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REVIEW

Cognitive fatigue in young, middle-aged, and older: Breaks as a way to recover

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Abstract

Maintaining productivity is of primary importance in organizational settings. Nowadays, the pressure for work efficacy is required until advanced age given the increased longevity in western societies. Worryingly, performing a work for a long-lasting duration may induce cognitive fatigue, which can alter job performance or cause work accidents. Regarding laboratory studies, cognitive fatigue, as induced in Time-on-Task designs, has been shown to increase reaction times (RTs). According to the Effort-Recovery Model (ERM), work breaks are able to relieve cognitive fatigue and to maintain performance. However, few studies have investigated age-related effects in such a context. In this study, young, middle-aged, and older people performed a 160-min Stroop task in a "NoBreak" or a "Breaks" condition. To assess changes in RTs with Time-on-Task, the task duration was divided into four 40-min blocks in which the ex-Gaussian τ parameter (i.e., an index of longer RTs) was extracted from individual RT data. Our main results showed that young and middle-aged people increased their τ with Time-on-Task while older people did not. Importantly, participants in the NoBreak condition increased their τ with Time-on-Task while those in the Breaks condition kept this parameter constant, suggesting a beneficial effect of breaks independently of age.

KEYWORDS
aging workforce, Belgium, breaks, cognitive fatigue, ergonomics, middle age, organization, Time-on-Task, work

INTRODUCTION

In our modern societies, maintaining performance and productivity at sufficient levels is required in organizational settings. However, performing a working task over a long-lasting duration may induce cognitive fatigue. For example, duty length for commercial flights' pilots has been associated with fatigue level just before the landing procedure, no matter time of day (Powell et al., 2008). In industry, prolonged work shifts lead to impaired alertness and performance (Rosa & Bonnet, 1993). This phenomenon is also striking in emergency services like in intensive care unit physicians (Maltese et al., 2016). Moreover, cognitive fatigue has become one prevalent cause of accidents in everyday life (Dinges, 1995; Shen et al., 2008) as in the workplace (McCormick et al., 2012). For example, Dembe et al. (2005) reported a higher risk of injuries after an increase in the number of working hours. In stronger cases, cognitive fatigue can further develop into a permanent condition like in patients with chronic fatigue syndrome (Tanaka & Watanabe, 2010) or can lead to burnout (Maslach et al., 2001). Obviously, given the tragic consequences of cognitive fatigue, studies are needed to better understand how it will impact job performance and how it is possible to manage it in organizational settings.

Work breaks: A way to recover from job demands

According to the Effort-Recovery Model (ERM; Meijman & Mulder, 1998), employees expend resources and effort to address work demands. Unfortunately, psychological resources such as energy, motivation, and concentration can be depleted, leading to short-term physiological and psychological reactions. These acute strain or load reactions can manifest as increased blood pressure, negative affect, and reduced well-being (Meijman & Mulder, 1998; Sonnentag & Fritz, 2007). Therefore, in order to prevent the accumulation of adverse effects leading to long-term cognitive fatigue and reduced performance, it is essential to punctually recover and replenish our cognitive resources (Bennett et al., 2018; Meijman & Mulder, 1998).

Fortunately, adverse consequences of resource depletion are reversible or reduced when workers disengage from work because it allows functional systems to return to baseline levels (Meijman & Mulder, 1998). It is well established that respite activities *outside the work place*—such as weekends, evenings after work, or vacations—protect employees against psychological pressure, fatigue, and impaired performance (de Bloom et al., 2015; Fritz et al., 2013; Fritz & Sonnentag, 2005; Sonnentag et al., 2008; see Demerouti et al., 2009, for a review). By contrast, little is known about the effects of momentary recovery *inside the work place* (i.e., during working hours), which consists in work interruptions called work breaks, rest breaks, or microbreaks. A work break can be defined as a period of the workday when work-related tasks are not required or when employees proactively shift their attention away from work tasks

(Hunter & Wu, 2016). Work breaks enable the organism to restore energy levels by temporarily removing the ongoing demands and by engaging in recovery activities (Sonnentag & Fritz, 2007).

Regarding ergonomics and organization-based diary studies, work breaks have been associated with recovery outcomes and various beneficial effects (Bennett et al., 2018; Blasche et al., 2018; Bosch et al., 2018; Coffeng et al., 2015; de Bloom et al., 2015; Kim et al., 2017; Mijović et al., 2015; Norouzi, 2019; Trougakos et al., 2008; Trougakos & Hideg, 2009; Wendsche et al., 2016; Wood et al., 2013; Zacher et al., 2014). For example, work breaks have been shown to reduce the risk of accidents in industry (Mijović et al., 2015; Tucker et al., 2003), to improve productivity, job satisfaction (Dababneh et al., 2001), vigor (Hunter & Wu, 2016; Zacher et al., 2014), as well as employees' engagement (Kühnel et al., 2017). In their study, de Bloom et al. (2015) demonstrated that work breaks taken every hour positively affect short-term well-being. Likewise, Mijović et al. (2015) showed that frequent short breaks enhance sustained attention and overall well-being of assembly workers. Trougakos et al. (2008) found that respite activities during scheduled breaks are related to positive emotional experiences.

Besides diary-like studies, laboratory-like studies frequently explore fatigue effects by using the Time-on-Task approach, which consists in making people continuously perform a cognitive task over a relatively long period of time. Time-on-Task has long been associated with the energy depletion hypothesis according to which people become cognitively fatigued because their limited resource supply is depleted after a period of work (Hockey, 2013). In such studies, cognitive fatigue has been shown to increase reaction times (RTs), to decrease accuracy (Boksem et al., 2005, 2006; Boksem & Tops, 2008; van der Linden et al., 2003), and to negatively impact executive control (van der Linden et al., 2003), goal-directed attention (Boksem et al., 2005), action monitoring (Boksem et al., 2006; Lorist et al., 2005), planning and preparation (Lorist, 2008; Lorist et al., 2000), preferences and strategies (Mullette-Gillman et al., 2015), emotion regulation (Grillon et al., 2015), and economic decision (Blain et al., 2016).

In agreement with the ERM (Meijman & Mulder, 1998), it has been proposed that the resources necessary to maintain performance during a task are able to self-recover if the system is allowed to rest (Finkbeiner et al., 2016). Using the Time-on-Task approach, some studies have therefore introduced punctual breaks during a long-lasting task to assess the possibility of recovery from resource depletion. Most of them have found positive effects of breaks on performance (Arnau et al., 2017; Bennett, 2015; Chen et al., 2010; Finkbeiner et al., 2016; Helton & Russell, 2015; Lee et al., 2015; Phipps-Nelson et al., 2010; Richter et al., 2005; Ross et al., 2014). For example, Chen et al. (2010) showed that a 15-min break was associated with faster response and increased accuracy in a sustained calculation task. Bennett (2015) showed that individuals feel more energized, less fatigued, and more attentive by taking microbreaks between tasks. Lee et al. (2015) demonstrated that breaks boost attention in university students performing the Sustained Attention to Response Task (SART; Robertson et al., 1997). Studies also showed that post-break performance in a vigilance task was more efficient than a no-break continuous performance (Finkbeiner et al., 2016; Helton & Russell, 2015). Finally, some studies showed negative effect of longer as compared with shorter breaks (Lim & Kwok, 2016). For example, longer breaks have been linked to an immediate performance rebound followed by a larger Time-on-Task decline (Lim et al., 2016).

