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Assessing Fatigue Risk and Mitigation Strategies for Air Traffic Controllers in European Air Traffic Service Providers

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Abstract

Air Traffic Controllers face numerous fatigue-related challenges due to irregular working hours and demanding workload. In response to European regulations aimed at preventing fatigue and stress, a scientific evaluation funded by the European Union Aviation Safety Agency was undertaken across member states. The objective of this study, as one of the most comprehensive to date in Europe, is to assess fatigue risk levels and identify contributing factors within current operations.

The research methodology combined various data collection methods across European Air Traffic Service Providers, including an evaluation of current scheduling practices and fatigue management alongside a field data collection in representative entities. Sleep, fatigue, and workload data of 216 volunteers were collected and validated by sleep actigraphy measurements.

Statistical analysis of fatigue data on fatigue risk exposure revealed that 5.6% of analyzed duties were associated with critical levels of fatigue. The top five factors contributing to these critical levels are night shifts, challenging weather conditions, monotonous traffic situations, accumulated sleep debt, and extended working hours without breaks. Several recommendations were elaborated to improve fatigue prevention and mitigation at predictive, proactive and reactive levels, encompassing improvements to the rostering process, enhanced fatigue monitoring mechanisms, and practical interventions within organizations.

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1. Introduction

The aviation industry provides one of the safest modes of transport, with a continuous drive to actively manage known and emerging hazards which have the potential to degrade safety. Fatigue is a known hazard that impacts

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human performance and can be a contributing factor to different types of occurrences, even potentially accidents. As it has been shown in systematic review of peer-reviewed and grey literature, those insights also apply to Air Traffic Control Officers (ATCOs) (Gander, 2001; Li et al., 2021; Orasanu et al., 2012; Zhang et al., 2019). ATCOs' tasks constitute a unique set of requirements, with elements such as constant monitoring, resolute actions, multiple communications, high numbers of information items, tactical and strategic considerations, multiple interests, cognitive complex decisions, slow and fast-changing situations, limited representations of reality, and high risks. ATCOs have shift patterns rostered to provide services in a 24/7 environment, therefore some level of fatigue is inevitable and must be managed. That has brought this topic in the domain of the European Union Aviation Safety Agency (EASA).

Commission Regulation (EU) 2015/340 requires, as part of the ATCOs' licensing scheme, the provision of training on the effects and prevention of fatigue. In 2017, mandatory provisions applicable to Air Traffic Service Providers (ATSP) concerning the prevention and mitigation of ATCO fatigue and stress were introduced with Regulation (EU) 2017/373. Some years after the introduction of such requirements, EASA wished to comprehensively assess how Member States and their ATSPs have implemented these provisions and taken stock of the current EU landscape in this field. In this context, it is deemed opportune to collect additional data and undertake dedicated scientifically research, with a view to providing guidance and support to the ATSPs, as well as to support decision-making on a possible further development of the existing EU regulatory framework on this matter. Conjointly, the potential impact of innovative technologies on ATCOs' occupational health and working conditions is investigated.

The objective of this study is to obtain a representative dataset for the target ATCO population and to support the assessment of the causes of ATCO fatigue and their effects. The research activities include the analysis of a sample of ATCOs' rosters across different ATSPs and the practices in fatigue management thereof, as well as the collection campaign of subjective fatigue, sleep and workload data of the ATCOs of a sub-sample of six ATSPs. All ATCOs of these ATSPs were invited to participate, resulting in a sample of 216 ATCOs. The data collection on ATCOs fatigue is therefore one of the most comprehensive to date in Europe as it includes data collected during several consecutive days and covers roster related factors and non-roster related factors.

2. Methods

2.1. Approach

The data collection builds on the findings of current practices concerning fatigue and the analysis of a sample of the rosters of EASA member-state ATSPs. As fatigue is a complex phenomenon with many aspects for which there does not exist a single measure, the methodology considers several fatigue factors to obtain a holistic view of this multidimensional construct. This includes contributors to fatigue, as well as expressions of fatigue.

Collecting objective operational data on large samples is labour-intensive and not always possible, as it can interfere with task execution. Therefore, the step-wise approach to data collection started with previous bio-mathematical analyses of current work schedules, followed by collecting a broad, subjective dataset to investigate ATCOs' day-to-day fatigue. The campaign is based on the four scientific principles described by ICAO (Doc. 9966).

