioning (≥ 47 min vs. 2 - 15 min), whereas Leong et al. (2023) observed the opposite, with no effects on sustained alertness and an inertia duration of ≤ 30 minutes for cognitive functioning. Ikeda et al. (2008) observed a shorter inertia duration for sustained alertness than general cognitive functioning (≤ 15 min vs. 15 - 30 min). Ferrara et al. (2000) found that inertia lasted ~ 30 min for sustained alertness and cognitive throughput, but ≥ 75 minutes for motor performance. Despite longer-lasting impairments, inertia severity immediately upon awakening was less pronounced for motor performance than for the cognitive tasks, suggesting different inertia patterns: slow dissipation/moderate impairments vs. fast dissipation/severe impairments.

One study was conducted in a military-operation setting. Horne and Moseley (2011) examined tactical planning skills in junior officer reservists (i.e., having undergone part-time military training for the previous 18 months). Participants were confronted with a rather stressful military-type training exercise involving a simulated ‘surprise attack’, with enemy snipers opening fire on the participant’s platoon. The participants, without consultation, had to plan an appropriate response rapidly within 15 minutes to eliminate the enemy with minimal loss to their own troops and equipment. Half-way through the task, with the plan near completion, the presented situation suddenly changed, requiring a new strategy. The task was a paper-based exercise (no real troops involved) and deemed well within their capabilities, as they had already received adequate military training and experience of real exercises. It involved five domains: tactical awareness (e.g., recognize potential threats), planning and preparation (e.g., conceive and put operation into action), use of available assets (e.g., deployment of forces and weaponry), use of available cover (e.g., effective concealment), and extraction of information (e.g., separating relevant from irrelevant information). The control group performed the task 66 minutes after awakening at 8:36 after sleeping for 7.5 hours. The experimental group performed the task 6 minutes after awakening at 3:06 after sleeping for 3 hours. Accordingly, the experimental group experienced a ‘worst-case’ scenario, being exposed to a triad of detrimental conditions, i.e., adverse circadian timing, short sleep, and inertia. Compared to the control group, the experimental group performed significantly worse on three domains that predominantly involved decision-making and risk assessment (i.e., use of available assets, use of available cover, extraction of information), whereas highly trained and logical skills (tactical awareness, planning and preparation) were unaffected. Eight participants (80%) vs. 3 control-group participants (30%) were scored as having failed the task, and 4 participants (40%) vs. no control-group participant (0%) were unable to deal with the sudden change.

The remaining 4 studies addressed task complexity as a potential factor to modify inertia effects and are summarized in the next paragraph.

Effects of sleep inertia on simple vs. complex tasks

Two studies assessed multiple cognitive domains with the explicit aim to compare inertia effects on different tasks (Santhi et al., 2013; Burke et al., 2015). Santhi et al. (2013) examined the effects of morning inertia after 6.5 hours of sleep in 11 healthy participants on sustained alertness (10-min PVT), cognitive throughput (ADD), and working memory (n-back: 1-back and 3-back). They found that sustained alertness was more affected by inertia than cognitive throughput and working memory. Based on these findings, they concluded that simpler tasks (like the PVT, a simple reaction time task) were more susceptible to inertia effects than more complex tasks (like the 3-back task). Burke et al. (2015) studied 6 healthy participants over a period of 73 days including 2 forced desynchrony protocols to examine sustained alertness (20-min PVT), selective attention (two visual search tasks), cognitive throughput (ADD), general cognitive functioning (DSST), and the STROOP task (requiring, i.e., inhibitory cognitive control). They found the largest inertia effects on selective visual attention (specifically on the cognitive throughput component in the spatial-configuration task), followed by moderate effects on working memory and general cognitive functioning, with only small or no effects on sustained alertness, accuracy components of the selective visual attention tasks, and inhibitory control in the STROOP task, which was predominantly under circadian control. Working memory and selective attention speed were more strongly influenced by sleep inertia than by homeostatic or circadian processes. Thus, in contrast to Santhi et al. (2013), they concluded that more complex tasks (like the spatial-configuration task) were more impaired by sleep inertia than simpler tasks (like the PVT).

The other 2 studies did not compare multiple cognitive domains but manipulated cognitive load within the same task to assess effects of task complexity. Groeger et al. (2011) used the n-back working memory task with different levels of executive load, i.e., the 1-back, 2-back, and 3-back version of the task. They had two time points, one after a morning nap (10:00 - 11:30) and one after an afternoon nap (15:00 - 16:30). They did not find inertia effects on either n-back task after the morning nap, but did find impaired performance after the afternoon nap, for the 2-back and 3-back tasks with higher-executive load. The finding suggests that inertia following afternoon naps depends on task difficulty and supports Burke et al.’s (2015) conclusion was that complex tasks are more affected by inertia than simpler tasks. Ritchie et al. (2017) examined inertia effects on a visual search task assessing selective attention, in which participants are required to determine whether a target (the number 5) was present among distractor stimuli (the number 2) of four set sizes with 10, 20, 30, and 40 distractors. The set sizes represented different levels of attentional load. They found that performance during sleep inertia improved earlier for set sizes with intermediate attentional load (20 - 30 distractors), followed by the largest set size with the highest attentional load (40 distractors), and took the longest to improve for the set size with the lowest attentional load (10 distractors). Their finding, in turn, supports Santhi et al.'s (2013) conclusion that simpler tasks are more susceptible to sleep inertia.

Summary: Cognitive domains and task complexity

Overall, findings were inconsistent as to whether and what cognitive domains were differentially impacted by inertia, and no consensus could be reached. A similar inconsistency was observed for the association between sleep inertia and task complexity: of the 4 included studies, 2 found simple tasks to be more affected by inertia than complex tasks and 2 found complex tasks to be more susceptible to inertia than simple tasks.

3.1.2.3 Effects of sleep inertia on performance speed vs. accuracy

A total of 21 studies addressed the impact of sleep inertia on performance speed vs. accuracy. Of these, 8 studies found similar effects of inertia on speed and accuracy; 12 studies found speed to be more impaired than accuracy; and one study observed accuracy to be more impaired than speed.

Speed and accuracy similarly affected (n = 8)

Two studies were performed by the same research group and did not find any inertia effects on either the speed or accuracy component of a STROOP-like task measuring selective attention and inhibitory control (ARROW task) (Asaoka et al., 2010; Asaoka et al., 2012). Two studies by Balkin & Badia (1988) and Badia et al. (1989) examined inertia effects on cognitive throughput using a mathematical addition task (ADD). Speed and accuracy were affected similarly, with inertia lasting 15 - 20 minutes. A study by Kovac et al. (2021) examined speed and accuracy components in the domains sustained alertness, selective attention, and cognitive throughput (i.e., mathematical addition and subtraction task). All were impacted by inertia in a similar fashion. Using the n-back task to assess working memory, Signal et al. (2012) found no difference between performance speed and accuracy during simulated night shifts and extended shifts, with all inertia effects having dissipated after a maximum of 15 minutes. Comparing speed and lapses on the PVT, 2 studies found them to be similarly affected by inertia after a nighttime nap from 4:00 - 5:00 (Kubo et al., 2010) and in the morning after on-call nights in medical interns (Basner et al., 2017).

Speed more affected than accuracy (n = 12)

Eight studies found speed to be impaired but no inertia effects on accuracy in: cognitive throughput using a subtraction (Vallat et al., 2019) or an addition task (Hofer-Tinguely et al., 2005); general cognitive functioning using the DSST (Leong et al., 2023); the STROOP task (Tassi et al., 2006); and selective visual attention (Salamé et al., 1995; Burke et al., 2015). Two studies found PVT speed but not PVT lapses to be impaired by inertia (Miccoli et al., 2008, Ikeda et al., 2008). The remaining 4 studies observed inertia effects on accuracy but to a lower extent than on speed. Dinges et al. (1981) assessed cognitive throughput (i.e., subtraction task) in a sleep-conducive (sleeping in a dark, quiet room) vs. an alerting environment (sleeping in an upright position in a lounge chair with lights on and ambient 'corridor' noise) and found speed to be impaired in both conditions, yet accuracy only in the sleep-conducive environment. Santhi et al. (2013) examined cognitive throughput and working memory and found that regardless of task, the effect of sleep inertia was stronger in speed than in accuracy. Kovac at el. (2021) observed inertia to dissipate slower in speed than accuracy for selective attention using a spatial-configuration task (17 - 32 min vs. ≤ 17 min). Oriyama et al. (2018) investigated inertia after nighttime naps of different durations and timing and found that PVT lapses were only impaired after a nap from 4:30 - 5:00, while PVT speed was also impaired after 90-min naps at different times.

Accuracy more affected than speed (n = 1)
Ferrara et al. (2000) found accuracy to be more impaired than speed on a descending subtraction task (DST) in participants, who had been deprived of slow-wave sleep during the night.

Summary: Speed vs. accuracy

A clear majority of included studies found performance speed to be similarly (n = 8 studies) or more (n = 12 studies) impacted by inertia than accuracy. The finding is in line with the notion of a 'speed/accuracy tradeoff', describing the relationship between responding fast at the expense of making more errors vs. making fewer errors at the expense of responding more slowly. Under sleep inertia, this tradeoff may change toward the latter, with participants managing to perform more accurately (e.g., miss fewer targets) because they take longer to respond (e.g., spend more time to search for the target among distractors).

Only one study (Ferrara et al., 2000) observed the opposite effect, with accuracy being more impaired than speed. In their study, participants were almost entirely deprived of slow-wave sleep, which is considered central to restorative sleep. Previous studies have hypothesized that while inertia may primarily affect performance speed, sleepiness may impair accuracy (Tassi et al., 2003). In the study by Ferrara et al., increased sleepiness upon awakening due to less restorative sleep might thus have contributed to lower accuracy levels.

3.1.2.4 Comparing inertia effects on subjective vs. objective measures

Thirty out of 43 studies (71%) included both a subjective measure (e.g., self-reported sleepiness, alertness, fatigue) and an objective performance task (e.g., PVT, DSST). Of these, 24 studies were also included to determine the duration of inertia and thus provided data on the time course of inertia dissipation for subjective vs. objective measures. Most studies did not have the explicit aim to compare inertia effects between subjective and objective outcomes. Of the 30 included studies, 7 studies reported no difference, 11 studies reported more/longer inertia for subjective than objective measures, and 12 studies reported more/longer inertia for objective than subjective measures.

Subjective and objective measures similarly affected (n = 7)
Two studies by the same research group found no inertia in either subjective or objective measures after daytime naps (Kaida et al., 2003a,b). The remaining 5 studies observed similar inertia durations for subjective sleepiness and: cognitive throughput (>13.5 min; Balkin & Badia, 1988); cognitive functioning/selective attention (≤ 35 min; Brooks & Lack, 2006); cognitive functioning/sustained alertness (5 - 40 min; Tremaine et al., 2010); ≥ 55 min; Hilditch et al., 2016b); and sustained alertness (60 min; Basner et al., 2017).

Subjective more affected than objective measures (n = 11)
Two studies observed no inertia effects on objective performance, assessed by short-term memory (Hayashi et al., 2003) and sustained alertness (PVT unimpaired at the first time point 7 min post-awakening; Jay et al., 2019) but inertia durations of ≤ 15 minutes to 75 - 90 minutes for subjective sleepiness. Increased sleepiness but no difference in objective performance was observed after a short daytime nap from 12:20 - 12:40 (Hayashi et al., 1999) and after a short nighttime nap from 2:30 - 3:00 (Oriyama et al., 2008) for cognitive throughput and sustained alertness.

