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Additive Effects of Time Awake and Number of Flights on Fatigue in Short-Haul Pilots: Implications for Duty Time Regulation

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ABSTRACT

Time awake affects airline pilots' fatigue but it is less clear how workload during that time awake impacts fatigue. Although current flight time limitations take the number of flights within a duty period as a measure of workload into account, quantitative evidence for its fatiguing effect is scarce. Here, we analysed fatigue, subjective workload and flight-associated hassles at the end of 553 short-haul flights from 37 airline pilots. Two linear mixed-models with fatigue or subjective workload as the dependent variable were generated, adjusted for time awake, number of completed flights, number of hassles, prior sleep and pilot's responsibility (flying/monitoring). Results showed that fatigue was influenced by time awake, number of flights and pilot's responsibility, whereas no effect was found for number of hassles. The critical fatigue threshold (flying not recommended) was exceeded 2.4 h earlier when operating four flights compared with one flight. Fatigue was lower but subjective workload was higher when the pilot was flying instead of monitoring. Subjective workload increased with number of hassles, but not with number of flights or time awake. European duty time limitations are justified to include a penalty for additional flights but may underestimate the fatiguing effect.

1 | Introduction

Today's requirement for high crew utilisation, with tight schedules and short turn-around times between flights, contributes to increased perceptions of high workload and fatigue, especially on short-haul flights. Sources of fatigue include sleep–wake dependent (i.e., homeostatic) factors and circadian (i.e., relating to an individual's biological, endogenous time of day) factors. Homeostatic influences are fairly straightforward and consistent: the longer someone has been awake or the shorter the duration of their sleep period, the greater the performance decrements and the higher the risk of accidents and injuries (Arlinghaus et al. 2012; Van Dongen et al. 2003). Time awake has been repeatedly demonstrated as a significant predictor of aircrew fatigue and performance, on both short-haul (Vejvoda et al. 2014) and long-haul flights (Petrilli et al. 2006). Since time awake does not fall under regulatory control, efforts to prevent fatigue in the aviation industry have focused on flight time limitations (FTLs), including limiting the number of hours aircrew can work within a flight duty period (FDP). The maximum daily duration of FDPs is regulated based on the scheduled start time and the number of flights to be flown (flights = sectors; both terms are being used interchangeably) (EASA 2014). Current flight time limitations include a stepwise penalty for increasing the number of sectors beyond two within an FDP. While it is well-established

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to regulate maximum duty duration based on scheduled start time (Vejvoda et al. 2014; Arsintescu et al. 2022; Bourgeois-Bougrine et al. 2003; Roach et al. 2012; Gander et al. 2014; Sallinen et al. 2020), it is less clear to what extent the number of flights, per se, affects fatigue.

A study using a Dutch airline's register data on occupational accidents found that the cumulative exposure to short-haul flights was associated with an increased risk of occupational accidents among cabin crewmembers (van Drongelen et al. 2013). In a study on New Zealand short-haul pilots, Powell and colleagues (Powell et al. 2007) found that number of sectors and FDP length had the strongest effects on fatigue, with fatigue scores on the 7-pt Samn–Perelli scale increasing by 0.38 points for every sector (sector range: 1–5). A field study among European airline crews examined the effects of 10–20 sectors over a period of four consecutive daytime duties (15.3 sectors on average across the four workdays) (Goffeng et al. 2019). The authors found that reaction times on the Psychomotor Vigilance Test (PVT), which is a commonly used task to quantify sustained attention, slowed by five milliseconds with each additional sector, both in pilots and cabin crew members. Cognitive slowing is known to be an indicator of fatigue (Brezonakova 2017). A flight simulator study compared PVT performance and fatigue scores of US pilots between a 9-h duty with a single take-off and landing (i.e., one sector) versus a 9-h duty with multiple take-offs and landings (i.e., five sectors) (Honn et al. 2016). Results showed a greater build-up of fatigue in the multi-sector duty day than in the single-sector duty day. The most recent study by Akerstedt et al. (2021) examined fatigue in Norwegian pilots in ultra-short-haul operations that included up to eight sectors. They found that the number of sectors predicted fatigue in a simple regression analysis, but the significant effect disappeared in the multi-variable analysis with the inclusion of FDP duration.

The studies provide support for the number of flights as a relevant factor in regulating maximum duty duration, at least during daytime flights, when other fatigue-inducing factors are mostly absent (Sallinen et al. 2020). Although number of sectors, FDP duration, time awake and subjective workload often increase together, their influences on fatigue may be separate and additive. Here, we examined the effects of time awake, the number of completed flights and the number of flight-associated hassles (i.e., untoward occurrences, e.g., bad weather, technical defect) on fatigue and subjective workload in short-haul pilots of a German carrier. We hypothesised that both, the number of sectors and the number of hassles would increase pilots' fatigue levels as well as their perceived workload, whereas time awake would predominantly increase fatigue. Moreover, we sought to derive a model to estimate the extent to which the maximally allowed flight duty period would need to be adjusted as a function of number of sectors in order to avoid high levels of fatigue.

2 | Methods

Data from a previous study (Vejvoda et al. 2014) were used for the current analysis. Participants, procedures and measurements were described there in more detail and are briefly summarised below.

2.1 | Participants

Forty short-haul pilots of a German carrier (15 captains and 25 first officers) aged between 21 and 52 years (mean ± SD: 32 ± 6 years; all males) operating Airbus A319 were studied. During one work week (4 or 5 duty days), a pilot maintained the same shift schedule, meaning shift changes, e.g., from early to late on consecutive days, were avoided. Rosters were operated as part of pilots' regular employment.

2.2 | Procedures

The data collection period included one day before duty start, one work week (four or five duty days) and the night after the final duty. All pilots attended a briefing session at the Institute of Aerospace Medicine of the German Aerospace Center where study aims, procedures and recording devices were explained. The study was observational in nature and did not involve collection of data or variables that were deemed sensitive, invasive or dangerous to the participants and as such, the study was exempt from medical ethical review. All crew members took part as volunteers after having given written informed consent. The study procedures followed the 2008 Declaration of Helsinki.