The data was collected by means of a dedicated application that included questionnaires specifically adapted to the study's objectives, consisting of a profile questionnaire and an activity log. At the end of each working session, ATCOs were asked to indicate the factors encountered during their working session from a predefined list of factors, as well as to provide subjective ratings of perceived stress and workload using the Instantaneous Self-Assessment of Workload (ISA; Leggatt, 2005) and subjective ratings of fatigue using the Samn-Perelli Scale (SP; Samn et al., 1982).

The SP measures fatigue on a 7-point scale from 'Fully alert, wide awake' to 'Completely exhausted, unable to function effectively'. The scale is easy to use in operational environments, has been well-validated against objective measures (e.g. electrophysiological performance recordings), and is commonly used to measure subjective sleepiness in field studies. It is widely used in aviation and is one of the recommended methods by the ICAO (2020), providing a reference for acceptable levels of fatigue. Values higher than 5 are considered critical in terms of performance decrement (associated with microsleeps and impaired performance) (CASA, 2023). ATCOs reporting a critical level of fatigue were asked whether their fatigue was due to personal or professional aspects. As personal factors are highly volatile and not under the direct control of ATSPs, events in which fatigue was reported as mostly due to personal reasons were excluded. Only work-related factors were included in the analysis of fatigue contributing factors.

Along with this data collection, actigraphs were used to objectify ATCOs' sleep data in order to complement and validate their subjective sleep log, as actigraphy can reliably estimate wake and sleep periods. For this, 15 volunteer ATCOs of each ATSP were invited to participate in wearing the wrist-worn accelerometer.

Following the data collection, objective data, including eye tracking and reaction time tasks, were collected to substantiate the subjective findings, to perform detailed analyses on the effects of fatigue on ATCO performance and to assess their use in real time fatigue monitoring. This research is presented in another paper (Marsman et al., 2024).

2.2. Selection of the participant sample

The ATCOs of six EASA member-state ATSPs were invited to participate in the data collection campaign. These ATSPs were selected based on a set of criteria ensuring their representativeness of the landscape of EU ATSPs, as they represent different geographical zones and ATC sizes (based on ACC movements), and reflect different levels of fatigue management maturity, different types of scheduling (both individual and group-based scheduling), and various rostering characteristics (in terms of work hours per week, shift length, and shifts per month).

After this extensive inclusion procedure, designated Points of Contact (PoCs) of each ATSP were contacted and meetings were set-up to discuss the purpose and practicalities of the data collection. The study was promoted using the display of informative posters in work spaces and e-mailing campaigns to the ATCOs.

ATCOs who agreed to participate in the data collection signed the informed consent form, which contained information on the purpose of the study, the contents of the data collection on fatigue factors, details on the collection, protection and use of their personal information, and means of contacting the researchers.

2.3. Statistical data analysis

A first analysis showed no significant differences between the six ATSPs in fatigue scores nor in critical fatigue scores. Therefore, the data from all six ATSPs were merged and further analyses were carried out on the whole dataset.

Statistical analyses consisted of a univariate linear analysis on all fatigue data, followed by relative risk analysis for data with critical fatigue scores. The linear analysis investigated whether certain parameters significantly increased the given fatigue levels. The evaluation is defined as the absolute increase or decrease of fatigue (expressed as points on the SP scale) according to fluctuations of a parameter. The analysis of critical fatigue risk, using odd-ratios, investigates the impact of a parameter on the relative risk of obtaining critical fatigue scores. The evaluation is defined as the proportional increase or decrease of critical fatigue risk (expressed in percentages) according to a parameter's fluctuation.

The analyses of fatigue contributing factors were separated between factors not related to ATCOs' work, i.e. individual or personal factors, and factors related to ATCOs' work, differentiated as roster related and unrelated factors. Both a linear and relative risk analysis were carried out on acute fatigue levels reported in each event. For more stable parameters such as demographic elements, this approach was not considered relevant: as acute fatigue is, per definition, the level of fatigue at one time accounting for varying circumstances, combining it with stable parameters is not statistically relevant. Instead, the impact of demographic parameters on chronic fatigue is researched.