The first aim of the present study was to investigate whether cognitive fatigue, as assessed in a long-lasting Time-on-Task paradigm, can be relieved by punctual short breaks (Breaks condition) as compared with participants performing the task without break (NoBreak condition).

The aging workforce: The pros and the cons

These last decades, life expectancy has particularly increased in western societies (Christensen et al., 2009), which exerts major pressures on the public finances and raises questions about pension policy. In reaction to this demographic change, some organizations have started to promote extending working lives (OECD, 2011; Steenstra et al., 2017), constraining people to remain in the workforce with a delayed retirement (Phillipson et al., 2016; Winston & Barnes, 2007).

The aging workforce is associated with benefits and disadvantages (Santrock, 2015). Regarding benefits, increase in crystallized intelligence and emotional health is recognized. Moreover, age seems unrelated to core task performance at workplace (Ng & Feldman, 2008), meaning that both younger and older workers perform in an equivalent manner. Age is also unrelated to creativity (Eder & Sawyer, 2007), such that older workers contribute new ideas to the organization as well as younger workers. Growing older is also associated with greater job-relevant knowledge, greater conscientiousness, as well as greater safety-related behaviors (Cleveland et al., 2019). Likewise, older workers show higher motivation to volunteer (Okun et al., 1998) and have fewer nonfatal injuries as compared with younger workers (Schwatka et al., 2012).

Besides benefits, the disadvantages of older workers mainly come from the decline in physiological functioning, leading to health problems and long-term sickness absence (Streb et al., 2008), fatal injuries (Grandjean et al., 2006; Kemmlert & Lundholm, 2001), musculoskeletal disorders, chronic health conditions, or decreased tolerance to shiftwork schedules, although there is considerable individual variability (Czaja et al., 2020). More strikingly, diminished cognitive functioning efficiency is well recognized in older age (Collette & Salmon, 2014; Crawford et al., 2000; Salthouse et al., 2003; West, 1996, 2000) and to a lesser extent in middle age (Bielak et al., 2013; Cansino et al., 2015; He et al., 2013; Park et al., 2013; Strozyk & Jentzsch, 2012; Wolkorte et al., 2014). Obviously, one important condition that is likely to interfere with diminished physiological system and diminished cognition is cognitive fatigue.

However, studies investigating cognitive fatigue beyond the age of 40 are scarce. Two studies (Klaassen et al., 2014; Klaassen et al., 2016) suggest that middle-aged people resort more rapidly to cerebral compensatory process and reach the limit of cerebral compensation at a lower task level than young people (CRUNCH hypothesis; Reuter-Lorenz & Cappell, 2008). Middle-aged people have also been shown to act in an error-aversive manner and to preserve accuracy at the expense of speed when performing a long-lasting task (de Jong et al., 2018; Wolkorte et al., 2014). Regarding older people, the few existing studies did not systematically show fatigue-related impairments as compared with young people (Arnau et al., 2017; Falkenstein et al., 2002; Philip et al., 1999; Terentjeviene et al., 2018; Wascher et al., 2016). This lack of evident age-related effects in cognitive fatigue protocols has been explained by a better resistance to task monotony and higher motivation in elderly as compared with young people. Nonetheless, Burke et al. (2018) administered a 160-min Stroop task to a sample of older people and found preserved accuracy but increased RTs with Time-on-Task, supporting the existence of a speed–accuracy tradeoff in the elderly (Salthouse, 1979).

Sustainable work

Constructs such as "successful aging" (Zacher, 2015) or "productive aging" (Schulte et al., 2018) have emerged, according to which adverse effects of aging are not immutable but can be delayed and managed with appropriate actions. In this sense, occupational health programs have fostered age-friendly workplaces such as those supported by the European Foundation for the Improvement of Living and Working Conditions (Naegele & Walker, 2006). These programs focus on preventing exposure to occupational hazards (e.g., loud noise, harmful chemicals, vibration, radiation, extreme temperature, and stressful working conditions) that may lead to injury or illness (see, e.g., Varianou-Mikellidou et al., 2019).

As above-mentioned, cognitive fatigue is one major cause of accidents at the workplace (McCormick et al., 2012) while work breaks are associated with recovery, better performance, and well-being at work (de Bloom et al., 2015; Mijović et al., 2015). Allowing people to take breaks during a work day seems a relevant way to simultaneously reduce cognitive fatigue and risk of injury as well as increasing positive outcomes in young as well as older workers.

However, most studies investigating recovery breaks were not interested in age effect beyond its role as a control variable (Sonnentag et al., 2017). To the best of our knowledge, only one study (Arnau et al., 2017) investigated the age variable in the context of breaks and Time-on-Task but did not show behavioral difference between their young and older groups.

In addition to the comparison of a NoBreak versus a Breaks condition, the second aim of the present study was to investigate whether breaks would relieve cognitive fatigue at different ages as implemented by our Group variable (young, middle-aged, and older).

Ex-Gaussian analysis of RTs

Middle-aged and older people favor accuracy instead of speed during cognitively fatiguing tasks (Burke et al., 2018; de Jong et al., 2018). Therefore, assessing changes in RT distribution during a long-lasting fatiguing task seems relevant to catch age effects. Among the various mathematical models allowing to carry out distribution analysis, the ex-Gaussian function has proven to fit RT data very well (Dawson, 1988; Heathcote et al., 1991; Hohle, 1965; Lacouture & Cousineau, 2008; Luce, 1986; Ratcliff & Murdock, 1976; Schmiedek et al., 2007). The ex-Gaussian distribution is the convolution of the Gaussian and the exponential distributions (Burbeck & Luce, 1982; Luce, 1986) and is characterized by three parameters: μ and σ are respectively the mean and the standard deviation of the Gaussian component and τ is both the mean and the standard deviation of the exponential component. Changes in μ represent left or right shifts of the distribution, changes in σ reflect widening or narrowing of the distribution, and changes in τ represent changes in the overall skewness of the distribution. More precisely, increases in τ represent a thickening of the right tail of the distribution representing the extreme (i.e., longer) RTs made by the participant. Resorting to the ex-Gaussian approach is thus a promising method to catch which component of RT distribution (move of the entire curve—change in μ—or increase extreme RTs—change in τ) is affected by age or fatigue-inducing Time-on-Task paradigms.

Moreover, functional cognitive processes have been associated with the ex-Gaussian parameters. RTs would result from two successive components (Hohle, 1965; Luce, 1986): the time to make a decision about the response—the *decision component*—and the time to physically make the response—the *motor-transduction component*. RTs allocated to motor-transduction would be normally distributed, whereas RTs allocated to decision would be exponentially distributed (Dawson, 1988). Consequently, distributions following the ex-Gaussian function capture both transduction-motor processes (represented by μ and σ) and decision processes (represented by τ; Lacouture & Cousineau, 2008).