The remaining 7 studies did observe effects of inertia on both subjective and objective measures, but dissipation was longer for sleepiness than performance tasks: < 15 minutes vs. ≥ 30 minutes (sustained alertness; Figueiro et al., 2019); 47 - ≤ 60 minutes vs. ≤ 17 - 32 minutes (sustained alertness/selective attention; Kovac et al., 2020a); > 60 minutes vs. 0 - ≤ 30 minutes (sustained alertness/cognitive functioning; Ikeda et al., 2008); ≥ 60 minutes vs. ≤ 35 minutes (selective attention/cognitive functioning; Tietzel & Lack, 2001); > 70 minutes vs. 10 minutes (cognitive functioning in well-rested participants; McHill et al., 2019). Achermann et al. (1995) determined a longer time constant for subjective alertness than short-term memory (0.45 h vs. 0.30 h). Burke et al. (2015) found that inertia had the strongest effects on subjective sleepiness and the weakest effects on sustained alertness, as measured by the PVT.

Objective more affected than subjective measures (n = 12)
Three studies reported effects on both subjective and objective measures, but larger and/or longer impairments in objective performance than subjective sleepiness. Santhi et al. (2013) reported that morning inertia affected sleepiness more strongly than PVT performance. Kovac et al. (2021) reported fast dissipation of inertia for subjective sleepiness (< 5 min), with longer-lasting effects on a range of performance tasks (≤ 30 min). Jewett et al. (1999) determined a much longer time constant for cognitive throughput in a mathematical addition task than for subjective alertness (0.67 h vs. 1.17 h).

The remaining 9 studies did observe inertia-induced impairments in objective performance, yet no effects on subjective measures. Hilditch et al. (2017) found that sustained alertness was impaired at 12 minutes after awakening at 7:00, yet fatigue was not increased. Kubo et al. (2010) reported a similar finding, with the PVT impaired after a nighttime nap from 4:00 - 5:00 but no increased sleepiness. Seven studies that determined inertia durations for both subjective and objective measures, observed no inertia for sleepiness/fatigue, while inertia effects on various objective tasks ranged from less than 15 minutes to more than 47 minutes (Balkin et al., 1989; Sallinen et al., 1998; Hofer-Tinguely et al., 2005; Signal et al., 2012; Hilditch et al., 2016a; Centofanti et al., 2020; Leong et al., 2023).

Summary: Subjective vs. objective measures

Overall, studies on the effects of sleep inertia on subjective vs. objective measures were consistent in that the majority of studies reported a disconnect between subjective ratings and objective performance but they yielded inconsistent findings as to the direction of effects. Of 30 included studies, 11 studies reported larger inertia effects on subjective sleepiness and 12 studies reported larger inertia effects on objective performance tasks. For instance, of 2 studies quantifying time constants of inertia effects, one found a shorter dissipation rate (short-term memory; Achermann et al., 1995) whereas the other found a much longer dissipation rate for performance (cognitive throughput; Jewett et al., 1999) than for self-reported alertness. However, within the group of studies observing larger effects for objective performance, 9 out of 12 studies consistently reported no inertia effects on subjective measures.

3.1.2.5 Equivalent Level Of Performance (ELOP) findings

None of the included studies explicitly investigated Equivalent Level Of Safety (ELOS) findings, i.e., whether a pilot who is potentially in a state of sleep inertia due to prior napping provides a level of safety that is equal to the level of safety provided by a pilot staying awake. Therefore, we do not provide ELOS findings in this report. We present a summary of studies that compared performance data upon awakening of participants who took a nap with participants who stayed awake during that time, including whether naps resulted in subsequent performance benefits after inertia dissipated, over staying awake. The provided data do not quantify a 'level of safety'; rather, we determine the equivalence of the two conditions (napping vs. staying awake) based on the absence of inertia, as determined by a statistically non-significant difference in cognitive performance between the conditions. Therefore, we label the findings presented here Equivalent Level of Performance (ELOP) findings.

A total of 21 studies examined nap vs. no-nap conditions, including within-subject (n = 19) and between-subject (n = 2) study designs (Table 5). Seven out of 21 studies (33%) found no performance differences after napping compared with no-napping (Hayashi et al., 1999; Hayashi et al., 2003; Kaida et al., 2003a; Asaoka et al., 2010; Asaoka et al., 2012; Basner et al., 2017; Hilditch et al., 2017). Six of the 7 studies examined inertia during the morning (n = 2) or daytime (n = 4), with prior nap durations of 10 - 60 minutes. One study examined inertia effects during the early night at 2:00 and found no cognitive impairments after a 60-min nap compared to staying awake (Asaoka et al., 2012). Fourteen out of 21 studies (67%), however, did observe impairments in performance after waking up from a nap, compared to staying awake (Table 5). Of these, the majority examined inertia during the nighttime (9 of 14 studies, 64%). Performance testing occurred within 5 minutes from awakening in 19 of the 21 studies (90%), including all 14 studies that observed impaired performance after a nap vs. no nap. Prior nap durations varied from 5 minutes to 2 hours, yet significant impairments were mostly found after naps of 30 minutes or longer.

Of a total of 10 studies investigating inertia effects during the nighttime, 9 studies found performance was impaired after a nap vs. staying awake. Of a total of 11 studies examining inertia during the daytime or in the morning, findings were inconsistent, with 5 studies showing worse performance after a nap vs. 6 studies finding a similar level of performance after a nap, compared with not taking a nap. In the studies that did not observe significant impairments, naps tended to be shorter, between 10 - 20 minutes, whereas studies that observed impairments, did so only after naps of 30 minutes or more.

Delayed benefits of napping

Twelve of the 21 included studies also examined whether taking a nap resulted in improved performance at a later time point (e.g., delayed benefits), compared with not taking a nap (Table 5). Of these, 10 studies found delayed benefits, such that after the dissipation of sleep inertia, sleepiness was decreased and/or cognitive performance was improved for 30 - 240 minutes after awakening. The 2 studies that did not observe a beneficial effect of the nap, neither observed a detrimental effect (Takeyama et al., 2004; Hofer-Tinguely et al., 2005).

Summary: ELOP findings

Comparing cognitive performance after waking up from a nap with performance after having stayed awake, 14 out of 21 studies (67%) observed significant cognitive impairments. Two factors appeared to be of major influence: nap timing and nap duration. Nighttime napping consistently resulted in worse performance compared with staying awake, even though extending wakefulness increased sleepiness and decreased cognitive performance. Naps of ≥ 30 minutes duration significantly impaired performance below the level of participants who did not take a nap, even during the daytime.

The two factors, nap timing and nap duration, will be discussed in greater detail in the next section “Countermeasures”, as strategic ways to limit sleep inertia and detrimental effects on cognitive performance.

Table 5: Overview of studies for Equivalent Level Of Performance (ELOP) findings (n = 21). *Studies are listed according to (i) whether they found performance impairments; (ii) the timing of the nap (morning/daytime vs. nighttime); and (iii) their appearance in the text. O = objective measures. S = subjective measures.*

First author, Year	Nap opportunity	Design (nap vs. no-nap factor)	ELOP finding
Hayashi 1999	Daytime: 20min (12:20-12:40)	Within	Not different (O). Delayed benefits (S, not O).
Hayashi 2003	Daytime: 20min (ending at 13:00)	Within	Not different (O). Delayed benefits (S+O).
Kaida 2003a	Daytime: 15-20min (14:00-14:20)	Within	Not different (O). Delayed benefits not studied.
Asaoka 2010	Daytime: 1h (14:00-15:00)	Within	Not different O). Delayed benefits not studied.
Asaoka 2012	Nighttime: 1h (1:00-2:00)	Within	Not different (O). Delayed benefits (S+O).
Hilditch 2017	Morning: 2x10-min (ending at 4:00 and 7:00)	Within	Not different (O). Delayed benefits not studied.
Basner 2017	Morning: 0-540min (unclear timing, average testing at ~8:00)	Between	Not different (O). Delayed benefits not studied.
Brooks & Lack 2006	Daytime: 5/10/20/30min (ending at 15:00)	Within	Impaired. Delayed benefits (S+O).
Tietzel & Lack 2001	Daytime: 10/30min (ending at 15:10)	Within	Impaired Delayed benefits (S+O).
Leong 2023	Daytime: 10/30/60min (ending at 14:30)	Within	Impaired Delayed benefits (S+O).
Groeger 2011	Daytime: 1.5h (10:00-11:30 vs. 15:00-16:30)	Between	Impaired Delayed benefits not studied.
Hofer-Tinguely 2005	Daytime: 2h (14:00-16:00 vs. 18:00-20:00)	Within	Impaired No delayed benefits.
Hilditch 2016a	Nighttime: 10/30min (ending at 4:00)	Within	Impaired Delayed benefits not studied.
Sallinen 1998	Nighttime: 30/50min (ending at 1:50 vs. 4:40)	Within	Impaired Delayed benefits (S+O).
Tremaine 2010	Nighttime: 30min (2:30-3:00)	Within	Impaired Delayed benefits (S+O).
Signal 2012	Nighttime/Daytime: 20/40/60min (ending at 2:00 vs. 12:00)	Within	Impaired Delayed benefits (S+O) for extended shift only.
Oriyama 2018	Nighttime: 30-min (2:30-3:00 vs. 4:30-5:00), 90-min (22:30-0:00 vs. 0:30-2:00)	Within	Impaired. Delayed benefits (S+O).
Tassi 1992	Nighttime: 1h (0:00-1:00 vs. 3:00-4:00)	Within	Impaired Delayed benefits not studied.
Salame 1995	Nighttime: 1h (0:00-1:00 vs. 3:00-4:00)	Within	Impaired (O) Delayed benefits not studied.
Kubo 2010	Nighttime: 1h (0:00-1:00 vs. 4:00-5:00), 2h (0:00-2:00 vs. 4:00-6:00)	Within	Impaired. Delayed benefits not studied.
Takeyama 2004	Nighttime: 1h (0:00-1:00 vs. 4:00-5:00), 2h (0:00-2:00 vs. 4:00-6:00)	Within	Impaired. No delayed benefits.

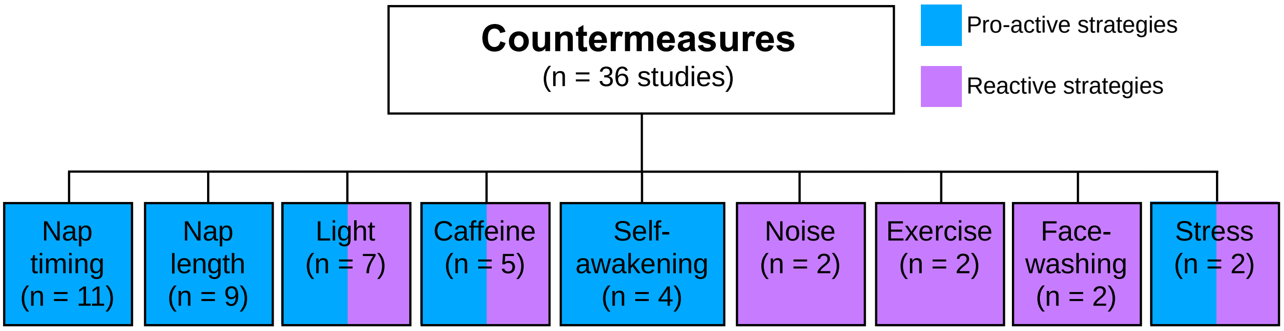
3.2 Additional results: Countermeasures and Individual Factors

3.2.1 Countermeasures

A total of 36 studies examined potential countermeasures for sleep inertia. These ranged from proactive strategies (i.e., strategic nap placement and/or limiting the duration of naps) to reactive measures, including environmental exposures (light, noise) and behavioral interventions (i.e., caffeine consumption, exercise, face-washing, self-awakening). Potentially relevant studies on pharmacological interventions were ultimately not included, because they did not examine substances to combat inertia but tested whether medications taken for a different purpose (e.g., to induce early-night sleep) might impair performance, and as such were out of this review's scope. One study tested a monitoring system to detect sleep and sleepiness in pilots, with the potential future application to minimize inertia via limiting nap duration, but the study did not assess inertia or the ability of the system to limit inertia (Cabon et al., 2003).