2.3 | Measurements

Pilots were provided with a small handheld computer and asked to enter information about each FDP (start and end time) as well as each flight (start and end time, flight destination) and rate their levels of fatigue on the 20-point Samn–Perelli fatigue scale (20-pt SP scale; Samn and Perelli 1982), sleepiness on the 9-point Karolinska Sleepiness Scale (KSS; Akerstedt and Gillberg 1990), and subjective workload using the NASA-Task-Load-IndeX (NASA-TLX; Hart and Staveland 1988) at the end of each flight and each FDP. The SP fatigue scale has been frequently used in the field of aviation and validated to reflect categories of operational significance (Samn and Perelli 1982; Samel, Wegmann, and Vejvoda 1997). The range between 12 and 16 points reflects moderate to severe fatigue, making some performance decrements probable; flying duty is still permissible, but not recommended. Ratings over 16 indicate severe fatigue; performance is considered impaired and flying duty is not recommended (Samn and Perelli 1982). The KSS is a 9-point Likert scale on which participants rate how sleepy they feel right now, with scores of ≥ 7 indicating the start of electroencephalographic (EEG) and electrooculographic (EOG) changes representing sleepiness (Kaida et al. 2006). The NASA-TLX, assessing subjective workload, consists of six scales covering mental demand, physical demand, temporal demand, performance, effort and frustration level, which are weighted by the individual's ranking and summed up resulting in a score between 0 and 300 points (0 meaning the lowest and 300 the highest task load; Hart and Staveland 1988). Workload is considered *very low* for

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scores between 0 and 60; *low* between 60 and 120; *moderate* between 120 and 180; *high* between 180 and 240; and *very high* between 240 and 300 (Hart and Staveland 1988; Pfendler and Schütte 2002). Number of flights, occurrence of hassles and an active, flying role of the pilot were considered objective workload (= more work). A questionnaire including a list of 21 duty-related hassles was completed after each flight (e.g., critical fuel status, aircraft change, bad weather, no break). The list was previously developed in an iterative process involving literature review, pilots' feedback and an FRM expert advisory group (Tritschler and Bond 2010), to reflect workaday factors that cause workload for and are frequently and regularly experienced by flight crews. Before and after each sleep period, the pilots completed a sleep log with questions concerning the beginning and end of sleep (i.e., bedtime, lights off, sleep latency, wake-up time, get-up time) (Samel, Wegmann, Vejvoda, et al. 1997). Visual inspection of wrist motor actigraphy recordings (GEFATEC, Tiefenbach, Germany), worn throughout the study period, were used to verify the sleep period times. Sleep duration was determined as time between sleep onset and final sleep offset.

2.4 | Dataset

Of 40 participants with a total of 588 flights, 35 flights were excluded due to missing or conflicting data, leaving 37 pilots and 553 flights with complete data for analysis. Of the 35 excluded flights, (i) 15 flights were excluded due to missing flight start/end times or fatigue ratings; (ii) 4 flights were excluded due to conflicting sleep and duty times (i.e., sleep offset occurring after duty begin); and (iii) 16 flights were excluded due to conflicting flight and duty times (i.e., duty begin reported to have occurred after start of first flight or duty end to have occurred before end of last flight).

2.5 | Statistical Analyses

2.5.1 | Descriptive Assessment of Time Awake, Number of Flights and Fatigue

The relationship of time awake and number of flights with fatigue was first assessed descriptively, using a scatterplot and fitting least-square regression lines (one line for every number of sectors, i.e., s_1 to s_4 where s is the slope of the fitted line). A boxplot was used to visually juxtapose fatigue scores at the end of the 1st and 4th flight, restricting time awake to 8–12 h to reduce its confounding effect on fatigue. Last, the proportion of high fatigue scores (≥ 12 on the 20-pt Samn–Perelli scale) at the end of the 1st and 4th flight are presented in a bar plot, with time awake restricted to 8–12 h.

2.5.2 | Mixed Regression Modelling

The dependent variables fatigue (via the 20-pt SP scale) and subjective workload (via the NASA-TLX) were assessed after each flight, making flight the unit of analysis. Each pilot had multiple duty days and each duty within one pilot contained multiple flights. Hence, flights are clustered within duty days and duty days are clustered within pilots. Linear mixed models with two random effects, one for the pilot and one for the duty day within a pilot, were used to model the data (West et al. 2022). Both random effects were modelled as random intercepts.

Potential predictors included: number of completed flights (= sectors, i.e., objective workload), number of hassles, time awake, time of day, FDP duration, sleep duration in the previous night and whether the pilot was in an active role (Flying = Yes vs. No). Time of day was categorised into six groups using k-means clustering: 5:30–8:59, 9:00–11:29, 11:30–14:29, 14:30–17:29, 17:30–21:29, 21:30–5:29. Collinearity was expected and checked among predictors, using variance inflation factor (VIF). Due to the categorical nature of the time-of-day variable, several VIFs were obtained (one for each category) and their range is reported. VIF values below 5 were deemed acceptable. Presence of collinearity between FDP duration and number of sectors as well as time awake led to the exclusion of FDP duration from the final model. Time of day showed collinearity with time awake and time awake was given preference due to its more pronounced effect on fatigue.

This resulted in the inclusion of time awake, number of flights, number of hassles, sleep duration and pilot's role (Flying = Yes vs. No) in the final regression model. An interaction effect between time awake and number of sectors was tested but ultimately excluded, due to large increases in VIF scores and standard errors, specifically of the sectors effect, yielding unreliable estimations of the model coefficients. The final model was calculated twice, once with fatigue (20-pt SP scale) and once with subjective workload (NASA-TLX) as the dependent variable. In addition to unstandardised parameter estimates (b), standard errors and p-values, standardised estimates (β) are also provided, which were computed as described in Gelman (2008). The linear mixed model analyses were performed in R (version 4.4.1) using the package "lme4" (Bates et al. 2015), with significance level set to 0.05.