In a previous study (Gilsoul et al., 2021), we applied the ex-Gaussian approach to discriminate between age groups in the context of cognitive fatigue by administering young, middle-aged, and older people a 160-min Stroop task without break. The total duration was artificially divided into four 40-min blocks, and we fitted the ex-Gaussian function to individual RT distributions in each time block for each item type. The results showed a significant age effect on μ but not τ, suggesting that aging was more likely to influence the time to perform the motor-transduction component of the response. By contrast, we found a significant Time-on-Task effect on τ but not μ, suggesting that cognitive fatigue is more likely to increase extreme RTs reflecting the decision component of the response. Interestingly, we also found a Group by Time-on-Task interaction on τ showing that middle-aged people significantly increase their τ values (i.e., they became slower) with Time-on-Task.

The present study

In this study, we investigated the influence of breaks on the same 160-min Stroop task as in Gilsoul et al. (2021) in young, middle-aged, and older people that were allocated to a "NoBreak" or a "Breaks" condition. Accordingly, most participants from our first study constituted the NoBreak condition and new participants were recruited to constitute the Breaks condition. As longer breaks have been associated with subsequent performance declines as compared with shorter breaks (Lim et al., 2016; Lim & Kwok, 2016), we integrated short 5-min breaks that were granted every 40 min in the Breaks condition. To analyze changes in RT distributions with Time-on-Task, we fitted the ex-Gaussian function to individual RT data in four successive time Blocks (Block 1, Block 2, Block 3, and Block 4) for each Item types (Congruent, Incongruent, and Neutral). Based on the literature (Wang et al., 2014) and on results from our first study showing that Time-on-Task significantly impacts τ but not the other parameters, analyses of this study only focus on τ.

As τ has been associated with decisional processes (Hohle, 1965; Luce, 1986), we predict a main effect of Item type, with Incongruent items being associated with larger τ than Congruent and Neutral items. We also predict that τ should significantly increase with Time-on-Task (Wang et al., 2014). Given age-related studies on cognitive fatigue are very scarce, it is more difficult to have hypotheses about Time-on-Task effect as a function of the age Groups. However, given middle-aged people have been shown to react in an error-aversive manner at the expense of speed (de Jong et al., 2018; Wolkorte et al., 2014), we expect a Group by Time-on-Task interaction on τ, with the middle-aged group showing larger τ increase under cognitive fatigue as compared with the young group. Regarding older people, increased RTs with Time-on-Task were observed with a 160-min Stroop task (Burke et al., 2018). Therefore, we should also observe τ increase with Time-on-Task in the older group. Regarding the Condition effect, we predict that the Breaks condition would be associated with smaller τ than the NoBreak condition. More crucially, if allowing people to take breaks is beneficial for cognitive performance (Finkbeiner et al., 2016; Meijman & Mulder, 1998), we should observe a Condition by Time-on-Task interaction showing τ increase in the NoBreak condition versus τ invariance in the Breaks condition as a function of the time spent on the task. Given age effects have scarcely been studied in the context of breaks, we tentatively propose that all age groups should benefit from breaks and show τ invariance with Time-on-Task in the Breaks condition.

METHODS

Participants

One hundred sixty-six participants were initially recruited thanks to advertisements on the internet or flyers in letter box as well as word of mouth. Most participants belonging to the NoBreak condition were part of our previous study (Gilsoul et al., 2021).[1] Participants were screened for the following inclusion criteria: (1) no neurological, psychological, or psychiatric disorders; (2) no abusive consumption of alcohol or drugs; (3) no color blindness, as assessed by the Farnsworth D-15 test (Farnsworth, 1947) and no dyslexia; (4) free of depressive symptoms, as measured by the Center for Epidemiologic Studies Depression Scale (CES-DS; Radloff, 1977), with a cut-off score of 20 (Vilagut et al., 2016); (5) being Caucasian and native French speakers; (6) older people had to be community dwelling and autonomous in everyday life; (7) no diagnosis of neurodegenerative disease or dementia. The cognitive status of middle-aged and older participants was checked with the Mattis Dementia Rating Scale (Mattis, 1976). All middle-aged and older participants scored above 129, which constitutes the cut-off threshold for risk of dementia (Monsch et al., 1995), and all ranged between 132 and 144; and finally, (8) all participants had normal or corrected-to-normal vision and hearing.

Participants were required to follow a stable sleep–wake rhythm and to sleep for at least 6.5 to 8 h the night before the experiment. They were also asked to refrain from consuming caffeine, psychoactive, or energy drinks during the 24 h before the experiment (see Duncan et al., 2019, for caffeine).

Following the strict application of these criteria, 19 participants were excluded and 33 others were dismissed for technical issues, give-up, missing values, or demographical data homogenization (see supporting information for more details).

The final sample was composed of 114 participants that were allocated to the NoBreak or Breaks conditions: 21 Young_NoBreak (10 men, $M_{\text{Age}} = 22.24$ years; $SD = 2.07$; range 19–28), 21 Young_Breaks (10 men, $M_{\text{Age}} = 22.38$ years; $SD = 2.40$; range 18–29), 18 Middle-aged_NoBreak (8 men, $M_{\text{Age}} = 50.56$ years; $SD = 6.20$; range 39–59), 18 Middle-aged_Breaks (6 men, $M_{\text{Age}} = 50.22$ years; $SD = 6.01$; range 40–59), 18 Older_NoBreak (9 men, $M_{\text{Age}} = 64.94$ years; $SD = 3.13$; range 62–72), and 18 Older_Breaks (9 men, $M_{\text{Age}} = 70.06$ years; $SD = 4.28$; range 62–78).

Demographic data

Demographic data are given in Table 1. A Pearson chi-square (χ^2) test of independence showed that the Sex distribution did not significantly differ between the six subgroups (Pearson $\chi(5)^2 = 1.45$, $p = .92$, $\varphi = .11$). Another χ^2 test performed between the testing time (morning or afternoon) and the six subgroups was also not significant (Pearson $\chi(5)^2 = 4.24$, $p = .52$, $\varphi = .19$), meaning that the experimental sessions were well balanced between the subgroups, which allows to discard any confound related to circadian effect. For metric variables, single-factor ANOVAs were performed to compare the six subgroups. Globally, all pairs of subgroups (i.e., Young_NoBreak and Young_Breaks; Middle-aged_NoBreak and Middle-aged_Breaks; and Older_NoBreak and Older_Breaks) were well matched in terms of demographical data. Moreover, all six subgroups had comparable levels of Sleepiness and Sleep quality. This equality on sleep-related demographic variables is important in establishing that Group, Condition, or