The most studied countermeasure was the timing and/or length of naps (n = 15 studies), followed by exposure to light (n = 7 studies) and consumption of caffeine (n = 5 studies). The behavioral strategy 'self-awakening' was examined by 4 studies, while the remaining 4 countermeasures exposure to noise, exercise, face-washing, and anticipation of stress upon awakening) were all investigated by 2 studies each. Figure 6 shows an overview of the examined countermeasures.

Figure 6: Overview of included countermeasures against sleep inertia. *The shading indicates whether the countermeasure was applied as a pro-active strategy (= blue; i.e., applied before or during sleep) or as a reactive strategy (= purple; i.e., applied upon awakening).*



3.2.1.1 Naps

Of the 15 studies examining the impact of naps on inertia and performance, 4 studies examined nap duration, 6 studies focused on nap timing, and 5 studies included both, the duration and timing of naps. The different nap set-ups across the included studies are illustrated in Figure 7.

Naps: duration

Three studies investigated naps during the daytime (all naps ending around 15:00) comparing durations of 5/10/20/30 minutes (Brooks & Lack, 2006), 10/30 minutes (Tietzel & Lack, 2001), and 10/30/60 minutes (Leong et al., 2023), and one study examined naps during the nighttime ending at 4:00 comparing durations of 10/30 minutes (Hilditch et al., 2016a). Independent of daytime or nighttime placement, naps of ≤ 20 minutes consistently showed no inertia effects on performance, whereas nap durations of 30 and 60 minutes yielded performance decrements upon awakening, compared with not taking a nap.

Naps: timing

The 6 studies examining the impact of nap timing on inertia included relatively long nap durations of 60, 90, and 120 minutes. Three studies varied nap timing during the daytime, i.e., naps ending in the morning (11:30), afternoon (~ 15:00), or evening (20:00/21:00) (Lavie and Weler, 1989; Hofer-Tinguely et al., 2005; Groeger et al., 2011). Two studies examined 60-min naps during the nighttime, ending at 1:00 at night (Tassi et al., 1992; Salamé et al., 1995). The only nap not resulting in impaired performance was the 90-min nap in the morning from 10:00-11:30. All others showed at least some degree of inertia, with potentially more severe and/or longer-lasting inertia effects after naps in the evening or at night. Dinges et al. (1985) studied the interaction of previous sleep deprivation and sleep inertia upon awakening from 2-h naps placed either near the circadian low (least alerting effect, ~ 5:00) or the circadian peak (most alerting effect, ~ 15:00) based on core body temperature. They found that while inertia worsened when tested near the circadian low and with increasing hours of sleep deprivation, the major driving factor of sleep inertia was the amount of slow-wave sleep (SWS) obtained during the nap.

Naps: timing and duration

The naps examined by the 5 studies ranged in duration from 20, 30, 60, 90 to 120 minutes, and took place during the night, with wake-up times between 0:00 and 6:00 (with one exception, where performance was assessed when waking up at 12:00 after ~30-h of wakefulness). Results were generally consistent with previously described findings for nap timing and duration: irrespective of duration, naps ending near the circadian nadir (~ 4:00 - 5:00) produced inertia resulting in impaired performance; and naps of less than 30-min duration showed less inertia effects than longer nap durations of 40 and 60 minutes (e.g., Signal et al., 2012). In the studies by Sallinen et al. (1998) and Signal et al. (2012), inertia did not differ by nap timing. Oriyama et al. (2018) found that long naps of 90 minutes resulted in impaired performance regardless of timing, whereas of the 30-min naps, only the nap ending near the circadian low showed inertia effects. In contrast, two studies by the same research group and identical study set-ups, including timing and length of naps as well as applied tasks, observed inertia only after a 60-min nap ending near the circadian nadir, whereas performance was not impaired after a 60-min nap ending at 1:00 or after 120-min naps ending at 2:00 and 6:00, respectively (Takeyama et al., 2004; Kubo et al., 2010). The control group in these studies did not sleep and continued to fill out the performance test battery at 6 times throughout the night. The repeated testing may have decreased the control group's performance due to fatigue and monotony, resulting in similarly impaired performance of the inertia group and the control group.

Summary: Naps

Findings on the effects of nap timing and duration on inertia suggest that inertia effects decrease when the duration is limited to ≤ 20 minutes and seem less severe after daytime naps, especially compared with naps ending near the circadian low (~ 4:00 - 5:00).

Figure 7: Overview of nap settings in studies on nap duration, nap timing, or both. *Black bars indicate that the study observed no inertia effects (= cognitive performance not impaired) after awakening from the nap. Light red bars indicate that the study did observe inertia effects after awakening form the nap. Dark-red bars indicate that, within the same study, inertia effects after awakening from a dark-red colored nap were worse than inertia effects after awakening from a light-red colored nap.*

3.2.1.2 Light exposure

Of the 7 studies examining the effect of light exposure on inertia and performance, 3 studies examined bright and/or blue light, 2 studies tested the effects of green, respectively, red light, and 2 studies investigated artificial dawn.

Bright/blue light

The rationale behind using bright light, blue-enriched light, or short-wavelength light to achieve an alerting effect is based on the circadian system being most sensitive to this light spectrum. Specific photoreceptors in the eye, so-called intrinsically photosensitive retinal ganglion cells (ipRGCs), contain the protein melanopsin, which is activated by short-wavelength light with peak sensitivity at ~ 480 nm (Bailes & Lucas, 2013). All 3 studies tested the effects of light as a reactive countermeasure (light administered upon awakening, i.e., during performance testing).

Hayashi et al. (2003) investigated three countermeasures (e.g., light, caffeine, face-washing), after a 20-min daytime nap ending at 13:00. They employed a within-subject design, comparing 5 conditions: no nap/rest vs. nap + placebo vs. nap + 200 mg caffeine vs. nap + placebo + face-washing (cold water 25°C) vs. nap + placebo + bright light (2000 lx for 1 min). Caffeine was ingested as 2 g of decaffeinated instant coffee mixed with 200 mg caffeine. In the other 4 conditions, they drank an equal amount of decaffeinated coffee as placebo. The brief daytime nap increased subjective sleepiness for 15 minutes but did not produce inertia effects on objective performance (i.e., short-term memory task). Hence, the 3 countermeasures light, caffeine, and face-washing were not evaluated regarding their efficiency to reduce inertia but regarding their potential to improve sleepiness and performance (i.e., whether they had delayed benefits). Caffeine was the most effective intervention, followed by bright light exposure for 1 minutes after awakening: compared with napping alone, napping plus bright light reduced sleepiness and fatigue from 30 to 60 minutes post-nap and improved accuracy in the search task from 45 to 60 minutes post-nap.

Santhi et al. (2013) studied the effects of 3 different white light conditions on morning inertia in several tasks after 6.5 h of sleep during the night. In a within-subject design, the lighting conditions were compared with a dim-light condition (19 lx, 2700 K) and included different combinations of light intensity and spectrum (i.e., color temperature): blue-intermediate white light (200 lx, 2700 K) vs. blue-enhanced white light (195 lux, 17000 K) vs. bright, blue-enhanced white light (750 lx, 17000 K). While inertia effects were present in all 3 light conditions, there was no differential effect on performance across conditions, except in a working memory task with high executive load (i.e., 3-back task): in the two blue-enhanced white light conditions at the end of 4 hours, response times were significantly faster than at wake time, suggesting greater delayed benefits by blue-enhanced light on performance.

A recent study by Hilditch et al. (2022) tested the effects of blue-enriched light following nocturnal awakenings from slow-wave sleep. In a counterbalanced, within-subject design, participants were awakened twice during the night from PSG-verified slow-wave sleep and immediately exposed to dim, red ambient light (< 0.3 lx, 714 nm) vs. polychromatic, blue-enriched light (l243 lx, 456 nm). Performance (i.e., PVT) was assessed every 15 minutes for 50 minutes. Compared with the control condition, participants exposed to blue-enriched light did not differ in reaction speed but had fewer lapses and felt less sleepy. There was no difference between conditions across time, suggesting that the beneficial effects of light on inertia were immediate.

Summary: Bright/blue light

Bright and/or blue light may not produce large performance gains during the daytime but appears promising to reduce inertia following naps during the night. It may affect accuracy more than speed, but more research is needed. It may also carry delayed benefits, such that, after inertia has dissipated, alertness and performance are improved over napping without light exposure.

Green/red light

Two studies investigated the effects of other light spectra, using green (500 nm) or red (628 nm) light. They also differed from studies on bright/blue light in that they examined effects of light administered *during sleep* via light-emitting goggles or light masks.

Harrison et al. (2011) had participants wear goggles with a diffused green (500 nm) LED light during 90-min daytime naps (starting between 13:00 and 15:30). In a within-subject design, participants were exposed to 4 different light intensities during the nap: 0 lx (physiological darkness) vs. 1 lx (moonlight) vs. 80 lx (typical indoor lighting) vs. 6400 lx (indirect outdoor light). The authors assessed sleepiness and performance on a mathematical subtraction task immediately (3-min) before and after the nap. While sleepiness and performance showed inertia effects in all lighting conditions, there were no differences across light intensities. Thus, light exposure to narrowband 500 nm green light of up to 6400 lx during a 90-min nap opportunity had no effect on the severity of sleep inertia immediately upon awakening. Given a single measurement time point following the nap, differences in the dissipation of inertia were not studied.

Figueiro et al. (2019) investigated the effects of red light on inertia, either delivered during sleep via a light mask or delivered upon awakening via light-emitting goggles. Participants had a 90-min nap opportunity between 23:30 and 1:00, with sleep supposed to occur between 0:00 and 1:00. Sleep was not verified independently. In a within-subject design, participants underwent three lighting conditions: dim light (< 5 lx) vs. red light during sleep received through closed eye lids via a light mask (~55 lx at the eyes, no light during testing) vs. red light upon awakening and during testing delivered via light goggles (~55 lx at the eyes, no light during sleep). Performance on auditory reaction time tests (e.g., Go_No-Go task: responding as fast and accurate as possible to target sounds while ignoring inhibitor sounds) was assessed every 7 minutes for 30 minutes post-awakening. Inertia was present in all conditions but dissipated after 15 minutes in the control condition (dim light). Severity of inertia upon awakening was lowest in the mask condition (i.e., exposure to red light during sleep), whereas inertia dissipated faster in the goggles condition (i.e., exposure to light during wakefulness). The results suggest that red light delivered during sleep as well as upon awakening can be effective in reducing inertia after an early-night nap. The findings further suggest that a combination of red light delivered during both sleep and wakefulness may be most effective in reducing severity and accelerating dissipation of inertia, without affecting the circadian system.

Summary: Green/red light

Red light more than green light appears promising to reduce inertia following naps, but more research is needed. The absence of beneficial effects of exposure to bright green light on inertia may have been due to naps taking place during the daytime and the fact that inertia dissipation was not included in the study by Harrison et al. (2011). Red light delivered during sleep may reduce inertia severity upon awakening, whereas red light delivered during performance testing may benefit a faster dissipation of inertia.