The parameters included in the analyses were chosen based on previous literature review and data from the ATSPs.

3. Results

3.1. Analysis of data quality, completeness, and validity

The data collected through the actigraphs and in the smartphone app were analysed and matched to the corresponding participant. Then, the analyses of the individual and work-related data were carried out.

A total of 2.416 work sessions were recorded, of which 2.248 were complemented with a fatigue assessment. One work session is defined as a period of continuous work. Two or more work sessions separated by breaks form an operational duty. Overall, 1.445 duties were recorded, including 288 non-operational duties.

As the representativeness of the samples was satisfactory, the results obtained on this sample could be generalized to the general ATCO population. The distribution of fatigue scores within the sample appears homogeneous between

ATSPs, and sample of cases of critical fatigue showed to be quite homogeneous between ATSPs, too. The confidence level in the collected data is very high. The participants showed a satisfactory participation level despite the constraints imposed by the data collection, requiring them to enter data every day. The collinearity index used, the variance inflation factor (Johnston et al., 2018), showed an independence between variables may be assumed: effects of any possible relationship between variables within the model may therefore be assumed to lie within acceptable margins.

In the validation study, the data of 54 actigraphs were matched to the corresponding participants' data registered in the app and correlated. These data included data on bedtime, wake-up time, sleep duration, and sleep efficiency. The sleep schedules as subjectively reported by the participants may be considered as valid as correlations were very high for bedtime ($r = .99$) and wake-up time ($r = .94$). Correlations between sleep duration reported by the participants and recorded by the actigraphs were found to be strong ($r = .82$), indicating that results based on the analyses using mean sleep durations, such as sleep debt, are robust. Given the high correlation values, conclusions for the ATCOs who participated in actigraphy may be applied for the entire population of participating ATCOs.

3.2. Sample description and distribution of fatigue scores

216 ATCOs participated in the data collection campaign, representing a mean participation rate of around 7% of the six ATSPs' populations. This rate is deemed sufficient to produce reliable results. The sample contains 131 Tower controllers, 135 Approach controllers, and 91 Area controllers (some participants had multiple endorsements). The sample counts 37% female for 63% male ATCOs, pointing at a slight over-representation of female ATCOs compared to the population of the ATSPs. The ages are rather evenly distributed, with a mean age of 39.6 years. As 5.6% of all duties hold critical fatigue levels, further analyses assume the baseline risk of critical fatigue at 5.6%.

3.3. Results: personal factors contributing to fatigue

The impact of individual parameters on chronic fatigue was investigated. The selected parameters included age, sex, job position, commute time, experience and perception of the work conditions.

While demographic parameters were evenly distributed across the sample, a few of the parameters appear to exert a notable influence on chronic fatigue levels. Neither gender, age, nor experience significantly influenced chronic fatigue levels. The demographic parameters that stand out are commuting time ($p < 0.05$) and perception of the work environment ($p < 0.1$): an increase in the average commute time increases chronic fatigue levels slightly but significantly, while increasing the perception of the quality of the work environment appears to reduce chronic fatigue significantly. Differences in job position (Tower, Area, Approach) were not found to impact fatigue levels.

3.4. Results: roster-related factors contributing to fatigue

The investigation of the role of roster-related factors on fatigue level and critical fatigue risk included duty type, sleep debt, and the eight roster elements of EU Regulation (EU) 2017/373. The outcomes are shown in Table 1.

Table 1. : Summary of roster related parameters, risk coefficient and significance. The significance is reported for the following levels: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; NS: Not Significant.

Roster-related parameter			Relative risk of critical fatigue	Significance (p)
Duty type	As defined by the ATSPs	Evening duties	−24% for every evening duty	< 0.001 ***
		Night duties	+253% for every night duty	< 0.001 ***
	As defined by the data	Morning duties	+289% for every morning duty	0.02 *
		Night duties	+333% for every night duty	< 0.001 ***
Sleep debt			+86.3% for each additional 10% of sleep debt	0.009 **
Eight	Duty period length		+10% for every additional duty hour	< 0.001 ***
elements of	Rest period after night duties		−43% for every additional rest day after a night duty	0.06
Regulation	Consecutive duties		+27% for every additional working day	0.08
(EU)	Work session length		+33% for every additional hour in one work session	0.09
2017/373	Ratio of duty periods to breaks		NS	0.19

Rest between duties	NS	0.28
Consecutive night duties	NS	0.49
Number of rest periods within a roster cycle	Insufficient data for analysis	

3.4.1. The effect of duty type on fatigue levels and critical fatigue risk

The effect of duty type on fatigue levels and critical fatigue risk was analysed using two different definitions: duty types were defined by the current practices in the ATSPs, as well as through a data driven approach.