TABLE 1 Demographic data for the six "Group by Condition" subgroups

	Young		Middle-aged		Older	
	NoBreak	**Breaks**	**NoBreak**	**Breaks**	**NoBreak**	**Breaks**
N	21	21	18	18	18	18
Sex (M/F)	10/11	10/11	8/10	6/12	9/9	9/9
Age (years)	22.24 (2.07)	22.38 (2.40)	50.56 (6.20)	50.22 (6.01)	64.94 (3.13)	70.06 (4.28)
Educational level (years)**	14.05 (1.75)	13.71 (1.42)	13.50 (2.87)	14.31 (1.78)	11.50 (2.33)	14.44 (3.15)
Depression[a], **	12.19 (3.91)	10.71 (5.08)	8.22 (6.06)	8.56 (6.24)	8.39 (5.78)	5.61 (4.30)
Mill Hill (%)[b], ***	71.85 (13.69)	69.89 (10.64)	79.41 (11.46)	81.62 (6.92)	80.39 (12.64)	85.29 (14.16)
Sleepiness[c]	6.95 (3.98)	7.76 (2.41)	7.22 (4.45)	8 (3.69)	7.83 (3.99)	5.83 (3.31)
Sleep quality[d], *	5 (2.26)	5.14 (2.90)	3.94 (2.65)	5.25 (2.54)	5.94 (2.90)	3.61 (2.99)
Mattis DRS	-	-	140.82 (1.85)	140.69 (2.96)	141.06 (2.70)	139.67 (2.54)
Day time						
Morning	13	9	13	10	10	12
Afternoon	8	12	5	8	8	6
Chronotype[e]						
Morning	0	0	0	2	2	3
Mod. Morning	4	2	10	6	10	10
Neutral	13	13	6	8	6	5
Mod. Evening	2	5	2	0	0	0
Evening	2	1	0	0	0	0

Note: Values are shown as means (*SD*) except for the Sex, Day time, and Chronotype distributions (count).

[a] Total score on the CES-DS scale (Radloff, 1977). Participants scoring higher than 20 were excluded.

[b] Percentage of correct answers on the French version of the Mill Hill vocabulary scale (Deltour, 1993).

[c] Total score on the Epworth Sleepiness Scale (Johns, 1991).

[d] Total score on the Pittsburgh Sleep Quality Index (Buysse et al., 1989).

[e] Labels are based on the Horne and Ostberg test (Horne & Ostberg, 1976); Mod., moderate. There was two missing values in the Middle-aged_Breaks subgroup.

*$p < .05$. **$p < .01$. ***$p < .001$.

Group*Condition differences cannot be explained by sleep disturbances. We also report the distribution of the chronotype (Horne & Ostberg, 1976) as a function of the six subgroups.

All participants gave their informed consent to participate, and the study was approved by the Ethics Committee of the Faculty of Psychology, Speech and Langage Therapy, and Educational Sciences of the University of Liège and was in accordance with the Declaration of Helsinki (1964).

Procedure

A first meeting was dedicated to explanations of the study and completion of the informed consent form and the above-mentioned demographic scales and questionnaires. For the second meeting, participants were invited to the GIGA-CRC in Vivo Imaging facility to perform a 160-min computerized Stroop task (Stroop, 1935). In the NoBreak condition, participants had to perform the 160-min task without any interruption while in the Breaks condition, participants were given 5-min breaks every 40 min, leading to three breaks in total. All experiments started in the morning or in the afternoon but never in the evening. Participants were not allowed to take part to the study after a period of work. Similarly, students were not allowed to start the experiment after a long period of cognitively demanding activities such as a course or an exam.

The fatigue-inducing Stroop task

A modified version of a computerized Stroop task (Stroop, 1935) was administered for 160 min. Instructions and stimuli were displayed on a PC using MATLAB 2015 (Mathworks Inc., Sherborn, MA). Different words ("BLUE," "RED," "YELLOW," and "GREEN") or the "XXXX" symbol appeared one at a time printed in one of the following colors: blue, red, yellow, or green. The task was composed of Congruent (C) items (i.e., the ink color is similar to the printed word), Incongruent (I) items (i.e., the ink color is not similar to the printed word), and Neutral (N) items (i.e., "XXXX" symbol printed in one of the four colors). Furthermore, Buffer Neutral (B) items were inserted after each I item. These items are visually similar to the truly Neutral (N) items, but they are not taken into account in statistical analyses because they are only used to eliminate an undesired negative priming effect.[2] N items always appear directly after a C item and do not possess any relationship with the latter. Participants performing the task are unable to distinguish between truly Neutral (N) and Buffer Neutral (B) items; instead, they just see "XXXX" items appearing systematically every second item. Stimuli in our time-constrained design were presented for a fixed duration of a maximum of 2500 ms and were separated by a fixation cross for 500 ms. Our procedure also ensured that each participant responded to the same number of items during the 160 min and not a number varying as a function of participants' speed. Participants received only one instruction: to react to the ink color of the presented stimuli as accurately and quickly as possible.

All stimuli were presented on a black background, and participants had to answer by pressing one out of four possible answer keys. Participants were allowed to train on the task until they were comfortable with it. They were tested individually in a testing room free of visual or auditory disturbance, in which the temperature was kept constant and the light set at 250 (±10) lux for better ergonomics (Hu et al., 2018).

Subjective scales

To control for subjective feelings before and after the 160-min Stroop task, participants filled the Karolinska Sleepiness Scale (KSS; Akerstedt & Gillberg, 1990; Kaida et al., 2006), which is a 9-point scale ranging from 1 (*very alert*) to 9 (*very sleepy*). They also rated their levels of demotivation (the higher the score, the less motivated), fatigue (the higher the score, the higher the fatigue), and effort (the higher the score, the higher the effort) on visual analogue scales (VAS) from 0 to 100. Participants in the Breaks condition also filled in subjective scales during each break, leading to five assessment times (Start/Before, Break 1, Break 2, Break 3, and End/After) in the Breaks condition.

Analysis of RT: The ex-Gaussian distribution

As mentioned in Section 1, middle-aged and older people favor accuracy instead of speed during cognitively fatiguing tasks (Burke et al., 2018; de Jong et al., 2018). Therefore, assessing changes in RT distribution during a long-lasting fatiguing task seems relevant to catch age effects.

Because RT data are rarely normally distributed but are often positively skewed (i.e., right-tailed), estimates like means and medians do not fully describe RT distributions (Heathcote et al., 1991). Among the mathematical models allowing to carry out distribution analysis, the ex-Gaussian function has proven to fit RT data very well (Dawson, 1988; Heathcote et al., 1991; Hohle, 1965; Lacouture & Cousineau, 2008; Luce, 1986; Ratcliff & Murdock, 1976; Schmiedek et al., 2007). Therefore, we fitted the ex-Gaussian distribution to RT data in order to understand the influence of cognitive fatigue on RT distributions in our six subgroups by implementing an algorithm based on Nelder and Mead's (1965) work and a greedy approach. We provide some supplementary material with a description and a free access to our algorithm (osf.io/8d7hb).