3 | Results

3.1 | Descriptive Results

3.1.1 | Sample Description

Complete data were available for 178 FDPs/553 flights from 37 pilots, with an average of ~5 FDPs per pilot (Table 1). Mean age of the sample was (mean ± standard deviation) 32 ± 6 years and all pilots were male. The number of flights per FDP ranged from 2 to 4 flights (77 FDPs with 2 flights, 5 FDPs with 3 flights, 96 FDPs with 4 flights). Most FDPs started early in the morning between 5:00 and 5:59 (47%), with 64% of FPDs having started before 13:30, after which the daily maximum FDP duration is penalised by 15 min for every half-hour delay in FDP start time, as per European FTL regulation. During the time window 6:00–13:29, the maximum daily FDP duration of 13 h can be operated. Most duties in this sample were well below these limits, with less than 10% of FDPs being longer than 11 h. Most FDPs ended during the daytime between 13:30 and 16:59 (44%), with 16% of FDPs qualifying as late finishes (ending between 23:00 and 1:59) and 3% ending between 2:00 and 2:30, encroaching the window

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TABLE 1 | Sample description ($n = 37$ pilots, observations = 178 FDPs/553 flights).

Variable	Mean ± standard deviation/*N* (%)
Age (years)	32 ± 6
Sex (male)	37 (100%)
FDPs (per pilot/total)	4.87 ± 0.35/178
Flights[a] (per FDP/total)	3.11 ± 0.98/553
FDP start[b] (hh:mm)	06:55 ± 4.75
05:00–05:59	83 (46.6%)
06:00–13:29	31 (17.4%)
13:30–14:59	8 (4.5%)
15:00–16:59	18 (10.1%)
17:00–04:59	38 (21.4%)
FDP end[c] (hh:mm)	16:28 ± 4.70
06:00–13:29	31 (17.4%)
13:30–16:59	79 (44.4%)
17:00–22:59	35 (19.7%)
23:00–01:59	28 (15.7%)
02:00–02:30[d]	5 (2.8%)
FDP duration (h)	9.10 ± 1.49
Flight duration (h)	1.66 ± 0.66
Time awake[e] (h)	11.25 ± 2.89
Sleep duration[f] (h)	6.83 ± 1.49
Fatigue (20-pt SP scale)	8.94 ± 3.50
Subjective workload (NASA-TLX)	113.3 ± 48.09
Hassles (per flight)	1.95 ± 1.77
Pilot responsibility[g] (flying; number of flights)	276 (49.9%)

Note: FDP = flight duty period; 20-pt SP scale = 20-point Samn–Perelli fatigue scale; NASA-TLX = NASA-Task-Load-IndeX; Pilot responsibility refers to the pilot's role: pilot flying vs. pilot monitoring.
[a]FDPs included primarily 2 flights ($n = 77$ FDPs) or 4 flights ($n = 96$ FDPs), with only five 3-sector FDPs.
[b]Categories were selected to reflect FDP start times that, together with the number of sectors, determine maximum daily FDP duration according to European FTL regulation.
[c]Categories were selected to include late finishes (23:00–01:59) and FDPs ending during the window of circadian low (WOCL, 2:00–5:59).
[d]The latest FDP end was at 2:30. No FDPs ended between 2:31 and 5:59.
[e]At the end of the last flight.
[f]The night before the duty.
[g]The number of flights, respectively, percentage of flights during which the participating pilots assumed the role of pilot flying vs. pilot monitoring.

of circadian low (WOCL). No FDP ended between 2:31 and 5:59. FDPs were on average 9 h long (±1.5 h, range 4.5–13.6 h), with an average flight duration of 1.7 h (±0.7 h, range 0.8–3.8 h). Time awake at the end of the last flight was on average 11.3 h (±2.9 h, range 4.8–22.1 h), with a mean sleep duration of 6.8 h (±1.5 h, range 1.9–10.9 h) during the preceding night. Across all flights, pilots' fatigue ratings were on average at 8.9 on a 20-point scale

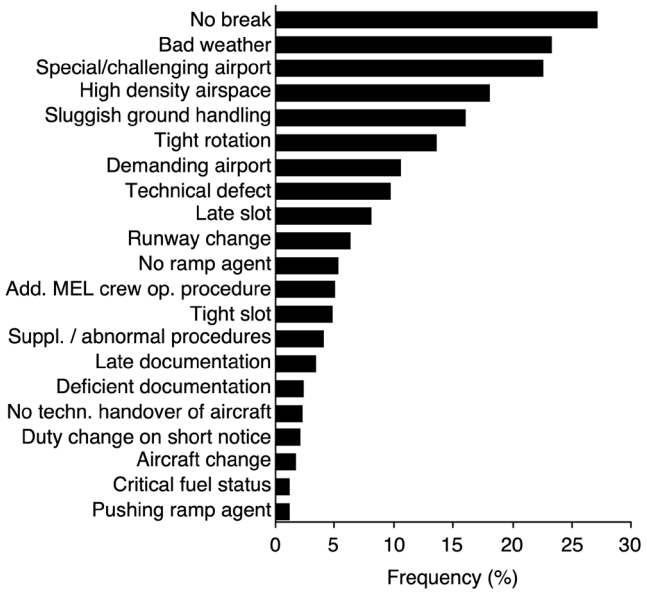


FIGURE 1 | Reported frequency of 21 pre-defined hassles. Multiple hassles (or no hassle) per flight could be selected. A "special/challenging airport" is characterised by a difficult location and/or approach procedure that requires pilots to be briefed beforehand (e.g., Santorini JTR). A "demanding airport" is characterised by a high traffic volume and complex navigation (e.g., Paris CDG). MEL = Minimum Equipment List.