In the first approach, three duty types were predefined by the ATSPs, counting 381 day duties (mainly worked between 0700 and 1500, ending at maximum 1900), 323 evening duties (mainly worked between 1500 and 2300, ending at maximum 0100), and 158 night duties (mainly worked between 2300 and 0700, ending at maximum 0900). Linear analysis showed that night duties appear significantly more fatiguing than day duties, increasing fatigue by 0.22 points on the SP. Evening duties seem marginally significant, even slightly less fatiguing than day duties. The same trend was observed in the risk analysis: night duties increase critical fatigue risk significantly by 353% compared to day duties, while evening duties significantly reduce the risk of critical fatigue by 25% to day duties.

The second approach to defining duty types consisted of comparing mean fatigue levels for the start and end time of each duty. Fatigue levels that significantly distinguish themselves from others were clustered in one type, resulting in three duty types: 16 morning duties (starting between 0200 and 0600), 747 day duties (starting after 0600 and ending before 0200), and 142 night duties (ending between 0200 and 1100). In the linear analysis, night duties were found to be significantly more fatiguing than day duties: at the start of night duties, fatigue levels were 0.28 points higher. Similarly, morning duties were significantly more fatiguing than day duties with an increase of 0.21 points. Compared to day duties, critical fatigue risk increases by 289% for morning duties and 333% for night duties.

Both approaches of defining duty type yielded significant results: night duties emerged as most fatiguing, increasing fatigue levels and critical fatigue risk significantly. After correcting for age, duty length, duty-to-break ratio and workload, the critical fatigue risk increases by 1181% for night duties as defined by data-driven thresholds: this result may be interpreted as the effect of night work if countermeasures (such as breaks) were removed.

3.4.2. The effect of sleep debt on fatigue levels and critical fatigue risk

To investigate the impact of sleep on fatigue levels and critical fatigue risk, more than only sleep duration must be regarded, as analysing only data on sleep durations would not account for individual variability in sleep need. Hence, sleep debt is used as a metric in the analysis, calculated as a percentage of sleep duration compared to the associated individual's sleep need. Positive values represent the proportion of sleep that is missing to achieve one's sleep requirement; negative percentages indicate that the participant slept more than needed, reflecting a recovery process. ATCOs who indicated needing 8 hours of sleep but slept only 6 hours thus carry 25% of sleep debt, as they miss two hours (25%) of sleep. Naps and main sleep periods occurring less than 24 hours prior to duty start were combined.

The data were very evenly distributed, with the median duty starting between 0 and 10 percent of sleep debt. Sleep debt emerges as a significant contributor to fatigue levels and critical fatigue risk: for every percent of sleep debt, fatigue levels increase by 0.30 points, and for each additional 10% of sleep debt, the risk of critical fatigue increases by 86.3%. When controlling for duty type (according to data-defined thresholds), sleep debt plays an only marginally significant role in the increase of fatigue: it is found to affect critical fatigue risk, but when corrected for duty type, the effect vanishes. The impact of sleep debt on fatigue seems to be modulated by the type of duty executed.

3.4.3. The effect of non-operational duties on fatigue levels and critical fatigue risk

The effect of non-operational duties on fatigue levels and critical fatigue risk, including office duties, instructor duties, simulator duties, training duties, medical checks, and other duties, were analysed. While none of these non-operational duty types showed significant impacts on fatigue levels, their duration did seem to show a significant positive effect: for every additional hour of non-operational duty, fatigue levels increase by 0.09 points.

When comparing fatigue levels of both operational and non-operational duties, operational duties stood out as significantly more fatiguing than non-operational duties, regardless of the nature of the non-operational duty. No significant effect on the risk of critical fatigue was found in this context. Non-operational duties, although not individually significant, did collectively contribute to fatigue levels, particularly through their duration.