The ex-Gaussian distribution results from the convolution of a Gaussian and an exponential distribution (Burbeck & Luce, 1982; Luce, 1986). Its probability density function (pdf) is given by the multiplication of the exponential function by the complementary error function (erfc), which is essentially the same as the cumulative density distribution of the Gaussian function and can be written as follows:

$$f(x;\mu;\sigma;\lambda) = \frac{\lambda}{2} e^{\frac{\lambda\,(2\mu+\lambda\sigma^2-2x)}{2}} \operatorname{erfc}\left(\frac{\mu+\lambda\sigma^2-x}{\sqrt{2}\sigma}\right),$$

$$\text{where}\, \operatorname{erfc}(x) = 1-\operatorname{erf}(x)$$

$$= \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-t^2} dt.$$

In this equation, μ and σ are respectively the mean and the standard deviation of the Gaussian component and τ, which is equal to $1/\lambda$, is both the mean and the standard deviation of the exponential component. μ and σ are localization and variability indicators, while τ corresponds to the right tail of the distribution (Lacouture & Cousineau, 2008). In other words, a change in μ reflects a left or right shift in the RT distribution, a change in σ reflects a narrowing or a widening of the distribution, and a change in τ represents a change in the overall skewness of the distribution, namely, a thickening of the tail of the distribution representing extreme RTs made by the participant (Schmiedek et al., 2007). Finally, the mean and variance of an RT distribution can be expressed as a function of the three ex-Gaussian parameters. The mean of the distribution can be obtained by the sum of μ and τ, while the variance of the distribution is the sum of σ^2 and τ^2.

As also mentioned in Section 1, fatigue effect has been shown to exclusively appear on τ (Gilsoul et al., 2021; Wang et al., 2014) while remaining the other parameters unaffected. Hence, this study only focuses on the ex-Gaussian τ representing the extreme (i.e., longer) RTs committed by the participants.

Statistical analyses

Subjective feelings: KSS and VAS scales

To test whether changes in subjective feelings significantly differed between the six subgroups, mixed models were carried out on the ([After–Before]/Before) scores. This index provides a relative score allowing to account for interindividual changes as well as to control for subgroup differences in baseline subjective level. We adjusted the critical α by applying Bonferroni correction, leading to a corrected α of .013 (four comparisons).

To test whether our protocol induced feelings of sleepiness, fatigue, demotivation, and effort, paired sample *t*-tests[3] were performed to compare subjective scales Before versus After the Stroop task inside each subgroup. We adjusted the critical α to prevent Type 1 error by applying Bonferroni correction, leading to a corrected α of .002 (24 comparisons).

We also performed mixed models restricted to participants belonging to the Breaks condition in order to test changes in subjective feelings throughout the five assessment times (Start, Break 1, Break 2, Break 3, and End).

Objective cognitive fatigue: The Stroop task

Global task performance

Regarding global Stroop task performances, we report the overall rate (in percentage) of correct responses (CR), incorrect responses (IR), and nonresponses (NR) on the entire task as a function of Item type in each Condition. We also report the overall mean of RT as a function of Condition and as a function of Item types in each Condition. We performed a mixed design ANOVA with age Group (Young, Middle-aged, and Older) and Condition (NoBreak and Breaks) as between-subjects factors and Item types (C, I, and N) as within-subjects repeated measures on the overall mean of RT.

Analyses of Group, Condition, Time-on-Task, and Item on τ

The task duration of the NoBreak condition was artificially divided into four blocks of 40 min in order to match the four 40-min blocks of the Breaks condition. We fitted the ex-Gaussian function to the RT distributions in those four blocks separately for each Item type (C, I, and N) for each subject. Only RTs to correct answers were taken into account. Moreover, post-error trials were removed from analysis in order to eliminate the classical slowdown effect in post-error responses (Heathcote et al., 1991). The 12 data sets (3 item types × 4 blocks) comprised at least 100 RT observations required to obtain stable estimates of the ex-Gaussian parameters (Heathcote et al., 1991). We performed a mixed design ANOVA with age Group (Young, Middle-aged, and Older) and Condition (NoBreak and Breaks) as between-subjects factors and Block (Block 1, Block 2, Block 3, and Block 4) and Item (C, I, and N) as within-subjects repeated measures on τ.

Mixed models contained a random intercept per participant and were implemented using the *lme* function from the *nlme* statistical R package (Pinheiro et al., 2020). Significant effects in *lme* models were followed by post hoc tests with a probability value of $p < .05$ and Tukey's adjustment for multiple comparisons of least square means using the *lsmeans* R package (Lenth, 2018).

RESULTS

Subjective feelings: KSS and VAS results

There was no difference between subgroups in the development of subjective sleepiness, fatigue, demotivation, or effort ([Before–After]/Before indices; Table 2).

However, in order to test whether each subgroup increased its subjective feelings after as compared with before the task, we also performed *t*-tests (Before vs. After). The results showed that each subgroup increased its subjective feelings on at least one scale After as compared with Before the task (Table 3). While young people in the NoBreak condition increased on all scales, young people in the Breaks condition only increased on the effort scale. Middle-aged people in the NoBreak increased on sleepiness and fatigue while they only increased on effort in the Breaks condition. By contrast, older participants increased on sleepiness, fatigue, and effort in both the NoBreak and the Breaks conditions.

We also checked changes in subjective scales throughout the five assessment times (Start, Break 1, Break 2, Break 3, and End) in participants belonging to the Breaks condition (see Table S1 and Figure 1a–d). The results showed that all scores increased from Start to Break 1 (all $ps < .001$) but stayed stable afterwards. Scores also increased from Break 1 to End for VAS Effort ($p < .001$) and from Break 1 to Break 3 and End for KSS ($p < .05$).

TABLE 2 Changes in subjective scales between the six subgroups

	DF			
Index	**Num.**	**Den.**	***F***	***p***
KSS	5	108	2.02	.08
VAS Motivation	5	108	0.74	.6
VAS Fatigue	5	108	1.62	.16
VAS Effort	5	108	1.17	.33

Note: Results of mixed models performed on Index scores ([Before–After]/Before) between the six subgroups.
Abbreviations: Den., denominator; DF, degrees of freedom; Num., numerator.

TABLE 3 Changes in subjective scales within each subgroup

Subgroup		KSS Before	KSS After	VAS Motivation Before	VAS Motivation After	VAS Fatigue Before	VAS Fatigue After	VAS Effort Before	VAS Effort After
Young Breaks	Raw scores	3.86 (1.42)	5.62 (2.58)	30.29 (17.08)	48.95 (25.19)	42.05 (15.03)	55.81 (20.06)	28.95 (21.96)	54.29 (26.42)
	Statistic	$t = -3.05$		$t = -3.37$		$t = -2.44$		$t = -4.07$	
	p values	.006		.003		.02		.001*	
	d	0.67		0.74		0.53		0.89	
Young NoBreak	Raw scores	4.19 (3.76)	6.14 (2.29)	35.76 (16.77)	57.1 (16.41)	42.38 (16.45)	61.52 (13.84)	36.1 (18.06)	67.81 (14.52)
	Statistic	$t = -3.8$		$T = 1$		$t = -6.32$		$t = -6.57$	
	p values	.001*		<.001*		<.001*		<.001*	
	d	0.83		1.38		1.38		1.43	
Middle-aged Breaks	Raw scores	3.56 (4.03)	6.17 (2.75)	24.39 (18.41)	36.5 (25.21)	37.56 (16.76)	50.44 (23.75)	24.78 (20.32)	56.11 (25.02)
	Statistic	$t = -3.7$		$t = -1.83$		$T = 44.5$		$t = -4.41$	
	p values	.002		.09		.23		<.001*	
	d	0.87		0.43		0.13		1.04	
Middle-aged NoBreak	Raw scores	2.5 (1.72)	5.83 (2.64)	23.83 (22.2)	40.1 (26.97)	26.94 (21.67)	55.56 (29.84)	30.06 (22.18)	58.06 (26.19)
	Statistic	$t = -5.95$		$T = 22.5$		$t = -5.19$		$t = -3.73$	
	p values	<.001*		.04		<.001*		.002	
	d	1.4		0.73		1.22		0.88	
Older Breaks	Raw scores	3.17 (1.29)	5.78 (2.1)	22.11 (14.38)	32.89 (16.69)	34.11 (13.04)	50.22 (12.72)	29.22 (14.48)	53.5 (12.63)
	Statistic	$t = -5.53$		$t = -3.31$		$T = 6$		$t = -5.73$	
	p values	<.001*		.004		.001*		<.001*	
	d	1.3		0.78		1		1.35	