(±3.5, range: 1–18), which qualifies as mild fatigue; the absence of severe fatigue is consistent with the planning of these duties under appropriate European fatigue risk management principles. Subjective workload across all flights was 113.3 on average on a 0–300 scale (±48.1, range 22–252), indicating low workload on average. Participants had an active, flying role (being the pilot flying, as opposed to the pilot monitoring) on approximately half of all flights.

3.1.2 | Reported Hassles During Flights

Of 21 pre-defined hassles, an average of two hassles (±1.8) was reported per flight, with the number of hassles per flight ranging between 0 and 9. "No breaks" was indicated most often (28%), followed by "Bad weather" (24%) and "Special/challenging airport" (23.5%) (Figure 1). The least frequently reported hassles were "Aircraft change" (2%), "Critical fuel status" (1%) and "Pushing ramp agent" (1%).

3.1.3 | Descriptive Assessment of Time Awake, Number of Flights and Fatigue at End of Flight

Fatigue at the end of a flight increased with longer time awake (Figure 2a,b). Fatigue also increased with the number of sectors: keeping time awake to 8–12 h, the difference in fatigue between completing one and four flights amounted to 1.6 points on average (8.8 vs. 10.4, Figure 2c). Fatigue scores exceeded the threshold of 12—above which flying is not recommended (Samn and Perelli 1982)—more often at the end of four flights, compared with one flight (including only flights with prior time awake

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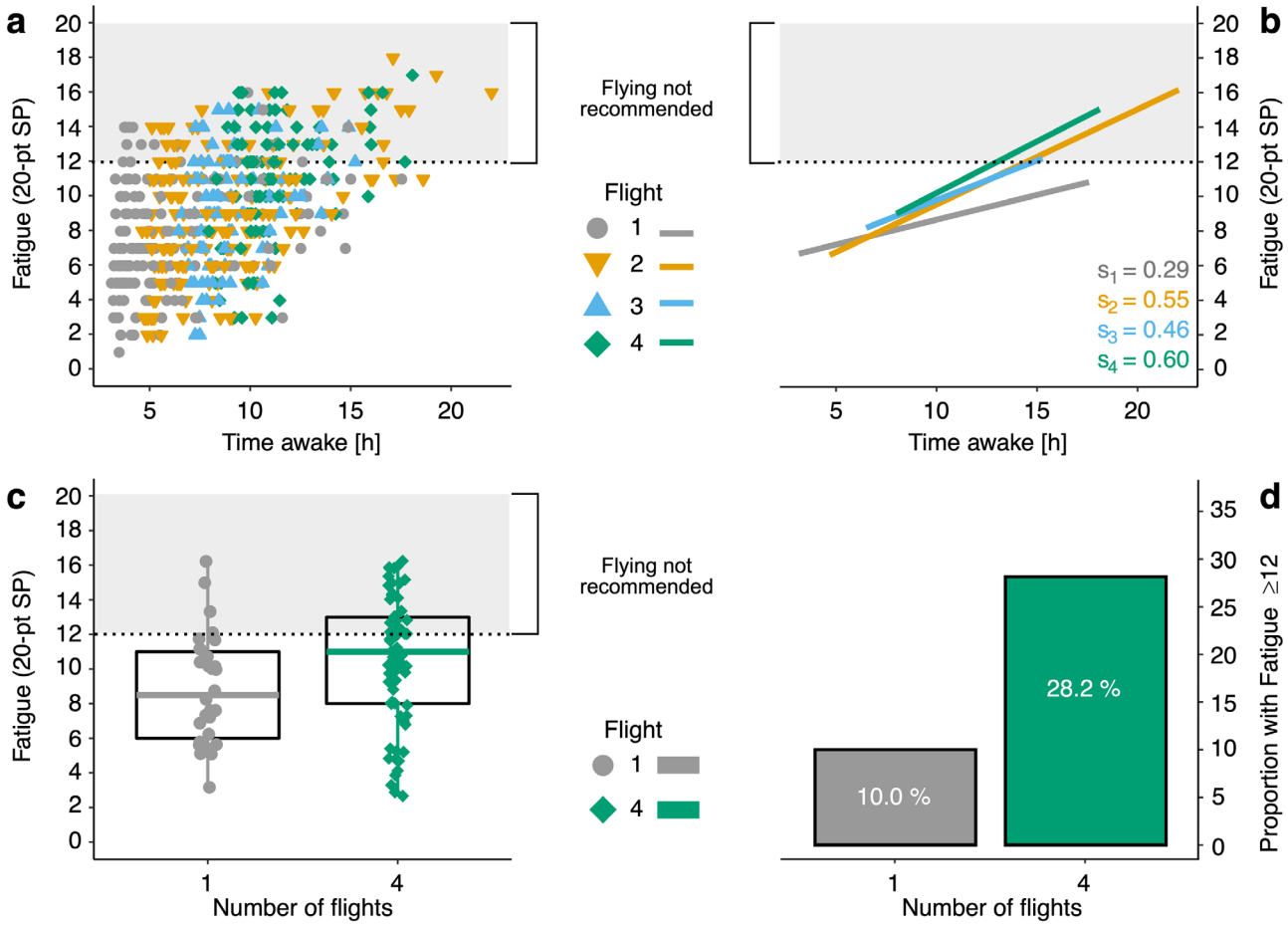


FIGURE 2 | Descriptive relationship between fatigue, time awake and number of flights. (a) Scatterplot between fatigue ratings and time awake, shown for the 1st, 2nd, 3rd and 4th flight within a flight duty period. (b) Fitted lines of the scatterplot shown in panel a, according to the number of flights. The slopes (s_1–s_4) are based on an unadjusted, linear fit to the fatigue data and do not reflect statistically different increases. (c) Fatigue scores at the end of one and four completed flight sectors, only including flights with prior awake time between 8 and 12 h. Boxplots show median and interquartile range. (d) Proportion of flights with fatigue above the threshold, where flying is not recommended (SP ≥ 12), only including flights with prior awake time between 8 and 12 h. 20-pt SP = 20-point Samn–Perelli fatigue scale.

between 8 and 12 h) (Figure 2c). Pilots reported high fatigue (i.e., SP ≥ 12) almost three times as often at the end of the 4th flight sector (28%), compared with the 1st sector (10%, Figure 2d).