Artificial dawn

Two studies examined the effects of simulating artificial dawn 30 minutes before habitually waking up from nighttime sleep on morning inertia.

Van de Werken et al. (2010) compared in a within-subject design a control condition, in which participants woke up from an 8-h nighttime sleep opportunity at their habitual wake time and were exposed to regular light (300 lx) for the testing period, with an experimental condition, in which participants were additionally exposed to light during sleep, i.e., 30 min before habitual wake-time. In this ‘artificial dawn’ condition, light gradually increased to the maximum of 300 lx during the half-hour period. Subjective sleepiness was decreased in the artificial dawn condition, such that the severity of inertia was lower, yet the rate of dissipation was not affected by prior light exposure during sleep. Objective performance, assessed by a mathematical addition task and a reaction time test, did not differ between the lighting conditions. The beneficial effects of artificial dawn on subjective sleepiness seemed to be mediated by an accelerated skin temperature and increased amount of wakefulness during sleep (i.e., lighter sleep before waking up).

Thompson et al. (2014) employed a very similar design as Van de Werken et al. (2010), comparing sleeping in darkness vs. simulating artificial dawn (i.e., light intensity gradually increases to 300 lx) during the last 30 min before habitually waking up from an 8-h nighttime sleep opportunity. They assessed subjective sleepiness as well as objective performance including a mathematical addition task and reaction time test (responding to visual stimuli of different color and in different places). Artificial dawn significantly reduced sleepiness and improved objective measures, both performance speed and accuracy.

Summary: Artificial dawn

Artificial dawn (i.e., increasing light intensity during sleep 30 min before waking up) appears effective at reducing subjective sleepiness, with inconsistent results for objective performance. More research is needed to test the effectiveness of artificial dawn for shorter sleep periods such as naps. If individuals may feel less sleepy due to the intervention without a concurrent improvement in their cognitive performance, such an intervention may be a double-edged sword. Since samples in both studies consisted of late chronotypes, effectiveness of simulated dawn in reducing morning inertia may not apply to early and/or intermediate chronotypes.

Summary: Light

Overall, exposure to light appears a promising countermeasure for sleep inertia. The included studies suggest that light may be more effective at reducing inertia during the night than during the day and, based on limited evidence, may improve accuracy more than speed. It is important to balance alerting effects with circadian consequences: blue or blue-enriched light may be most effective at reducing inertia but can affect the circadian clock and result in unwanted side effects (e.g., affecting sleep quality and sleep duration following duties). Red light appeared to not affect melatonin suppression (a proxy of circadian effects), but reduced inertia severity immediately upon awakening when delivered during sleep and accelerated inertia dissipation when delivered following sleep. Simulating artificial dawn during the last 30 minutes of a full night's sleep also reduced inertia severity in subjective sleepiness upon awakening but had no effect on dissipation of sleepiness. Findings for the effects of artificial dawn on objective performance were inconsistent, potentially raising concerns if individuals feel less sleepy but are still cognitively impaired.

Light as a countermeasure against inertia is non-invasive and relatively easy to implement in a cockpit environment, with little interference expected on pilots' tasks. Depending on how light is administered, it is, however, dependent on pilots putting on a light mask and/or googles or switching to an ambient, 'inertia-specific' light setting. Using light as a reactive countermeasure (i.e., following awakening) may also not be suited to stressful and/or emergency situations, in which the Pilot Resting needs to take immediate action and turning on a different light may not be high on the priority list. This issue could be resolved, if such light settings were to be automatized.

3.2.1.3 Caffeine

Five studies examined the potential of caffeine to reduce or eliminate sleep inertia. Caffeine consumption ranged from drinking coffee (Hayashi et al., 2003; Centofanti et al., 2020) to ingesting a pill (Van Dongen et al., 2001) or capsule (Dornbierer et al., 2021) and chewing gum (Newman et al., 2013), and was either consumed before nap/sleep (pro-active countermeasure: Hayashi et al., 2003, Centofanti et al., 2020; Dornbierer et al., 2021) or upon awakening (reactive-countermeasure: Van Dongen et al., 2001; Newman et al., 2003).

Hayashi et al. (2003) who investigated 3 countermeasures (e.g., light, caffeine, face-washing) against inertia following a brief daytime nap did not find impairments in objective performance upon awakening. Accordingly, they examined whether the 3 interventions would improve outcomes at a later time. They found that napping plus caffeine was the most effective intervention. Caffeine was ingested as 2 g of decaffeinated instant coffee mixed with 200 mg caffeine. In the other 4 conditions, they drank an equal amount of decaffeinated coffee as placebo. Compared with napping alone, it reduced sleepiness and fatigue from 15 to 60 min post-nap, decreased reaction time from 30 to 60 minutes post-nap and improved accuracy from 45 to 60 minutes post-nap. It was also better (i.e., reduced reaction time from 45 to 60 minutes) compared to napping plus face-washing upon awakening.

Centofanti et al. (2020) tested a similar caffeine intervention as Hayashi et al. (2003) in a counter-balanced, double-blind, crossover, simulated night shift protocol. Participants had 200 mg of caffeine or decaffeinated coffee (placebo) immediately prior to a 30 minutes nap opportunity from 3:30 - 4:00. Lapses on a 3-min PVT were assessed immediately after wakening every 15 minutes for 50 minutes. Nap sleep was affected in the caffeine condition: total sleep time was lower and sleep onset latency longer (both by ~10 minutes) in the caffeine condition, and participants entered SWS in the placebo condition only. While inertia was present in the placebo condition, no cognitive impairment was observed in the caffeine group. There were significantly fewer PVT lapses and less fatigue in the caffeine vs. placebo condition and this improvement was sustained over the entire 50 minutes post-nap period. The positive effects observed in this study may be attributed to a combination of caffeine effects and the shorter nap-sleep in the caffeine condition, which was reduced to a duration of 20 minutes, previously shown to minimize inertia upon awakening.

Van Dongen et al. (2001) investigated the effects of hourly low-dose caffeine consumption on inertia throughout an 88-h period of extended wakefulness. Participants were kept awake for 88 hours except for 7 x 2-h nap opportunities, scheduled every 12 hours from 14:45 to 16:45. During the last 66 hours, participants received either a placebo pill or a low-dose caffeine pill (0.3 mg/kg, about a quarter cup of coffee) in a randomized, double-blind, between-subject design. The pills were administered every hour as well as within 5 minutes after abrupt awakening from the naps. Sustained alertness was assessed on the PVT every 2 hours and immediately upon awakening. They observed that performance was significantly impaired in the placebo condition, whereas no such impairment occurred in the caffeine condition. Nap sleep was only modestly affected by the repeated caffeine consumption (e.g., 1 out of 7 naps had less non-REM sleep in the caffeine vs. placebo condition). Since caffeine's main mechanism is the antagonism of adenosine receptors, the authors proposed increased adenosine upon awakening as the cause for sleep inertia, with caffeine reducing inertia via blocking adenosine from binding to receptors and taking effect.

In a double-blind, crossover (within-subject) design, Newman et al. (2013) tested the effects of a caffeine chewing gum in active-duty military personnel on inertia following awakenings at 1:00 (following a 1-h nap; after testing, participants went back to sleep) and at 6:00 (following ~ 4.5 h of sleep). Participants were administered a gum pellet containing 100 mg of caffeine or placebo immediately upon awakening and chewed the gum during the first test session, for about 5 min (equaling the release of 85% of the dose). Performance on the 5-min PVT was assessed every 6 min for 25 min. After awakening at 1:00 following a 1-h nighttime nap, response speed in the caffeine condition increased from 0 min to 6 minutes after awakening, was maintained for the rest of the test session and was significantly faster at 12 min and 18 minutes than placebo. At waking up at 6:00 after 4.5-h sleep, the pattern was similar, with significantly faster response speed in the caffeine than placebo condition at 18 minutes post-awakening. Results for lapses mirrored the results for response speed. Sleep onset latency following the 1-h nap did not differ between the conditions.

In a randomized, double-blind, placebo-controlled, crossover study, Dornbierer et al. (2021) had participants ingest a capsule with or without 200 mg caffeine 8.5 hours before a scheduled 4-h nighttime sleep opportunity. The profile of the pulsatile-release caffeine formula yielded a maximal plasma concentration after 10.5 hours. Performance on the 10-min PVT and working memory using the n-back task were assessed immediately upon awakening at 6:00 - 7:00 in the morning. Caffeine improved PVT reaction time by ~ 10 ms between 5 to 15 minutes after awakening compared to placebo, with no difference in lapses. Caffeine had no effect on the other tasks which took place later in the testing session (at 47 minutes post-awakening), which suggests that inertia had dissipated by then. Caffeine had only minor effects on sleep quality and length.

Summary: Caffeine

Caffeine was found to be an effective countermeasure against inertia in all 5 studies, both when taken before sleep or immediately upon awakening. It is easily applicable and already a commonly used countermeasure for fatigue in working populations. In a study with active-duty military personnel, chewing caffeine gum for 5 min after awakening from a 1-h nighttime nap took 6 - 12 min (incl. chewing time) to show effects and reduce inertia below the level of the placebo condition (Newman et al., 2013). In a simulated night-shift study, drinking 200 mg of caffeine right before a 30-min nap eliminated inertia effects upon awakening at 4:00, potentially due to a combination of caffeine and shortened nap-sleep (Centofanti et al., 2020). Overall, caffeine seemed to affect subsequent sleep to a small to moderate degree.

3.2.1.4 Noise/sound

Two studies tested the effects of noise or alarm tones on inertia, either after waking up from a nighttime nap (Tassi et al., 1992) or in the morning after waking up from nighttime main sleep (McFarlane et al., 2020a). Tassi et al. (1992) exposed participants to intense pink noise of 75 dB(A) upon awakening from a 1-h nighttime nap (0:00 - 1:00 vs. 3:00 - 4:00). They found that this type of noise completely abolished inertia effects on cognitive performance that otherwise lasted 9 minutes (after awakening at 4:00), respectively, 15 minutes (after awakening at 1:00) in the control group (exposure to a neutral acoustic environment). McFarlane et al. (2020a) investigated melodic vs. rhythmic sounds upon awakening at home as inertia countermeasures. Compared to a control sound, that was neither melodic nor rhythmic, the rhythmic sound condition had no effects on PVT performance. The melodic sound significantly decreased PVT lapses and false starts (i.e., pressing the button without a stimulus present), but did not affect reaction time nor speed.

Summary: Noise/sound

Exposure to auditory countermeasures (e.g., noise, waking sounds) may be a promising means to reduce inertia effects on performance, yet data is insufficient for a firm conclusion. A systematic review on auditory countermeasures against sleep inertia came to a similar conclusion, stating that for abrupt awakenings in adults, findings are promising but insufficient (McFarlane, 2020b). Auditory countermeasures could be relatively easily implemented in the cockpit. However, as a reactive and behavioral countermeasure, they are dependent on the Pilot Resting having the time and capacity to employ them and recognizing that a countermeasure may be needed, all of which is likely to be impaired under sleep inertia. Behavioral and reactive countermeasures may be automated in the future, such that they are automatically activated upon awakening with pilots having to opt out, not in.