3.4.4. The effect of the eight elements of Regulation (EU) 2017/373 on fatigue levels and critical fatigue risk

Regulation (EU) 2017/373 requires Air Traffic Service Providers (ATSPs) to define eight roster elements, impacting fatigue and baseline risk. The first element, maximum working days with duty, shows that while fatigue levels don't change with additional consecutive duties, critical fatigue risk increases by 27% per consecutive duty. The second element, maximum hours per duty period, indicates that most duties last around 8 hours. Longer shifts slightly raise fatigue levels and critical fatigue risk, especially at night, but current processes effectively mitigate these risks.

Operational duties, consisting of work sessions separated by breaks, are the focus of the third element. Most sessions last two hours, and while fatigue increases with longer sessions, critical fatigue risk does not. The ratio of work sessions to breaks also shows no significant impact on fatigue, suggesting current practices are adequate.

The minimum rest period between duties, the fourth element, showed no significant effect on fatigue due to limited data on consecutive duties. For the fifth element, maximum consecutive night duties, the analysis revealed that ATCOs rarely work consecutive night shifts, aligning with recommendations to avoid such schedules. This suggests current practices are effective in managing fatigue risk.

The sixth element, the minimum rest period after night duties, demonstrated that additional rest significantly reduces fatigue. For every extra day of rest, the risk of critical fatigue in subsequent duties decreases by 43%. The seventh element, the minimum number of rest periods within a roster cycle, couldn't be conclusively analyzed due to insufficient data.

Overall, the study highlights that maximum consecutive duty periods, duty length, and rest periods after night duties are critical factors influencing fatigue and fatigue risk. These findings underscore the importance of carefully managing rosters to mitigate fatigue-related risks in ATSPs.

3.5. Results: non-roster related factors contributing to fatigue

Parameters not related to ATCOS' rosters were also investigated, assessing both workload and task load. Workload is analysed by means of a generalized linear mixed model. As task load is defined by several factors encountered during the duty, which have a potential to increase workload, it is opted for an approach of both linear and risk analysis.

3.5.1. The effect of workload on fatigue levels and critical fatigue risk

Workload, measured on the 5-point scale ISA, was included in a generalized linear mixed model containing age, duty type, duty length, and duty-to-break ratio. Workload was found to affect fatigue levels, but not critical fatigue risk, even when accounting for latter mentioned factors: for every point on the ISA, fatigue increases by 0.27 points.

3.5.2. The effect of factors encountered during the duty on fatigue levels and critical fatigue risk

When reporting their events, ATCOs had the possibility to report specific events they encountered during the duty. The list of events contained difficult weather conditions, high traffic density, high traffic complexity, low traffic volume, uneventful/ monotonous traffic situations, coordination with colleagues or other centres, coordination with management, the presence of specific flights, traffic unpredictability, the opening or closing of a sector, issues with tools and/or equipment, time pressure or delays, the presence of unexpected events, or the absence of all these factors.

Despite this large palette of events, only very few factors seem to affect fatigue: monotonous traffic situations appear to increase fatigue levels most by 0.15 points. High traffic complexity also plays a major role, increasing fatigue levels by 0.13 points, as does coordination with colleagues or other centres with 0.12 points. ATCOs who did not indicate any of these elements appear more fatigued by 0.11 points. Neither high traffic volume nor high traffic density affect fatigue levels significantly, contrary to traffic complexity. Similarly, the opening and closing of sectors has no significant impact on fatigue levels.

When analysing the events' impacts on critical fatigue risk, monotonous traffic situations and coordination with colleagues stand out significantly, with increases of respectively 120% and 93%. Additionally, difficult weather situations increase the risk by 192%. Contrarily, unexpected events appear to reduce critical fatigue risk by 85%. Other surveyed factors did not have significant impacts on the risk of critical fatigue levels.

This emphasizes the value of addressing both workload and task-related factors in fatigue management strategies.