3.2 | Linear Mixed Model Results

3.2.1 | Influence of Time Awake and Number of Flights on Fatigue

Linear mixed model regression revealed time awake (unadjusted estimate $b = 0.43$, $p < 0.001$), number of flights ($b = 0.34$, $p = 0.02$) and the role pilot flying ($b = -0.41$, $p = 0.01$; compared with pilot monitoring) as significant predictors of fatigue (Table 2). Sleep duration and the number of reported hassles had no significant effect ($p > 0.16$ in each case). Fatigue increased by 0.4 points with every hour awake and by 0.3 points with every completed flight. Flying, compared with a monitoring role, was associated with 0.4-points lower fatigue, comparable to the effect of 1 h less awake time. Although correlated ($r = 0.48$), collinearity between time awake and number of sectors was moderate (VIF = 3.4). Including an interaction term between time awake and number of flights rendered the estimation of the sectors effect unreliable (see Section 2.5), suggesting that in this dataset the effects of time awake and number of flights were more appropriately modelled in an additive than a multiplicative fashion.

TABLE 2 | Linear mixed model with fatigue scores (20-pt Samn Perelli scale) after each flight as dependent variable, adjusted for time awake, number of flights, number of hassles, sleep duration in the previous night and the pilot's role (pilot flying yes/no).

	b	SE	*p*	*β*
Intercept	5.49	0.91	< 0.001	9.10
Time awake[a] (h)	**0.43**	0.06	**< 0.001**	2.96
Number of flights	**0.34**	0.15	**0.02**	0.74
Number of hassles	0.09	0.07	0.17	0.33
Sleep duration (h)	−0.15	0.11	0.16	−0.46
Flying Yes (ref: No)	**−0.41**	0.16	**0.01**	−0.41

Note: *b* = unstandardised estimate; SE = standard error; *β* = standardised estimate.
[a]Calculated as the time between sleep offset and end of each flight (i.e., when pilots completed their fatigue rating).

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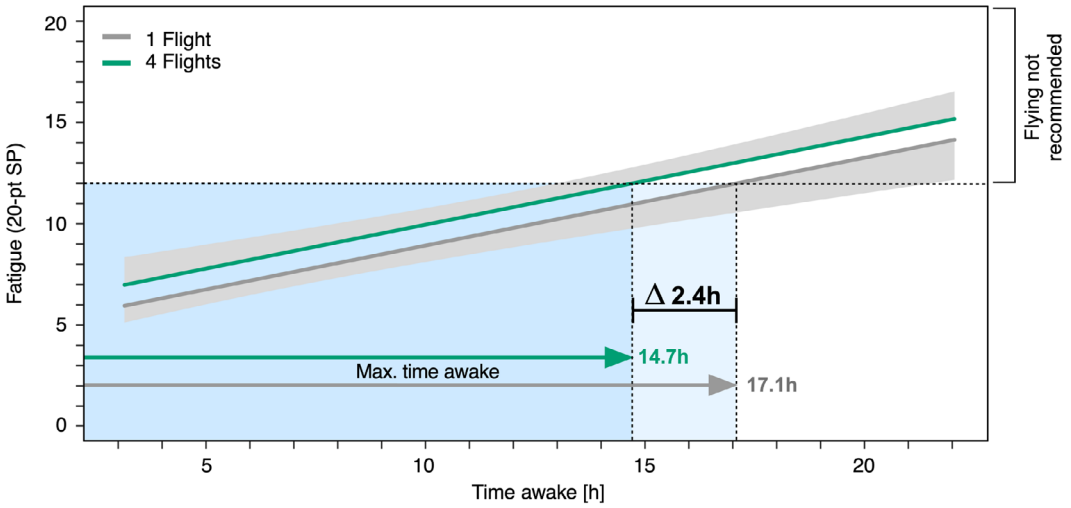


FIGURE 3 | Predicted fatigue scores as a function of time awake and number of flights. The maximum time awake below the critical fatigue threshold is reduced by 2.4 h when operating four flights, compared to one flight. Predictions are derived from the linear mixed model coefficients for time awake and number of sectors, keeping the other variables constant: Number of hassles = 2 (median), sleep duration = 6.75 h (median), pilot flying = yes. The equation is given as: *Fatigue* = 4.24 + 0.43 × *Time awake* + 0.34 × *Number of flights*. 20-pt SP = 20-point Samn–Perelli fatigue scale. Grey shades indicate one half of the 95% confidence interval derived from linear mixed model.

TABLE 3 | Linear mixed model with subjective workload scores (NASA-TLX) after each flight as dependent variable, adjusted for time awake, number of flights, number of hassles, sleep duration in the previous night and the pilot's role (pilot flying yes/no).

	b	SE	*p*	*β*
Intercept	98.04	11.50	< 0.001	109.46
Time awake[a] (h)	−0.78	0.78	0.31	−1.01
Number of flights	3.26	1.86	0.08	1.75
Number of hassles	**7.82**	0.93	**< 0.001**	8.41
Sleep duration (h)	−0.63	1.26	0.62	−1.87
Flying yes (ref: No)	**6.20**	2.27	**0.01**	6.20

Note: *b* = unstandardised estimate; SE = standard error; *β* = standardised estimate.
[a]Calculated as the time between sleep offset and end of each flight (i.e., when pilots completed their fatigue rating).

The linear mixed model coefficients were used to predict fatigue based on time awake and number of flights (keeping the number of hassles, pilot's role and sleep duration constant). The threshold for high fatigue on the SP scale, above which flying is not recommended, is predicted to be crossed after 17.1 h when one flight is operated, whereas this threshold is already exceeded after 14.7 h when four sectors are flown (Figure 3). Hence, the difference in time awake before critical levels of fatigue are reached amounts to 2.4 h between operating one or four flights.