3.2.1.5 Exercise

Two studies by the same research group tested exercising upon awakening as an inertia countermeasure. The study rationale is based on emergency responders often crediting an ‘adrenaline rush’ as the reason why they might be able to respond quickly and perform unimpaired by inertia. During an ‘adrenaline rush,’ the sympathetic nervous system triggers a fight or flight reaction, mobilizing the body’s resources and creating a heightened state of alertness. The first study tested whether exercise could counteract sleep inertia by inducing a burst of noradrenaline, which promotes sympathetic activity, including increased heart rate and blood pressure and releasing stored glucose for energy. In a repeated-measures, crossover (within-subject) design, Kovac et al. (2020b) exposed participants to two conditions: after waking up from a 2-h nap opportunity from 0:00 - 2:00, participants either exercised, which included a 2-min warm-up on a cycle ergometer at an intensity predicted to elicit 60% of age-predicted maximal heart rate, followed by a 30-s maximal sprint, or sat quietly for 2.5 minutes in the sedentary control condition. Subjective sleepiness and plasma noradrenaline levels were assessed every 15 minutes for 75 minutes. Noradrenaline levels were significantly higher at 5 minutes following the burst of exercise compared to when sedentary at 5 minutes. It decreased over time, matching sedentary levels at approximately 30 minutes after waking. Participants felt less sleepy in the exercise compared to the sedentary condition. Based on these promising results, Kovac et al. (2021) conducted a second study using a similar study setting, but this time included several objective performance tasks. They compared 3 conditions: after waking from a 2-h nap (0:00 - 2:00), participants completed a cycling bout of high-intensity (30-s sprint), low-intensity (30 seconds at 60% max heart rate) or did not exercise (sedentary control). Participants again felt less sleepy in the high-intensity condition, but no significant differences in cognitive performance were observed between the conditions.

Summary: Exercise

Exercise may reduce feelings of sleepiness upon waking from a 2-h nighttime nap but does not seem to improve cognitive performance. A recent review by Kovac et al. (2020c) on exercise as an inertia countermeasure concluded that duration and intensity are key when determining how well exercise may work against inertia. The combination of feeling less sleepy while not being less cognitively impaired may raise concerns and should be treated with caution. High-intensity exercise may be difficult to implement in a cockpit environment and situations that trigger the abortion of an eMCO segment may not permit for such a behavioral countermeasure.

3.2.1.6 Stress

Exposure to stress may act in similar ways to exercise, via heightened alertness levels, but a stressful situation may also impair cognitive functioning. Two studies investigated effects of stress, respectively, anticipation of a stressful task, on sleep inertia during simulated on-call nights. In one study by Kovac et al. (2020a) participants expected to be awoken to either a low- or a high-stress task (i.e., pro-active countermeasure), yet were not awakened during the night but had a full night’s sleep. Performance after awakening in the morning was not affected by anticipation of a stressful task. Jay et al. (2019) also simulated on-call nights in the laboratory but did awaken participants during the night at 4:00 after 5 hours of sleep, either gently by study staff or by an alarm followed by a mobilization procedure, involving putting on a firefighter jacket and shoes and walking quickly to the testing room. No difference in performance was found between the 2 conditions.

Summary: Stress

Neither study observed a mitigating effect of stress upon awakening on inertia. However, none of the studies measured physiological stress levels and the employed measures were rather mild, so that no conclusion can be drawn. Stress exposure may be less of a countermeasure in eMCOs than a situational characteristic when a segment is aborted due to system failure or emergency. More research on the effects of a stressful environment on inertia-impaired performance is therefore warranted vital for assessing inertia-associated risks in eMCOs.

3.2.1.7 Face-washing

The study by Hayashi et al. (2003) investigated 3 countermeasures bright light, caffeine, and face-washing. Participants washed their faces in a washbowl with 2 liters of water at 25 ± 2 °C for 2 minutes after waking up from a brief daytime nap, sitting on the edge of the bed which somewhat limited their physical activity level during face-washing. Since Hayashi et al. did not observe inertia effects, they analyzed whether the countermeasures might have beneficial effects on performance over not napping, respectively, napping without a countermeasure. Face-washing after a 20-min daytime nap reduced fatigue from 30 to 60 minutes post-waking compared to napping alone but had no effects on objective performance. Hirose et al. (2003) tested the effects of wiping the face with a cold towel and getting a cold breeze from a fan for 1 - 2 minutes vs. no such intervention in the control condition. Participants were instructed to sit quietly with closed eyes for 15 minutes during the daytime. Based on EEG recordings, participants were then classified into 2 groups: those who fell asleep during the rest period vs. those who only dozed off (i.e., in a drowsy state during the rest period). Face-wiping with a wet towel and getting a cold breeze improved performance in the first 10 minutes of testing in both groups (asleep or drowsy), compared to those without the intervention. In addition, the performance improvement due to face-wiping was sustained for ~ 50 minutes in those who were asleep during the rest period.

Summary: Face-washing

The 2 included studies suggest that face-washing may have a moderate beneficial effect on sleep inertia. Inertia did not occur in the study by Hayashi et al. (2003) after a short daytime nap and thus they could not evaluate the merit of face-washing as an inertia countermeasure. Their findings suggest a delayed benefit of napping plus face-washing for subjective fatigue. In the study by Hirose et al. (2003), face-wiping with a wet towel was effective regardless of participants being asleep or resting during a 15-min rest period. Depending on the situation leading to the abortion of an eMCO segment, providing wet towels to wipe one’s face may be a relatively easy countermeasure to increase alertness and/or performance, with further benefits after the dissipation of inertia, but more research is needed.

3.2.1.8 Self-awakening

Four studies examined whether the behavioral strategy to self-awaken from sleep may ameliorate inertia effects. In these studies, participants were instructed to wake up by themselves after a pre-determined period (e.g., 15 minutes after lights are turned off). Waking up within ± 5 minutes of the target wake time was considered successful self-awakening in two studies by Kaida et al. (2003a,b). They compared the effects of self-awakening vs. forced awakening (by the experimenter) from a 15 - 20 minutes daytime nap starting at 14:00 on a selective attention task, assessed every 5 minutes for 25 minutes. In both studies, there was no significant difference in performance or sleepiness during the first testing session, neither between conditions nor compared with pre-nap performance, indicating that no inertia occurred. From the 2nd to 4th/5th testing session, sleepiness was lower in the self-awakening than in the forced-awakening condition. Ikeda et al.

(2014) aimed to determine the effects of self-awakening on morning inertia after partial sleep deprivation. They conducted a cross-over study comparing 2 conditions: forced awakening vs. self-awakening (within 30 minutes of a predetermined wake-up time) after nighttime sleep at home restricted to 5 h. In the self-awakening condition, reaction speed was faster and 10% fastest reaction times were shorter, while there was no difference for 10% slowest reaction times, lapses, and subjective sleepiness. Inertia effects were overall moderate. A similar study by Ikeda et al. (2010) confirmed those results: self-awakening improved reaction time immediately after awakening and reduced fatigue for up to 45 minutes post-awakening, compared to forced awakening. In the 4 studies, 70 - 90% of participants managed to wake up by themselves.

Summary: Self-awakening

The findings suggest that self-awakening may improve reaction time upon waking in the morning under conditions of chronic sleep restriction. Overall, inertia effects in the 4 included studies were modest. Two studies examined self-awakening from short daytime naps and did not see inertia effects; thus, they did not evaluate self-awakening as a behavioral countermeasure for inertia but as a possibility to improve sleepiness later-on. While self-awakening may be an easy and feasible, pro-active strategy to reduce inertia, effects on the recuperative function of sleep as well as the efficacy under aggravated conditions, such as self-awakening from nighttime naps near the circadian low, are unclear.

3.2.1.9 Overview: Countermeasures

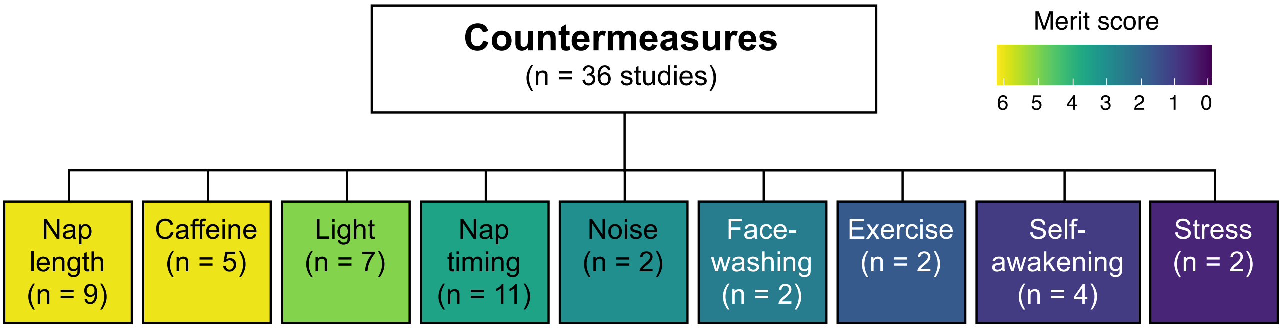
A total of 9 potential countermeasures were identified during the systematic literature review: nap length, nap timing, light exposure, caffeine consumption, noise/sound exposure, exercising, anticipation of stress, face-washing, and self-awakening. To assess their respective merit for use in eMCO settings, the countermeasures were rated according to 3 criteria by one reviewer and cross-checked by another, with consensus reached by discussion. The 3 criteria were: effectiveness (e.g., whether inertia is effectively reduced and/or shortened); quality of evidence (e.g., whether the studies are scientifically sound); and feasibility (e.g., whether the countermeasures are deemed applicable in a cockpit environment). Scores in each dimension range from 0 to 2, resulting in a maximum sum score of 6 (Table 6). The maximum score was achieved by both nap length (i.e., limiting naps to ≤ 20 minutes) and caffeine consumption, making them the best currently available countermeasures, closely followed by light exposure (Figure 8), which can be applied either as a pro-active measure (e.g., wearing light-emitting masks during sleep) or a reactive measure (e.g., increasing light intensity immediately upon awakening). The countermeasures nap timing, noise/sound exposure, and behavioral strategies like exercising, self-awakening and face-washing appear promising, but more research is needed, and their implementation may require some effort. The impact of stress on performance under inertia is unclear but given that stress may be an unavoidable situational aspect when taking over due to an emergency, more research is clearly warranted. Another aspect related to the application of countermeasures is how to arrange the waking-process of the PR. A study examining a vibro-tactile system for awakening reported the highest arousal scores for continuous tactile stimulation, potentially reducing inertia via increased arousal upon waking up (Korres et al., 2018).

Table 6: Merit scores of included countermeasures. *Scores were based on 3 criteria: effectiveness (e.g., whether inertia is effectively reduced and/or shortened); quality of evidence (e.g., whether the studies are scientifically sound); and feasibility (e.g., whether the countermeasure is deemed applicable in a cockpit environment).*

Countermeasures	Effective?*	Quality of evidence?**	Feasible?***	Merit score
Nap length	Yes	Good	Yes	6
Nap timing	Medium	Good	Medium	4
Light: blue	Yes	Good	Medium	5
Light: green/red	Yes	Good but limited	Yes	5
Caffeine	Yes	Good	Yes	6
Noise/sound	Medium	Good but limited	Medium	3.5
Exercise	Unclear	Good but limited	Difficult	1.5
Face-washing	Medium	Fair but limited	Medium	2.5
Stress	Unclear	Fair but limited	Difficult	0.5
Self-awakening	Unclear	Poor	Medium	1

*Yes = 2, medium = 1, no/unclear = 0
**Good = 2, good but limited = 1.5, fair = 1, fair but limited = 0.5, poor/unclear = 0
***Yes = 2, medium = 1, no/difficult = 0

Figure 8: Ranking of countermeasures by merit score. *n denotes the number of included studies per countermeasure.*



3.2.2 Individual factors

A total of 4 studies provided data on inter-individual factors potentially associated with inertia. Of these, 2 studies examined age (Bonnet et al., 1987; Frey et al., 2011), 1 study investigated chronotype (Ritchie et al., 2017), and 1 study assessed inertia as an individual trait or phenotype (Lundholm et al., 2021).