(Continues)

TABLE 3 (Continued)

Subgroup		KSS		VAS Motivation		VAS Fatigue		VAS Effort	
		Before	**After**	**Before**	**After**	**Before**	**After**	**Before**	**After**
Older NoBreak	Raw scores	2.06 (.87)	4.33 (2.59)	16.72 (13.62)	40.72 (28.81)	26.39 (16.22)	45.17 (20.02)	27.11 (17.25)	57.33 (21.81)
	Statistic	$t = -4.07$		$T = 12$		$T = 3$		$t = -4.67$	
	p values	.001*		.002		.001*		<.001*	
	d	0.96		0.86		1.05		1.1	

Note: Results of *t*-tests for paired samples contrasting KSS and VAS scores Before and After the Stroop task in each subgroup; raw scores represent the raw mean scores Before and After in each subgroup on a 9-point scale for the KSS and as a percentage for the VAS; *t* stands for Student's *t*-test; *T* stands for the Wilcoxon signed-rank test.
Abbreviations: KSS, Karolinska Sleepiness Scale; VAS, visual analogue scale.
$^*p < .002$ (corrected threshold).

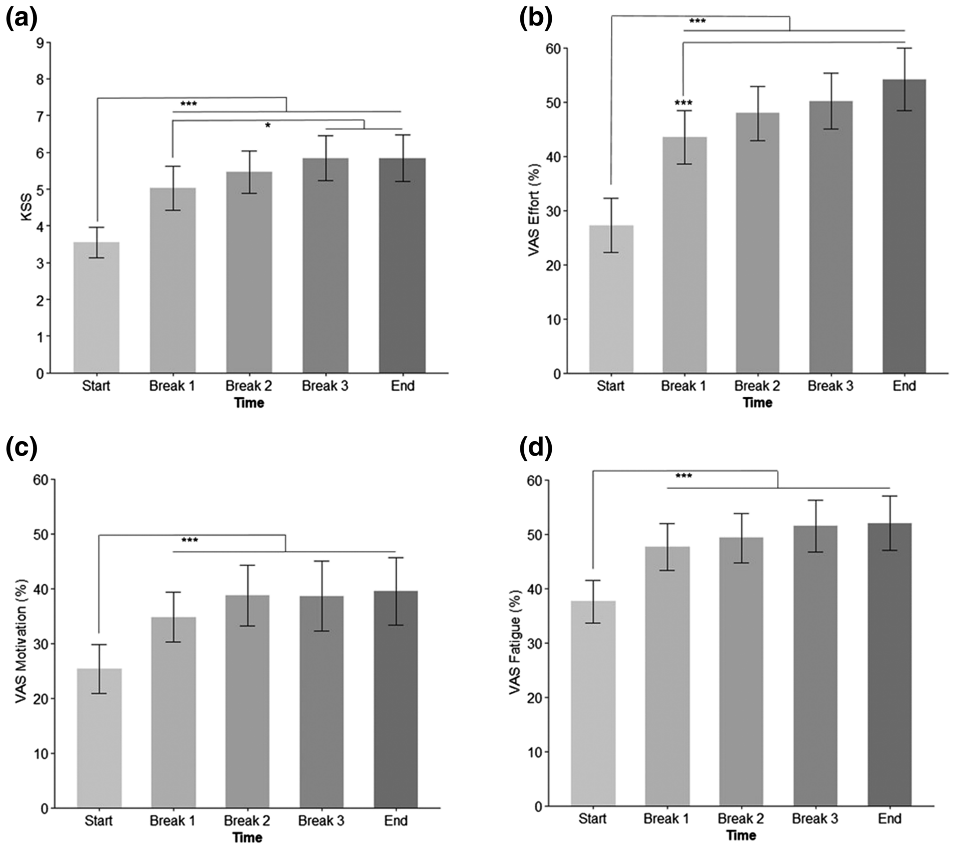

FIGURE 1 Changes in subjective scores throughout the five assessment times. These results are specific to participants belonging to the Breaks condition. (a) KSS (the higher the score, the sleepier); (b) VAS Effort (the higher the score, the higher the effort); (c) VAS Motivation (the higher the score, the more demotivated); and (d) VAS Fatigue (the higher the score, the more fatigued). $*p < .05$; $**p < .01$; $***p < .001$

Objective cognitive fatigue: Results of the Stroop task

Global task performance

The mean number of items used as a function of Condition and Item types is described in the supporting information under Description of the material. The overall rate of correct responses (CR) on the entire task in the NoBreak condition was 96.83% ($SD = 3.06$), the rate of incorrect responses (IR) was 2.2% ($SD = 2.18$), and the rate of nonresponses (NR) was 0.84% ($SD = 1.48$). Similarly, the Breaks condition has an overall rate of CR of 97.33% ($SD = 2.5$), the rate of IR was 1.95% ($SD = 1.9$), and the rate of NR was 0.52% ($SD = 0.84$). For a better clarity, the distribution of CR by Item types and by Condition is also given in Figure S1.

The overall mean RT for correct answers was 975.15 ms ($SD = 191.57$) in the NoBreak condition and 931.4 ms ($SD = 197.72$) in the Breaks condition. More precisely, it was distributed among the three Items types in the two Conditions as follows: 895.16 ($SD = 159.42$) for C items, 1086.27 ($SD = 197.89$) for I items, and 944.02 ($SD = 163.6$) for N items in the NoBreak condition and 862.89 ($SD = 166.63$) for C items, 1039.53 ($SD = 209.42$) for I items, and 891.79 ($SD = 169.64$) for N items in the Breaks condition (see Figure S2).