3.2.2 | Influence of Time Awake and Number of Flights on Subjective Workload

Unlike fatigue, subjective workload (measured by NASA-TLX) was not significantly influenced by time awake or the number of flights ($p > 0.08$ in all cases) (Table 3). It did, however, increase with the number of reported hassles as well as the role of pilot flying (Table 3 and Figure 4): workload rose by 7.8 points with every additional hassle ($p < 0.001$) and by 6.2 points when the pilot was actively flying, compared to a monitoring role ($p = 0.01$). The number of hassles was the strongest predictor of subjective workload in the model ($\beta = 8.41$). Moderate levels of workload (scores between 120 and 180) are predicted to be reached with three or more hassles during the first flight (assuming median values for the other predictors: time awake = 8.32 h, sleep duration = 6.75 h, pilot flying = yes). Sleep duration had no significant effect ($b = -0.63$, $p = 0.62$).

4 | Discussion

The study investigated the effects of time awake, number of sectors and number of hassles on fatigue and subjective workload in short-haul pilots at a German carrier. Fatigue increased with prior time awake and the number of sectors but was not affected by the number of reported hassles. Conversely, subjective workload (measured by the NASA-TLX) increased with the number of hassles but was not impacted by time awake or number of sectors, suggesting that this type of objective workload (i.e., number of sectors) may not be well captured by the NASA-TLX. Time awake and the number of flights had an additive effect on fatigue, such that high fatigue levels above the critical threshold of 12 on the 20-pt Samn–Perelli scale (flying not recommended) were reached 2.4 h earlier when operating four flights compared to one flight.

Although time awake, FDP duration and number of sectors often increase together, our study suggests that their influences on fatigue are separate and additive. This is in line with previous, but limited research. In a study using a high-fidelity flight simulator, Honn and colleagues (Honn et al. 2016) varied the number of sectors (1 vs. 5) while keeping duty duration constant and observed a greater build-up in fatigue and cognitive performance impairment in the multi-sector FDP, manifesting as significant differences in the second half (i.e., during and beyond

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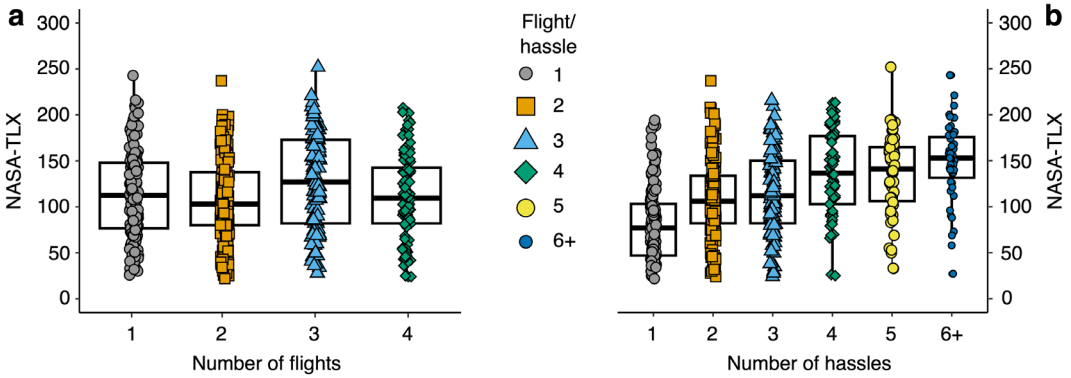


FIGURE 4 | Subjective workload in relation to number of flights and hassles. (a) Number of completed flights. (b) Number of hassles per flight. NASA-TLX = NASA Task Load IndeX.

the 3rd flight) of the 9-h duty period. Having controlled for duty duration, the study demonstrated a direct effect of the number of sectors on fatigue. In one of the first studies on drivers of fatigue in short-haul pilots, Powell and colleagues (Powell et al. 2007) found that duty hours (range 1–10) and number of sectors (range 1–5) were the strongest predictors of fatigue at top-of-descent. While they illustrated additive effects of duty length and time of day on fatigue, they did not present a similar analysis for duty length and the number of sectors. Neither Honn et al. nor Powell et al. examined time awake as a predictor of pilot fatigue. Time awake and duty length are often highly correlated, potentially preventing analyses that directly compare their predictive strength. While this was true for our sample as well, number of sectors showed high collinearity with duty length, but not with time awake. This allowed us to determine how long pilots could stay awake (on average) before reaching high levels of fatigue as a function of the number flights they operate. To the best of our knowledge, this is the first study to do so.

Sleep duration has been shown in many previous studies to be a main predictor of fatigue, with less sleep before the duty resulting in higher fatigue ratings throughout different flight phases, including at top-of-descent (Honn et al. 2016; Sallinen et al. 2017; van den Berg et al. 2016). We did not find an effect of sleep duration on fatigue nor subjective workload. Two characteristics of our sample may explain why sleep duration had no significant impact. First, sleep duration was on average 6.8 h long, which is close to the recommended 7 h or more per night for healthy adults (Watson et al. 2015) and it varied only moderately among FDPs (coefficient of variance = 22%). Second, the flights in our sample were operated mostly during the daytime, which are different from flights during the night. Nighttime flights are more fatiguing, are accompanied by longer time awake (> 16 h) as well as shortened and misaligned sleep (Sallinen et al. 2017; Gander et al. 2015; Hartzler 2014; Caldwell et al. 2019). Due to nonlinear interaction with circadian phase, prior sleep history was reported to have a larger effect on the occurrence of attentional failures during the biological night than during the biological day (Aeschbach et al. 2024). Taken together, sleep may become more important as a preventive and mitigating measure against high fatigue during nighttime than daytime duties (Sallinen et al. 2020).