3.2.2.1 Age

The findings of the 2 included studies suggest that younger individuals may be more vulnerable to the effects of inertia than older individuals. In a 64-h sleep deprivation protocol using a simple auditory reaction time test, Bonnet et al. (1987) compared younger (18 - 28 years) with older participants (55 - 71 years) and found that, while response time was not different between the two age groups at baseline, it was slower in younger individuals upon awakening during the night and in the morning, regardless of waking up after baseline sleep or recovery sleep. Frey et al. (2011) compared higher-order cognitive performance using the STROOP task and a mathematical addition task in younger (23 ± 2 years) vs. older (67 ± 4 years) participants upon nocturnal awakening after 110 min of scheduled sleep. Sleep inertia significantly impaired cognition in younger but not in older participants. In contrast to Bonnet et al. (1987), however, Frey and colleagues found that older participants performed worse during baseline, suggesting that even though inertia may affect younger individuals more, they may not necessarily perform worse than older adults under inertia conditions. In both studies, sleep characteristics may have contributed to the difference: younger participants had significantly more slow-wave sleep (Bonnet et al., 1987) and were more often awakened from deep NREM sleep (Frey et al., 2011) than older participants.

3.2.2.2 Chronotype

Ritchie et al. (2017) compared inertia upon habitual awakening in the morning after 8 hours of sleep between participants with an early vs. late chronotype. Chronotype is a circadian phenotype, based on how the circadian system synchronizes to the 24-h day, with rhythms in cognition and physiology peaking earlier (‘morning person’) or later (‘night owl’) in the day. They found that performance after waking for earlier chronotypes took approximately 10 - 20 minutes to improve, while it took approximately 30 minutes or longer to see a significant improvement in the performance of later chronotypes. Participants woke up at their habitual times and sleep duration was similar in both chronotype groups, suggesting that the longer dissipation of morning inertia was not due to late chronotypes being awakened too early und therefore sleep deprived and/or tested at an adverse time of day. It has been previously shown, however, that late chronotypes wake up closer to their biological night (e.g., when melatonin levels, a circadian regulated and sleep-facilitating hormone, have not subsided yet and awakenings are closer to the core body temperature minimum) (Duffy et al., 1999). Thus, performance testing in the morning may still be at an adverse circadian phase for late chronotypes despite habitual wake-times, and several studies have demonstrated that cognitive performance is most impaired near the circadian low/during the biological night (Scheer et al., 2008; McHill et al., 2019). The findings suggest that after a full night’s sleep, late chronotypes awaken at a different circadian phase closer to their biological night, which may make them more vulnerable to more severe and longer lasting sleep inertia upon morning awakening, even when prior sleep duration and architecture is the same as for early types. The findings underscore the importance of circadian phase for inertia severity and duration, with awakenings during the (individual biological) nighttime being most precarious.

3.2.2.3 Personality trait

Lundholm et al. (2021) examined inertia after waking up from sleep-restricted (6 h sleep) or sleep-extended (12-h sleep) baseline episodes before 36-h of sleep deprivation and following 12-h recovery sleep. Subjective sleepiness but no objective performance measures were assessed. They observed substantial differences in the effects of inertia on sleepiness between individuals, but those effects were highly stable within individuals and persisted after recovery from 36 hours of total sleep deprivation. The results provide evidence that inter-individual differences in sleepiness due to inertia constitute a trait or phenotype, with some individuals being generally more vulnerable to inertia than others. To date, it is unclear (i) whether these inter-individual differences in sleepiness may translate to similar differences in cognitive performance; and (ii) what characteristics differentiate inertia-vulnerable from inertia-resilient individuals.

Summary: Individual factors

Limited evidence is available for individual factors that may influence performance under sleep inertia. ***Age:*** Younger individuals may be more susceptible to inertia than older individuals, potentially mediated by their sleep architecture involving more deep sleep and/or awakenings from deep sleep stages. ***Chronotype:*** Late chronotype may be a risk factor for more pronounced inertia effects when performing upon awakening in the morning after a full night's sleep; these effects may be mediated by late types waking up closer to their biological night, despite a similar sleep history. ***Trait:*** One study provided evidence that vulnerability to sleep inertia appears to be stable within individuals, constituting a trait or phenotype, with some individuals being generally more susceptible to inertia than others. The underlying mechanism(s) are unclear, and no screening tools are available yet.

4. Conclusions

The deliverable D-4 is the report on Task 4 synthesizing the results of a systematic literature review of 4 aspects of sleep inertia: the **duration** of sleep inertia, its effects on different **types of task**, potential **countermeasures**, and the influence of **individual factors** on sleep inertia.

A systematic search was conducted in 3 online databases (i.e., PubMed, ScienceDirect, and PsychInfo), yielding 1,413 abstracts, each screened by 2 independent reviewers. Of these, 309 full texts were retrieved and again screened by 2 independent reviewers, resulting in a final set of 70 studies included in the literature review. Specific data relating to the studies' aims (e.g., which of the 4 aspects were addressed in the study), methodology (e.g., study design, performance tasks used), and main findings were extracted to synthesize the studies' results.

Of 70 included studies in the systematic literature review, the majority of studies were conducted in non-EU countries (71%), in laboratory settings (97%), and in non-occupational samples (e.g., healthy adults) (94%). Overall, there is scarce evidence of studies on the duration and effects of sleep inertia in aircrew, with only one study using a flight simulator task, that was however conducted at a time when sleep inertia had already dissipated (Paul et al., 2001). Hence, the conclusions drawn in this report are predominantly based on evidence from well-controlled lab studies in healthy adults, applying standardized tasks that are widely used and recognized in sleep/fatigue and performance research.

4.1 Duration

A total of 45 studies investigated the duration of sleep inertia, with 16 studies examining inertia after nighttime naps/awakenings; 15 studies after daytime naps; and 14 studies after main sleep episodes.

<u>Sleep inertia after nighttime naps/awakenings:</u> **12 of 16 studies (75%) reported inertia to last between 2.5 – 30 minutes.** The remaining 4 studies reported inertia durations of 10 - 40 minutes (owing to the study's wide 30-min measurement interval) (Tremaine et al., 2010), of ≤ 15 minutes to ≥ 47 minutes depending on the type of task (Hilditch et al., 2016a), of 60 minutes in a field study of medical interns based on a between-subject design with no repeated measurements (Basner et al., 2017), and of unclear duration due to the study design (Newman et al., 2013).

<u>Sleep inertia after daytime naps:</u> 13 of 15 studies reported objective performance measures. Of these, **all 13 studies (100%) reported inertia to last between 0 (no inertia) – 35 minutes.** The 2 studies without performance measures (i.e., assessing subjective sleepiness or resisting sleep) reported inertia durations of 20 - 60 minutes (Lavie & Weler 1989; Kräuchi et al., 2004).

<u>Sleep inertia after main sleep:</u> 12 of 14 studies reported objective performance measures. Of these, **10 studies (83%) reported inertia to last between < 7 (possibly no inertia) – 32 minutes.** The 2 remaining studies with performance measures reported inertia durations of ≥ 47 minutes (Hilditch et al., 2016b) and a time constant of 70 minutes for the dissipation of inertia (Jewett et al., 1999). The 2 studies without performance measures (i.e., assessing subjective sleepiness or alertness) reported time constants for the dissipation of sleep inertia between 20 - 40 minutes (Folkard & Åkerstedt, 1992; Lundholm et al., 2021). Results for inertia duration after main sleep episodes were more heterogeneous than for awakenings after naps, partly due to the exacerbating and/or prolonging effects of prior sleep loss on inertia.

In summary, the majority of studies (36 out of 45 studies, 80%) reported sleep inertia-related impairments to have dissipated after 35 minutes post-awakening.

4.2 Type of task

A total of 43 studies investigated the effects of sleep inertia on different tasks/cognitive domains, with (multiple referencing possible): 20 studies comparing types of tasks and/or task complexity; 21 studies comparing performance speed vs. accuracy; 30 studies comparing inertia effects on subjective vs. objective measures; and 21 studies comparing cognitive performance after napping vs. staying awake (Equivalent Level Of Performance findings, ELOP).

The most frequently studied cognitive domains were (multiple referencing possible): sustained alertness (n = 22 studies), followed by working memory/cognitive throughput (n = 15 studies), selective attention (n = 11 studies), and general cognitive functioning (n = 8 studies). Few studies examined effects of sleep inertia on logical reasoning (n = 3 studies) and decision-making (n = 1 study).

Type of task and task complexity: **Findings were inconsistent as to whether and what cognitive domains were differentially impacted by inertia,** and no consensus could be reached based on the available evidence. In studies where tasks differed with regards to their inertia duration, differences could be quite large (e.g., ≥ 47 minutes for sustained alertness and 2 - 15 minutes for general cognitive functioning, Hilditch et al., 2016a). A similar inconsistency was observed for the association between sleep inertia and task complexity, with a 50-50 split of studies over whether simple or complex tasks were more affected.

Performance speed vs. accuracy: **A clear majority of studies (20 of 21 studies, 95%) found performance speed to be similarly or more impacted by inertia than accuracy**, with studies often finding no inertia effects on accuracy. The finding is in line with the notion of a 'speed/accuracy tradeoff', describing the relationship between responding fast at the expense of making more errors vs. making fewer errors at the expense of responding more slowly. Under sleep inertia, this tradeoff changes toward the latter, with participants managing to maintain accuracy levels by taking more time to respond. To what extent this finding can be translated to eMCO scenarios, in which the Pilot Resting needs to take over control of the aircraft in a state of sleep inertia (e.g., should the Pilot Flying be incapacitated), depends on what tasks are deemed safety-critical in such scenarios and whether the correct execution of these tasks involves predominantly fast or accurate execution. It also depends on the actions that the Pilot Resting is allowed to perform under each airline's specific eMCO guidelines.

Subjective vs. objective measures: **A majority of studies (23 of 30 studies, 77%) found a disconnect between subjective ratings vs. objective performance.** However, studies yielded inconsistent findings for the direction of effects, with a ~ 50-50 split over whether subjective sleepiness/alertness or objective performance were more affected by inertia. The disconnect appeared larger when objective performance was reported to be more affected by inertia than subjective sleepiness, with several studies observing no inertia effects on subjective sleepiness. Implications of this disconnect will be further discussed in Chapter 5 "Evaluation of results in the context of eMCO".

Equivalent Level Of Performance (ELOP): None of the included studies explicitly investigated Equivalent Level Of Safety (ELOS) findings, i.e., whether a pilot who is potentially in a state of sleep inertia due to napping provides a level of safety that is equal to the level of safety provided by a pilot who stayed awake. Therefore, this report does not provide ELOS findings, but summarizes findings of studies that compared performance levels after waking up from a nap vs. having stayed awake during the same time (= Equivalent Level of

Performance (ELOP) findings). **The majority of studies (14 of 21 studies, 67%) observed significantly impaired cognitive performance after napping vs. staying awake.** Hence, an equivalent level of performance was not provided; however, most studies reported delayed benefits from napping, with improved performance and/or sleepiness levels for 30 - 240 minutes after the nap.

4.3 Countermeasures

A total of 36 studies examined potential countermeasures for sleep inertia, identifying 9 countermeasures ranging from proactive strategies (i.e., applied before or during sleep) to reactive measures (i.e., applied upon awakening). The most studied countermeasures were: the timing and/or length of naps (n = 15 studies), exposure to light (n = 7 studies) and consumption of caffeine (n = 5 studies), followed by the behavioral strategy 'self-awakening' (n = 4 studies), and exposure to noise, exercise, face-washing, and anticipation of stress upon awakening (n = 2 studies for each countermeasure).