We performed a mixed design ANOVA with Group and Condition as between effects and Item types as within effect on mean RT. There was a main effect of Item ($F[2, 216] = 518.06$, $p < .001$): C items ($M = 879.02$ ms, $SD = 163.15$) were significantly answered faster than N items ($M = 917.9$ ms, $SD = 167.97$, $t[216] = -6.31$, $p < .001$, $d = 1.08$), which were themselves significantly answered faster than I items ($M = 1062.9$ ms, $SD = 204.19$, $t[216] = 24.2$, $p < .001$, $d = 2.02$; Figure 2a). Moreover, there was also a main effect of Group ($F[2, 108] = 15.24$, $p < .001$): Both Middle-aged ($M = 985.4$ ms, $SD = 166.17$, $t[108] = -3.77$, $p = .001$, $d = 0.82$) and Older ($M = 1040.58$ ms, $SD = 207.74$, $t[108] = -5.32$, $p < .001$, $d = 1.03$) groups answered significantly slower overall than the Young group ($M = 850.91$ ms, $SD = 160.53$; Figure 2b). There was no main effect nor interaction with the Condition (Figure 2c).

Results on the ex-Gaussian parameter τ

Mixed model results are presented in Table 4, and descriptive statistics are given in Tables S2–S4. There was a significant effect of Block ($F[3, 324] = 10.54$, $p < .001$). Post hoc showed that τ

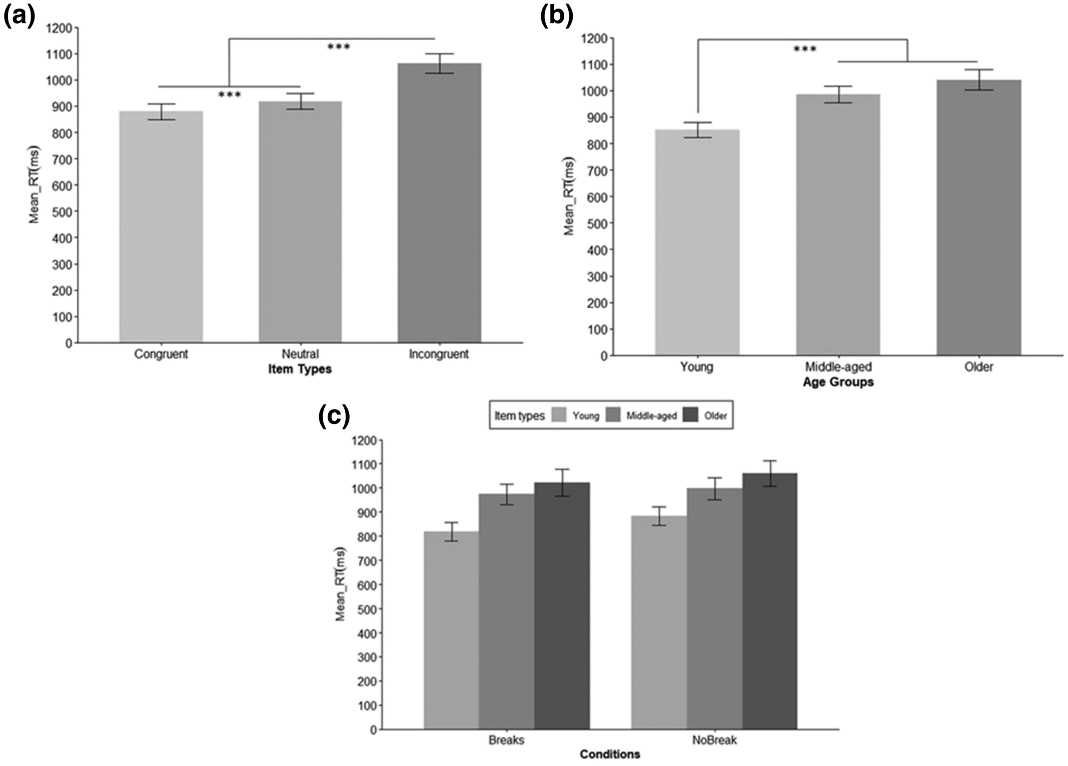

FIGURE 2 Results of the mixed design ANOVA on Item types, Group, and Condition on mean of reaction time (RT). (a) Main effect of Item types on mean RT; (b) main effect of Group on mean RT; and (c) the distribution of mean RT as a function of Group and Condition is also given (n.s.). Error bars are 95% confidence intervals of the mean; ms stands for milliseconds. $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .001$

TABLE 4 Linear mixed model on the ex-Gaussian parameter τ

	DF			
	Num.	**Den.**	***F***	***p***
Group	2	108	1.45	.24
Condition	1	108	3.15	.08
Block	3	324	10.54	<.001***
Item	2	864	77.59	<.001***
Group:Condition	2	108	0.44	.65
Group:Block	6	324	2.09	.05
Group:Item	4	864	2.5	.04*
Condition:Block	3	324	2.47	.06
Condition:Item	2	864	0.85	.43
Block:Item	6	864	2.47	.02*
Group:Condition:Block	6	324	0.65	.69
Group:Condition:Item	4	864	0.72	.58
Condition:Block:Item	6	864	1.03	.4
Group:Block:Item	12	864	0.89	.56
Group:Condition:Block:Item	12	864	0.76	.69

Note: Results of the *lme* model to determine the effects of Group, Condition, Block, and Item as well as the interactions on τ.
Abbreviations: Den., denominator; DF, degrees of freedom; Num., numerator.
$^*p < .05$. $^{**}p < .01$. $^{***}p < .001$.

values in Block 1 ($t[234] = -4.61$, $p < .001$, $d = 0.28$) and Block 2 ($t[234] = -4.87$, $p < .001$, $d = 0.29$) were smaller than in Block 4, meaning that participants became slower (i.e., they committed a higher number of longer RTs) as a function of the time spent on the task. There was also a significant effect of Item ($F[2, 864] = 77.59$, $p < .001$). Post hoc comparisons showed that τ for I items were higher than τ for C items ($t[864] = -10.64$, $p < .001$, $d = 0.45$) and N ($t[864] = 10.54$, $p < .001$, $d = 0.5$) but did not differ between C and N items ($t[864] = -0.11$, $p = .99$). This means that participants committed more slow answers for I items than for C and N items. The main effects of Group and Condition were not significant ($F[2, 108] = 1.45$, $p = .24$ for Group; $F[1, 108] = 3.15$, $p = .08$ for Condition). All main effects are presented in Figures S3–S6. The Group by Item interaction was also significant ($F[4, 864] = 2.5$, $p = .04$). However, post hoc showed globally the same pattern in each age Group: τ was higher for I items than for C (Young: $t[864] = -8.83$, $p < .001$, $d = 0.58$; Middle-aged: $t[864] = -5.84$, $p < .001$, $d = 0.48$; Older: $t[864] = -3.98$, $p = .002$, $d = 0.28$) and N items (Young: $t[864] = 7.94$, $p < .001$, $d = 0.64$; Middle-aged: $t[864] = 5.97$, $p < .001$, $d = 0.5$; Older: $t[864] = 4.49$, $p < .001$, $d = 0.35$; see Figure S7). The Block by Item interaction was significant ($F[6, 864] = 2.47$, $p = .02$). Post hoc tests revealed that τ values for N items were smaller in Block 1 than in both Block 3 ($t[324] = -3.66$, $p = .02$, $d = 0.44$) and Block 4 ($t[324] = -5.48$, $p < .001$, $d = 0.53$). τ values for N items were also smaller in Block 2 than in Bock 4 ($t[324] = -4.19$, $p = .002$, $d = 0.49$). This means than the quantity of longer RTs increased with the time spent on the task for Neutral items. However, τ values associated with C and I items did not vary as a function of the time spent on the task (Figure 3).