The roles of pilot flying and pilot monitoring had an impact on both fatigue and subjective workload: the more active task of flying increased subjective workload and decreased fatigue, compared to a monitoring role. This is in line with earlier research, showing that during descent and landing, the pilot flying showed greater increases in heart rate than the pilot monitoring (Gander et al. 1994). This was not dependent on whether the pilot flying was captain or first officer, but captains showed generally lower changes in heart rate between a flying and a monitoring role than first officers. A more recent study on pilot workload during approaches also observed that mean heart rate was higher and average blink frequency was lower for pilots who were actively flying, reflecting greater workload compared to a non-flying role (Elmenhorst et al. 2009). Time on task can negatively affect fatigue, particularly for monotonous tasks (Tritschler and Bond 2010; Cabon et al. 1993), which may have increased the fatigue of the pilot monitoring. The number of hassles associated with a flight was the strongest predictor of subjective workload, with moderate levels reached with three or more hassles during the first flight. From a risk mitigation perspective, avoiding certain hassles during scheduling, like a demanding airport, may be an effective way to reduce workload. The number of sectors as a measure of objective workload may not be well captured by the NASA-TLX.

In this study, both time awake and number of sectors were shown to be independent predictors of fatigue. Accordingly, a long time awake resulting in higher fatigue may be counteracted by a reduction in the number of sectors and vice versa. Since time awake cannot be regulated, flight time regulations aim at limiting FDP duration contingent on the number of sectors, to prevent critically high fatigue levels. The current European FTL regulation allows a maximum daily FDP duration (FDP_{max}) of 13 h when 1–2 sectors are operated (without use of extensions and for acclimatised crew members only; ORO.FTL.205). For each additional sector, the FDP_{max} is reduced by half an hour, resulting in a value of 12.5 h for three sectors and 12 h for four sectors. Based on our analyses, the maximum time awake avoiding high fatigue levels is 17.1 h for one flight, 16.3 h for two flights, 15.5 h for three flights and 14.7 h for four flights. This corresponds to a reduction of 0.8 h in time awake with each additional sector. Figure 5 illustrates several FDPs that are within the limits of the current European FTL regulation but are predicted to result in high fatigue. High fatigue levels could occur within the FDP_{max} if 1-sector FDPs start after 11:00; 2-sector FDPs start after 10:30; 3-sector FDPs start after 10:00; and 4-sector FDPs start after 9:30. If FDPs start later than these times, FDP_{max} would need to be reduced by 1 h for every hour delay in FDP start time (e.g., to 12 h for 1-sector FDPs

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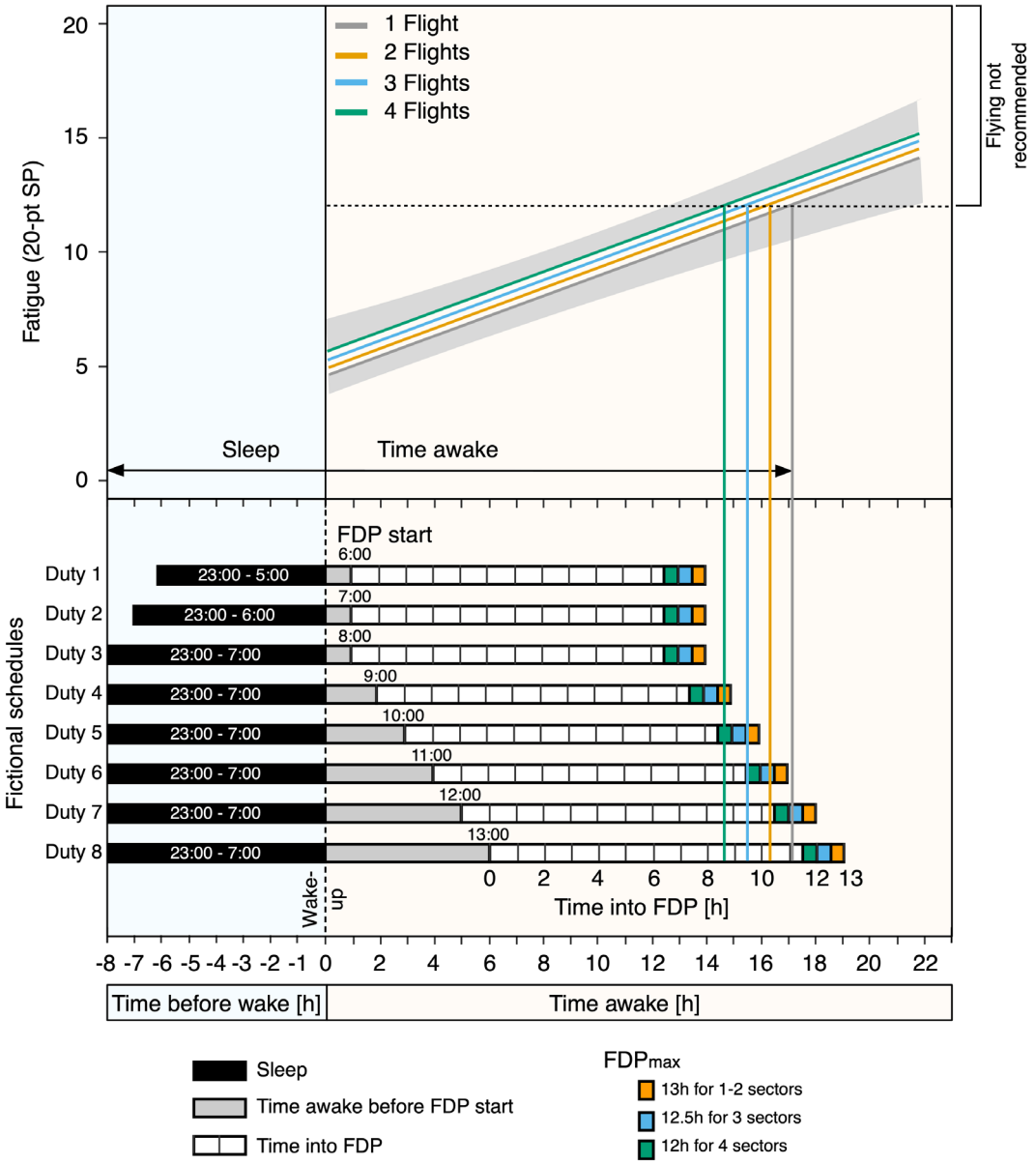