The countermeasures were rated according to 3 criteria: effectiveness (e.g., whether inertia was effectively reduced and/or shortened); quality of evidence (e.g., whether the studies were scientifically sound); and feasibility (e.g., whether the countermeasures were deemed applicable in a cockpit environment). The maximum score was achieved by both nap length (i.e., limiting naps to ≤ 20 minutes) and caffeine consumption, closely followed by light exposure, which can be applied either as a pro-active measure (e.g., wearing light-emitting masks during sleep) or a reactive measure (e.g., increasing light intensity immediately upon awakening). There was limited evidence available for the remaining countermeasures and more research is needed to assess their efficacy and/or feasibility. For all countermeasures, including short naps, caffeine use, and light exposure, studies to gauge their feasibility and implementation in an aircraft environment (i.e., in the cockpit and/or dedicated rest facilities) are lacking, and therefore strongly warranted to evaluate their use as countermeasures in eMCO settings. Behavioral and reactive countermeasures (e.g., exposure to light/noise) may be automated in the future, such that they are automatically activated upon awakening with pilots having to opt out, not in.

4.4 Individual factors

A total of 4 studies examined inter-individual factors potentially associated with sleep inertia, including age (n = 2 studies), chronotype (n = 1 study), and inertia as an individual trait or phenotype (n = 1 study). Results suggested that younger age and a late chronotype may worsen sleep inertia effects under certain circumstances and that vulnerability or resilience to inertia may present an individual trait. However, given the limited evidence due to the small number of studies, no reliable conclusions can be made regarding individual factors associated with sleep inertia.

5. Evaluation of results in the context of eMCO

Based on the results presented above, four aspects will be discussed in greater detail, for their relative importance for and/or challenge to apply in eMCO settings: (i) strategic placement of in-flight naps, balancing benefits for fatigue vs. inertia; (ii) potential use of so-called caffeine-naps in eMCOs; (iii) the evidence regarding decision-making as a key pilot task; and (iv) the implications of a potential disconnect between subjective feelings of sleepiness and objective impairments of performance.

5.1 Strategic placement of in-flight naps

The strategic decision for and placement of in-flight naps requires balancing several opposites. There is clearly a trade-off between napping and staying awake: staying awake makes individuals vulnerable to cognitive impairments by time-awake and/or time-on-task effects but they avoid acute, potentially severe effects by inertia, whereas taking a nap carries the risk of sleep inertia upon awakening but also bears the potential of cognitive improvements later-on. Of the 21 included studies in this review to examine Equivalent Level of Performance (ELOP) findings, 12 studies also examined whether taking a nap resulted in improved performance at a later time point (e.g., delayed benefits), compared with not taking a nap. Ten of the 12 studies (83%) found delayed nap benefits, such that after the dissipation of sleep inertia, sleepiness was decreased and/or cognitive performance was improved for 30 - 240 minutes after awakening. The 2 studies that did not observe a beneficial effect of the nap, neither observed detrimental effects (Takeyama et al., 2004; Hofer-Tinguely et al., 2005).

If napping is recommended over staying awake, the question is for how long and when to take a nap. This decision will also need to consider the structure (i.e., duration and timing) of the eMCO segment, which in most cases will be longer than the nap durations reported in this literature review. Studies are not sufficiently consistent to reach a conclusion regarding this decision. In general, awakenings near the circadian nadir (at ~ 4:00 - 5:00) should be avoided, regardless of prior nap duration, to prevent severe inertia. Ten to 20-min naps seem to limit sleep inertia to a minimum but do not produce the same lasting benefits as longer naps. The study by Leong et al. (2023), comparing 10-, 30-, and 60-min naps may offer a ‘best’ trade-off: while the 10-min nap produced no inertia but also no delayed benefits and the 60-min nap had some delayed benefits but severe inertia effects, the 30-min nap resulted in limited inertia and moderate delayed benefits. However, the naps in that study took place during the daytime and it is unclear if the findings translate to naps during the night.

While limiting sleep inertia may be an important goal, it is often not the only one. Alleviating fatigue through a reduction in time awake and sleep debt can help maintain cognitive performance over a longer period (i.e. throughout the flight duty). If this is the most important factor, longer nap durations of 60 minutes or more should be considered. In Task 6, the potential consequences of both shorter and longer naps for maximum daily flight duty periods in eMCO and single-pilot operations will be evaluated, taking into account the current scientific knowledge regarding the optimal resting cycle, individual differences, and the influence of different types of in-flight rest facilities.

Another factor that has been widely cited as a, if not the, major factor to intensify inertia, is slow-wave sleep (SWS). It was first reported by Dinges et al. (1985) that the amount of SWS obtained during a 2-h nap was the major driving factor of sleep inertia, more so than circadian timing and previous wakefulness. SWS has also been proposed as a rationale for why shorter naps may produce less inertia: if sleep inertia is directly related to the duration of slow-wave sleep during a sleep episode, it follows that inertia will be greater after longer naps that typically contain more slow-wave activity than shorter naps. However, findings regarding the association between SWS and inertia are less consistent than one may expect. Of 12 included studies in this review that examined the association between inertia and SWS or sleep stage upon awakening, 6 studies did observe a relationship (Dinges et al., 1985; Bruck & Pisani, 1999; Ferrara et al., 2000; Hilditch et al., 2016a,b; Lundholm et al., 2021), whereas 6 studies did not find an association (including several well-controlled sleep-laboratory studies; Achermann et al., 1995; Jewett et al., 1999; Achermann et al., 1995; Scheer et al., 2008; Signal et al., 2012; Santhi et al., 2013). Hence, monitoring systems that aim at limiting SWS or waking pilots up at the 'right time' (i.e., from non-deep sleep) may not always yield the least inertia and may in fact make things worse, if a longer nap had resulted in improved outcomes later-on. In addition, prior sleep loss also seems to exacerbate and/or extend sleep inertia effects.

The interactions between all these factors (the timing and duration of a nap, the amount of SWS obtained during the nap and the hours of sleep obtained before the nap as well as prior time awake) are unknown, which makes it very difficult to correctly place an in-flight nap to maximize its purpose-specific benefit.

5.1.2 Caffeine-nap

Caffeine is highly effective in increasing alertness and reducing inertia. It takes about 15 to 30 minutes until first effects can be perceived, and after 45 minutes the resorption of the substance is usually complete. So-called caffeine naps have become quite popular with workers across occupations. A caffeine-nap is typically referred to as the ingestion of caffeine (i.e., 150 - 200 mg) directly before a short nap of ~ 20 minutes. It aims at coinciding the time of waking up from a nap with the time it takes for caffeine to show first effects, potentially combining (some) restorative benefits from napping with avoiding sleep inertia upon waking up. While this approach will almost certainly minimize sleep inertia, it needs to be balanced with the need for longer rest/sleep periods to combat fatigue and with eMCO requirements. If an eMCO segment is several hours long, limiting the opportunity for sleep to a 20-min nap is probably not the best use of the rest period. In addition, caffeine use is complex to schedule accurately, due to a combination of physiological and individual factors that regulate how caffeine acts in the body, how it is metabolized, and how tolerance (i.e., reducing the efficacy of caffeine) builds up over repeated use. Its. Caffeine is metabolized through a liver enzyme which determines its average half-life of 5 to 6 hours. However, depending on genetics, substance use (e.g., nicotine, oral contraceptives, antidepressants), and hormonal status (e.g., pregnancy) much shorter and longer half-lives can be observed. Since caffeine prolongs the duration needed to fall asleep and impairs the recuperative property of sleep, the timing and dosage of consumption should be carefully planned, especially so if used as a countermeasure in an operational setting. Even so, the intake of caffeine cannot be imposed by procedures or regulations.

5.2 Decision-making

One cognitive domain deemed especially relevant for eMCO is decision-making, e.g., whether the Pilot Resting, once awakened, is in a condition to make decisions, should the Pilot Flying be in a significant medical condition. Of the 70 included studies in this literature review, only 2 examined sleep inertia effects on decision-making: while Bruck & Pisani (1999) observed that most impairments of inertia on decision-making in a simulated wildfire emergency scenario had dissipated after 20 minutes, Horne & Mosely (2011) found that the severity of impairments by sleep inertia was dramatic in a simulated military-type exercise. Eight of 10 participants (80%) in the inertia condition failed to successfully execute the task. The study did not aim to isolate inertia effects, but instead examined performance in a worst-case scenario, i.e., testing sleep-deprived participants near the circadian low in a state of sleep inertia. Accordingly, it is not entirely clear which one of these 3 factors was the dominant driver of lower performance. However, such a scenario may also occur in aviation, e.g., during long-haul night flights. Additionally, the study found that 40% of participants in the inertia group were unable to deal with a sudden change in the simulated scenario, raising concerns for emergency situations, that may require fast and dynamic action. Research on pilots' ability to make decisions when in a state of sleep inertia is lacking and therefore strongly warranted to evaluate potentially associated risks in eMCOs.

5.3 Disconnect between subjective and objective measures of inertia impairment

A majority of included studies observed a dissociation between inertia effects on subjective vs. objective measures. The disconnect may be of particular concern if cognitive performance is impaired but not reflected in subjective sleepiness: pilots who do not feel sleepy upon awakening, may over-estimate their ability to perform. For instance, in the study by Hayashi et al. (1999) self-rated performance increased under sleep inertia, with no parallel change in actual performance. McHill et al. (2019) found that chronic sleep restriction worsened inertia effects on objective performance, yet sleepiness levels remained unchanged. Tremaine et al. (2010) observed that the link between objective and subjective measures was stronger (i.e., impaired performance was more closely connected to perceived sleepiness), when individuals were totally sleep-deprived vs. when they were given a nap opportunity during the night. The finding suggests that people may be best able to estimate their level of sleepiness when they are severely sleep-deprived, but that this relationship deteriorates with the inclusion of a sleepiness countermeasure (e.g., a nap). The latter will most likely be more common in eMCO operations. Such a dissociated state, in which pilots do not feel sleepy but are cognitively impaired may threaten the efficacy of fatigue risk management systems, as individuals who do not feel sleepy upon awakening may also not take appropriate countermeasures. Accordingly, risk assessment/management of inertia should not be based on subjective self-reports alone.

6. Set of recommendations

Recommendation 1: It is recommended that an average sleep inertia duration of 35 min be taken as reference by EASA.

Recommendation 2: It is unclear from the published evidence whether, respectively, what tasks a pilot can be reasonably expected to undertake while in a state of sleep inertia. This is particularly true for the cognitive domain ‘decision-making’. It is therefore recommended that more research targeted at the effects of sleep inertia on tasks that are directly involved in performing flight duties be conducted.

Recommendation 3: It is recommended that effective and applicable countermeasures, as supported by scientific evidence, are made available to pilots as part of eMCOs. While exposure to alerting light and caffeine use appear promising, it is recommended that more research be undertaken to establish the best countermeasures against sleep inertia in an aircraft environment.

Recommendation 4: It is recommended that the design of eMCO segments (e.g., duration, timing, number of alternations between Pilot Resting and Pilot Flying) balance the inertia-limiting effect of shorter naps (≤ 20 min) with the fatigue-reducing benefit of longer naps (≥ 30 min). It is further recommended that determining this balance be based on more research than is currently available, particularly research in aircrew.