4. Discussion

The data collection on ATCOs' fatigue of this research is one of the most comprehensive to date in Europe. Data were collected from six representative ATSPs, selected to reflect the Member States' diversity of operations. The participation rate in the data collections averaged 7% of the selected ATSPs' populations, in line with the usual rates in similar studies. The sample is representative of the overall population with respect to several demographic factors. Compared to other studies, the strength of the research is that it includes a data collection over multiple days in a row, covering various factors associated with different aspects that may impact ATCOs' fatigue, including individual, roster and non-roster related factors. The results of the data collection address several questions that could be used to formulate recommendations on fatigue prevention and mitigation in European ATCOs.

But like any scientific study conducted in the field, certain limitations should be emphasized. The number of data points is sometimes too low to draw conclusions on specific parameters. Nonetheless, even if small, individual factors may multiply and emphasise each other in a combined context. For example, even if one parameter is found not to significantly impact fatigue, its increase might trigger other parameters, accentuating the precaution that must be taken regarding risks that may compound one another. Additionally, as the research is based on an observational study, it is difficult to extrapolate the effects of values exceeding the existing practices. While relative risks could be confidently calculated given observed data, this confidence level is weaker for predicted values. Hence, hypothesised effects can only be speculated as increases in risk may not be linear (e.g., it is difficult to predict the effects of very long duties, as they are not included in the data sample). As this research is not experimental, it is not possible to compare its scores with a valid control group. A lack of data can also be observed due to the ATSPs' different practices regarding fatigue, denoting rather effective fatigue risk management practices.

Overall, a low exposure to fatigue was found: 5.6% of the studied duties were associated with critical fatigue levels.

In terms of fatigue exposure, the results align with a previous roster analysis, demonstrating that only a few duties are associated with high risk of fatigue. Therefore, the results suggest that current ATSPs' fatigue management practices are effective in controlling fatigue risk and the average values observed correspond to low risk.

Individual and demographic factors do not appear to significantly affect chronic fatigue. Particularly, in this study, age showed to have a marginal effect on chronic fatigue, while previous research has shown that age decreases tolerance to shift work (Cabon et al., 2024). This result is consistent with recent studies conducted on Swiss ATCOs in the context of an increase in the retirement age. Several factors could explain these results: a healthy worker effect may mask the age effect, as ATCOs may have factors making them more tolerant to shift work, or ATCOs may have more non-operational duties with age (e.g., administrative, training), reducing their exposure to shift work. The only individual factors that significantly affect fatigue are commuting time and perception of the working environment.

Regarding the main contributing factors, it is clear that duty type has the highest impact on fatigue. Applying a data-driven approach, three duty types are distinguished regarding their impact on fatigue: morning, day, and night duties. Morning and night duties significantly increase critical fatigue occurrence when compared to day duties. Previous research showed that these two types of duties lead to circadian disruptions and sleep deprivation (Åkerstedt & Folkard, 1995). On the contrary, evening duties show significantly lower fatigue levels. This can be explained by the fact that these duties fall in the Wake Maintenance Zone, known to increase alertness and performance (Zeeuw et al., 2018) even after prolonged sleep deprivation. Sleep also shows to be a strong predictor of fatigue, as sleep debt increases critical fatigue risk by 8%, highlighting the importance of managing sleep duration and quality. Other factors increasing critical fatigue risk are the number of consecutive working days (+27% for every additional duty) and the length of duties (+10% for every additional worked hour). The number of rest days after a night duty significantly reduce the risk of critical levels: for every additional rest day, critical fatigue risk decreases by 43% in the next duty.

Apart from roster factors, monotonous traffic, traffic complexity, and coordination with colleagues or other centres most significantly increase fatigue levels. Monotonous traffic and difficult weather also increase critical fatigue risk.

4.1. Conclusions

The analysis of the causes and consequences of fatigue highlights that there are multiple factors contributing to ATCOs' fatigue and that ATSPs exert different influences thereon. Understanding the organisational and operational context proved to be important to support the understanding of these factors on performance.

As individual factors may multiply and emphasise each other in a combined context, precaution must be taken regarding compounding risks. Considering factors in different operational settings should be part of the ATSP's fatigue risk assessment. The research has identified some useful key themes that could be considered by ATSPs in terms of planning and supporting the management of those factors and in ATCO's education and awareness training.

This study's methodology is observational, the data collected to assess fatigue risk is based on current practices. Risk variations can be predicted to a certain extent, but cannot be extrapolated beyond certain values. Further research is required to provide evidence on hard limits while controlling other factors.

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