FIGURE 5 | Maximal FDP durations based on current duty time limitation and proposed FDP curtailment based on the present model to avoid high fatigue. Several FDPs (Duty 1–8) are visualised to determine which combinations are predicted to result in high fatigue, considering FDP start time, maximum daily FDP duration (FDP_{max}), number of flights and time awake. The following assumptions are made: (i) Bedtime is set to 23:00 and wake-up times to 5:00 (Duty 1), 6:00 (Duty 2) or 7:00 (Duty 3–8), depending on FDP start. (ii) Time awake starts 1 h before FDPs that begin between 6:00 and 8:00, mimicking shorter sleep durations for FDPs that start earlier than 8:00 (Duties 1 and 2). The little coloured boxes denote the maximum daily FDP duration (FDP_{max}) for 1–2 sectors (yellow), 3 sectors (blue) and 4 sectors (green), as per current European duty time regulation (ORO.FTL.205). If the coloured box either includes or extends beyond the vertical line of the same colour, the FDP is predicted to result in high fatigue (dashed horizontal line in top panel indicates level at which flying duty is not recommended) while the pilot is still on duty. 20-pt SP = 20-point Samn–Perelli fatigue scale. FDP = flight duty period. FDP_{max} = maximum daily flight duty period.

starting at 12:00 and to 11 h for 1-sector FDPs starting at 13:00) in order to avoid high fatigue levels. As a result, a high number of sectors may not be realised anymore under a reduced FDP_{max}. Conversely, a later wake-up time associating with a shorter time awake at the start of an FDP may allow for a longer FDP_{max} with fatigue remaining at acceptable levels. However, even with a wake-up time as late as 9:00, one-sector FDPs that start between 13:00 and 13:29 (the latest permitted FDP start time with an FDP_{max} of 13 h) would still be predicted to reach high fatigue levels within the current maximum daily FDP duration.

Several limitations need to be considered. Our sample consisted of male pilots in regular short-haul operations, from one carrier and operating one aircraft type, potentially limiting the generalisability of the findings. For instance, results may be different for pilots in regular long-haul or mixed short-haul and long-haul (SH/LH) operations. A previous study of pilots in mixed SH/LH operations reported a significant increase in fatigue across the limited range from 1 to 2 sectors (Powell et al. 2008). We would therefore expect the trends to be the same across different operations, with possibly varying effect

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sizes. Only a minority of the flights in our sample arrived late in the day, with 28 (15.7%) late finishes and only 5 (2.8%) night duties. Disruptive schedules, including late and nighttime arrivals, are considered the most fatiguing duties due to circadian (e.g., flights during the WOCL) and homeostatic (e.g., awake times of more than 24 h) effects (Sallinen et al. 2020; Caldwell et al. 2009). These effects may surpass the smaller effect of number of sectors; larger samples would be needed to investigate potential interaction effects. Moreover, we were unable to examine in the current data set the potential influence of varying chronic sleep debt. In a laboratory study, it was shown that time awake and chronic sleep debt interact in multiplicative fashion to increase fatigue, as quantified by the occurrence of spontaneous attentional failures (Aeschbach et al. 2024). The maximum number of sectors was limited to four in our sample, with predominantly two or four flights per FDP. The observed linear relationship between sectors and fatigue may not apply to a higher number of sectors. Studies on high numbers of sectors (> 5) are largely missing. The only published study (Akerstedt et al. 2021) examined a range of 1–8 sectors and found that the significant effect of sectors in the single-variable regression model disappeared with the inclusion of FDP duration in the multi-variable analysis, pointing towards a colinear influence. We encountered a similar issue in our data, with number of flights and FDP duration being highly correlated. However, collinearity between time awake and number of sectors was low, favouring a model that included time awake rather than FDP duration. Inclusion of time awake as a preeminent factor is consistent with physiologically based modelling of human performance (Phillips et al. 2017; McCauley et al. 2024).

5 | Conclusion

In this study of short-haul pilots, time awake and number of sectors were the main predictors of fatigue, whereas the number of flight-associated hassles was the main predictor of subjective workload. A more active role during the flight (i.e., being the pilot flying) increased subjective workload and decreased fatigue, compared to a monitoring role. Time awake and number of flights had independent and additive effects on fatigue, indicating that the negative impact of higher values of one variable (e.g., longer time awake) can be mitigated by lower values of the other (e.g., fewer sectors). Our analyses yielded a 2.4-h difference in time awake between one and four flights before high fatigue levels were reached, suggesting a 0.8-h reduction in time awake to offset one additional sector. Current European flight time limitations are justified in including a stepwise penalty on maximum daily FDP duration for increasing the number of sectors. With a stated half-hour reduction in FDP duration for every additional sector beyond the second one, they may, however, underestimate the size of the sectors effect on fatigue.

Author Contributions

Dorothee Steven: writing – original draft, visualisation, formal analysis. **Kristjof Tritschler:** conceptualisation, methodology, writing – review and editing. **Mathias Basner:** conceptualisation, methodology, writing – review and editing. **Eva-Maria Elmenhorst:** conceptualisation, methodology, writing – review and editing. **Daniel Aeschbach:** conceptualisation, methodology, formal analysis, writing – review and editing.

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Ethics Statement

The study was observational in nature and did not involve collection of data or variables that were deemed sensitive, invasive or dangerous to the participants and as such, the study was exempt from medical ethical review. All crew members took part as volunteers after having given written informed consent. The study procedures followed the 2008 Declaration of Helsinki.

Conflicts of Interest

K.T. was safety manager at the German carrier at the time of the data collection. D.S., M.B., E.-M.E. and D.A. declare no conflicts of interest.

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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