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Annex A List of included studies

Table S1: Overview of included studies (n = 70). *ELOP = Equivalent Level Of Performance findings.*

First author, year	Country	Study type	Population	Total sample size	Sample age (mean ± SD)	Sex ratio (% male)	Contributed to Question:	Contributed to Type-of-Task aspect:
Achermann 1995	Switzerland	Lab study	Non-occupational (healthy adults)	9	23.8 yrs (range 20-26)	100	Duration, Task	Disconnect
Asaoka 2010	Japan	Lab study	Non-occupational (healthy adults)	8	24.0 ± 1.1 yrs	75	Task	Speed, ELOP
Asaoka 2012	Japan	Lab study	Non-occupational (healthy adults)	20	21.3 ± 1.0 yrs	70	Task	Speed, ELOP
Balkin 1988	USA	Lab study	Non-occupational (healthy adults)	8	Range: 18-20 yrs	63	Duration, Task	Speed, Disconnect
Balkin 1989	USA	Lab study	Non-occupational (healthy adults)	24	23 yrs (range 18-39)	100	Duration, Task	Speed, Disconnect
Basner 2017	USA	Field study	Occupational (medical interns)	224	Interns: 27.6 ± 2.3 yrs, Residents: 29.1 ± 2.7 yrs	Interns: 49.6, Residents: 42.5	Duration, Task	Speed, Disconnect, ELOP
Bonnet 1987	USA	Lab study	Non-occupational (healthy adults)	36	Range: 18-28 yrs (younger) vs. 55-71 yrs (older)	100	Ind.Factors	
Brooks 2006	Australia	Lab study	Non-occupational (healthy adults)	24	22.5 ± 3.9 yrs	50	Duration, Task, Countermeasure	Type, Disconnect, ELOP
Bruck 1999	Australia	Lab study	Non-occupational (healthy adults)	12	22.3 ± 3.6 yrs	25	Duration	
Burke 2015	USA	Lab study	Non-occupational (healthy adults)	6	26.8 ± 5.2 yrs	83	Task	Type, Speed, Disconnect
Centofanti 2020	Australia	Lab study	Non-occupational (healthy adults)	6	Range: 21-36 yrs	33	Duration, Task, Countermeasure	Disconnect
Dinges 1981	USA	Lab study	Non-occupational (healthy adults)	67	Range: 18-33 yrs	54	Duration, Task	Type, Speed
Dinges 1985	USA	Lab study	Non-occupational (healthy adults)	35	Range: 18-30 yrs	57	Countermeasure	

Dornbierer 2021	Switzerland	Lab study	Non-occupational (healthy adults)	32	25.6 ± 3.7	100	Countermeasure	
Ferrara 2000	Italy	Lab study	Non-occupational (healthy adults)	10	Range: 20-30 yrs	100	Duration, Task	Type, Speed
Figueiro 2019	USA	Lab study	Non-occupational (healthy adults)	30	30.4 ± 13.7 yrs	40	Duration, Task, Countermeasure	Disconnect
Folkard 1992	UK	Lab study	Non-occupational (healthy adults)	4	N/A	N/A	Duration	
Frey 2011	USA	Lab study	Non-occupational (healthy adults)	25	21.9 ± 2.2 yrs (younger) vs. 67.4 ± 4.2 yrs (older)	44	Ind.Factors	
Groeger 2011	Ireland	Lab study	Non-occupational (healthy adults)	32	22.5 ± 3.0 yrs	28	Duration, Task, Countermeasure	Type, ELOP
Harrison 2011	USA	Lab study	Non-occupational (healthy adults)	17	23.2 ± 4.7 yrs	44	Countermeasure	
Hayashi 1999	Japan	Lab study	Non-occupational (healthy adults)	10	20.7 yrs (range 20-22)	50	Task	Type, Disconnect, ELOP
Hayashi 2003	Japan	Lab study	Non-occupational (healthy adults)	10	21.1 yrs (range 20-23)	20	Duration, Task, Countermeasure	Disconnect, ELOP
Hilditch 2016a	Australia	Lab study	Non-occupational (healthy adults)	31	24.3 ± 3.4 yrs	42	Duration, Task, Countermeasure	Type, Disconnect, ELOP
Hilditch 2016b	Australia	Lab study	Non-occupational (healthy adults)	16	26.0 ± 4.5 yrs	38	Duration, Task	Type, Disconnect
Hilditch 2017	Australia	Lab study	Non-occupational (healthy adults)	21	24.1 ± 3.7 yrs	43	Task	Disconnect, ELOP
Hilditch 2022	USA	Lab study	Non-occupational (healthy adults)	12	23.3 ± 4.2 yrs	50	Countermeasure	
Hirose 2003	Japan	Lab study	Non-occupational (healthy adults)	8	21.4 yrs (range 19-24)	100	Countermeasure	
Hofer-Tinguely 2005	Switzerland	Lab study	Non-occupational (healthy adults)	50	23 yrs (range 18-28)	50	Duration, Task, Countermeasure	Type, Speed, Disconnect, ELOP
Horne 2011	UK	Lab study	Occupational (military personnel)	20	21 yrs (range 20-22)	100	Task	Type
Ikeda 2008	Japan	Lab study	Non-occupational (healthy adults)	9	21.8 ± 0.6 yrs	29	Duration, Task	Type, Speed, Disconnect

Ikeda 2010	Japan	Lab study	Non-occupational (healthy adults)	9	21.8 ± 0.6 yrs	20	Countermeasure	
Ikeda 2014	Japan	Lab study	Non-occupational (healthy adults)	11	40.5 ± 6.9 yrs	100	Countermeasure	
Jay 2019	Australia	Lab study	Non-occupational (healthy adults)	16	24.6 ± 3.9 yrs	100	Duration, Task, Countermeasure	Disconnect
Jewett 1999	USA	Lab study	Non-occupational (healthy adults)	15	22.7 ± 3.4 yrs	100	Duration, Task	Disconnect
Kaida 2003a	Japan	Lab study	Non-occupational (healthy adults)	9	21.6 ± 1.24 yrs	33	Duration, Task, Countermeasure	Disconnect, ELOP
Kaida 2003b	Japan	Lab study	Non-occupational (healthy adults)	14	21.3 ± 1.3 yrs	43	Duration, Task, Countermeasure	Disconnect
Kolff 2003	Netherlands	Lab study	Non-occupational (healthy adults)	19	Range: 18-25 yrs	16	Duration	
Kovac 2020a	Australia	Lab study	Non-occupational (healthy adults)	24	27 ± 14 yrs	100	Duration, Task, Countermeasure	Type, Speed, Disconnect
Kovac 2020b	Australia	Lab study	Non-occupational (healthy adults)	4	23 ± 2 yrs	100	Countermeasure	
Kovac 2021	Australia	Lab study	Non-occupational (healthy adults)	15	25.9 ± 5.9 yrs	60	Duration, Task, Countermeasure	Type, Speed, Disconnect
Kraeuchi 2004	Switzerland	Lab study	Non-occupational (healthy adults)	25	Study 1: 24 ± 3 yrs, Study 2: 25 ± 4 yrs	Study 1: 100, Study 2: 50	Duration	
Kubo 2010	Japan	Lab study	Non-occupational (healthy adults)	12	21.6 ± 2.8 yrs	100	Task, Countermeasure	Speed, Disconnect, ELOP
Lavie 1989	Israel	Lab study	Non-occupational (healthy adults)	9	Range: 22-26 yrs	100	Duration, Countermeasure	
Leong 2023	Singapur	Lab study	Non-occupational (healthy adults)	32	5.6 ± 4.3 yrs	38	Duration, Task, Countermeasure	Type, Speed, Disconnect, ELOP
Lundholm 2021	USA	Lab study	Non-occupational (healthy adults)	20	29.3 ± 5.7 yrs	60	Duration, Ind.Factors	
McFarlane 2020a	Australia	Field study	Non-occupational (healthy adults)	20	Range: 18-49 yrs	Group A: 60, Group B: 50	Countermeasure	
McHill 2019	USA	Lab study	Non-occupational (healthy adults)	26	26.5 ± 4.4 yrs	41	Duration, Task	Disconnect

Miccoli 2008	Italy	Lab study	Non-occupational (healthy adults)	16	Range: 20-30 yrs	35	Task	Speed
Newman 2013	USA	Lab study	Occupational (military personnel)	15	28.6 yrs (range 22-40)	80	Duration, Countermeasure	
Oriyama 2018	Japan	Lab study	Non-occupational (healthy adults)	12	22.2 ± 0.4 yrs	0	Task, Countermeasure	Type, Speed, Disconnect, ELOP
Paul 2001	Canada	Lab study	Non-occupational (healthy adults)	13	Range: 22-50 yrs	100	Duration	
Ritchie 2017	USA	Lab study	Non-occupational (healthy adults)	14	22.1 ± 3.7 yrs	64	Duration, Task, Ind.Factors	Type
Salame 1995	France	Lab study	Non-occupational (healthy adults)	24	Group 1 22.1 ± 1.0 yrs, Group 2 23.8 ± 1.9 yrs	100	Duration, Task, Countermeasure	Type, Speed, ELOP
Sallinen 1998	Finland	Lab study	Occupational (shift workers)	14	Range 31-52 yrs	100	Duration, Task, Countermeasure	Disconnect, ELOP
Santhi 2013	UK	Lab study	Non-occupational (healthy adults)	11	22.3 ± 4.2 yrs	37	Task, Countermeasure	Type, Speed, Disconnect
Scheer 2008	USA	Lab study	Non-occupational (healthy adults)	12	23.7 ± 4.9 yrs	58	Duration	
Signal 2012	New Zealand	Lab study	Non-occupational (healthy adults)	24	P1: 25.1 ± 4.3 yrs; P2: 23.2 ± 3.5 yrs	100	Duration, Task, Countermeasure	Speed, Disconnect, ELOP
Takeyama 2004	Japan	Lab study	Non-occupational (healthy adults)	6	Range: 19-22 yrs	100	Task, Countermeasure	ELOP
Tassi 1992	France	Lab study	Non-occupational (healthy adults)	44	23 ± 2 yrs	100	Duration, Task, Countermeasure	ELOP
Tassi 2006	France	Lab study	Non-occupational (healthy adults)	17	22.8 ± 1.3 yrs	100	Duration, Task	Speed
Thompson 2014	UK	Lab study	Non-occupational (healthy adults)	8	24 ± 9 yrs	50	Countermeasure	
Tietzel 2001	Australia	Lab study	Non-occupational (healthy adults)	12	20.9 ± 4.17yrs (males) / ± 1.67 yrs (females)	50	Duration, Task, Countermeasure	Type, Disconnect, ELOP
Tremaine 2010	Australia	Lab study	Non-occupational (healthy adults)	24	22.2 ± 2.45 yrs	38	Duration, Task	Type, Disconnect, ELOP

Vallat 2019	France	Lab study	Non-occupational (healthy adults)	55	22.6 ± 2.4 yrs	51	Duration, Task	Speed
VanDeWerken 2010	Netherlands	Lab study	Non-occupational (healthy adults)	16	22.8 ± 4.6 yrs	50	Countermeasure	
VanDongen 2001	USA	Lab study	Non-occupational (healthy adults)	28	29 yrs (range 21-47)	100	Countermeasure	
Wertz 2006	USA	Lab study	Non-occupational (healthy adults)	9	29.1 ± 6.4 yrs	89	Duration	
Woerle 2020	Germany	Lab study	Non-occupational (healthy adults)	25	37.8 ± 11.8 yrs	56	Duration	
Woerle 2021a	Germany	Lab study	Non-occupational (healthy adults)	31	37 ± 12 yrs	58	Duration	
Woerle 2021b	Germany	Lab study	Non-occupational (healthy adults)	61	38.1 ± 11.9 yrs	52	Duration	

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