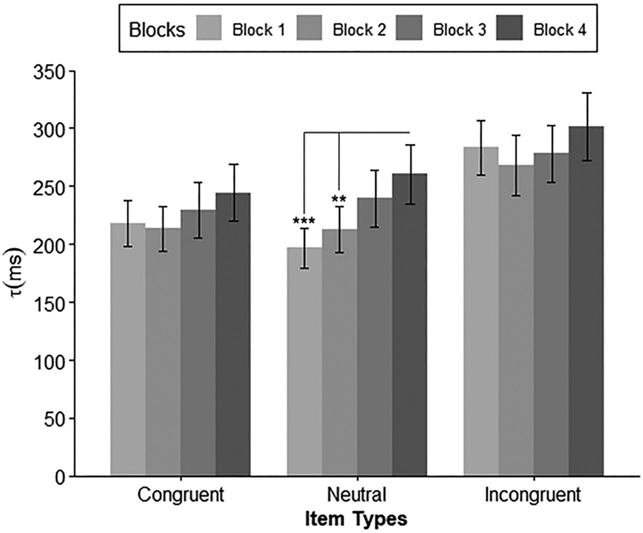

FIGURE 3 Block by Item interaction on the ex-Gaussian parameter τ. Bars represent the mean of τ in the different time Blocks (color shaded from Block 1 to Block 4) as a function of Item types. Error bars are 95% confidence intervals of the mean; ms stands for milliseconds. *$p < .05$ **$p < .01$ ***$p < .001$

The Group by Block interaction was almost significant ($F[6, 324] = 2.09$, $p = .05$) as well as the Condition by Block interaction ($F[3, 324] = 2.47$, $p = .06$). Post hoc tests for the for the Group by Block interaction showed that young people had smaller τ in Block 1 than in Block 4 ($t[324] = -4.2$, $p = .002$, $d = 0.45$). Moreover, τ values of middle-aged people were smaller in Block 1 ($t[324] = -3.48$, $p = .03$, $d = 0.34$) and Block 2 ($t[324] = -4.48$, $p < .001$, $d = 0.45$) than in Block 4. However, older people did not show τ variation as a function of Block (Figure 4). Post hoc tests on the Condition by Block interaction showed that τ values in the NoBreak condition were smaller in both Block 1 ($t[324] = -5.15$, $p < .001$, $d = 0.40$) and Block 2 ($t[324] = -4.51$, $p < .001$, $d = 0.33$) than in Block 4. However, τ values in the Breaks condition did not vary as a function of Block (Figure 5). These results mean that participants in the Breaks condition were more constant as they did not increase their rate of slow answers with the time spent on the task while participant in the NoBreak condition did commit a higher number of long RTs with Time-on-Task. To facilitate the understanding of the results, we also illustrate the distribution of τ as a function of Block in each Group by Condition subgroup (Figure 6).

DISCUSSION

Given the increase of life expectancy and working life but also the need of performance and productivity, it has become important to understand factors that impact cognitive efficiency and job performance as a function of age. Among the various factors, cognitive fatigue is recognized to impair cognitive abilities, to diminish well-being (Meijman & Mulder, 1998), and to cause accidents at the workplace (McCormick et al., 2012). At the same time, politics of sustainable work systems promoting recovery at work while maintaining productivity (Kira & Lifvergren, 2014) have become an important strategy to ensure long-term human sustainability

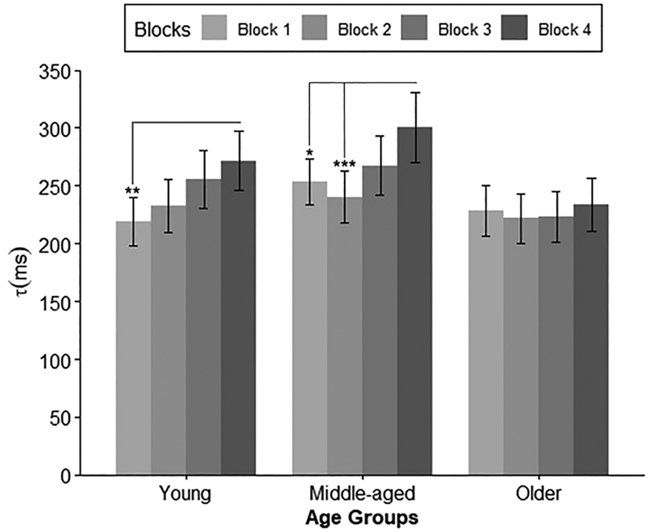

FIGURE 4 Group by Block interaction on the ex-Gaussian parameter τ. Bars represent the mean of τ in the different time Blocks (color shaded from Block 1 to Block 4) as a function of age Groups. Error bars are 95% confidence intervals of the mean; ms stands for milliseconds. $*p < .05$ $**p < .01$ $***p < .001$

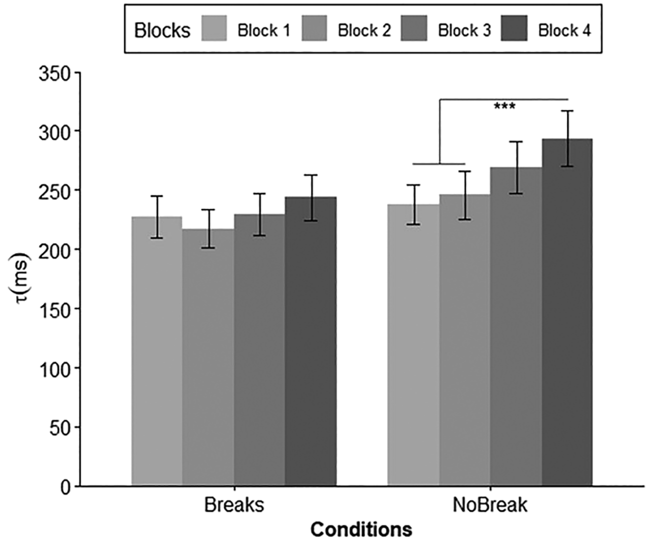

FIGURE 5 Condition by Block interaction on the ex-Gaussian parameter τ. Bars represent the mean of τ in the different time Blocks (color shaded from Block 1 to Block 4) as a function of Conditions. Error bars are 95% confidence intervals of the mean; ms stands for milliseconds. $*p < .05$ $**p < .01$ $***p < .001$

in certain organizational settings (de Jonge & Peeters, 2019). In this regard, based on the ERM (Meijman & Mulder, 1998), the present study was a first step in understanding whether breaks would relieve cognitive fatigue (i.e., maintaining performance and preserving subjective feelings) in different age groups, as assessed in a Time-on-Task paradigm carried out in a controlled laboratory environment. Indeed, a better understanding of cognitive fatigue and its

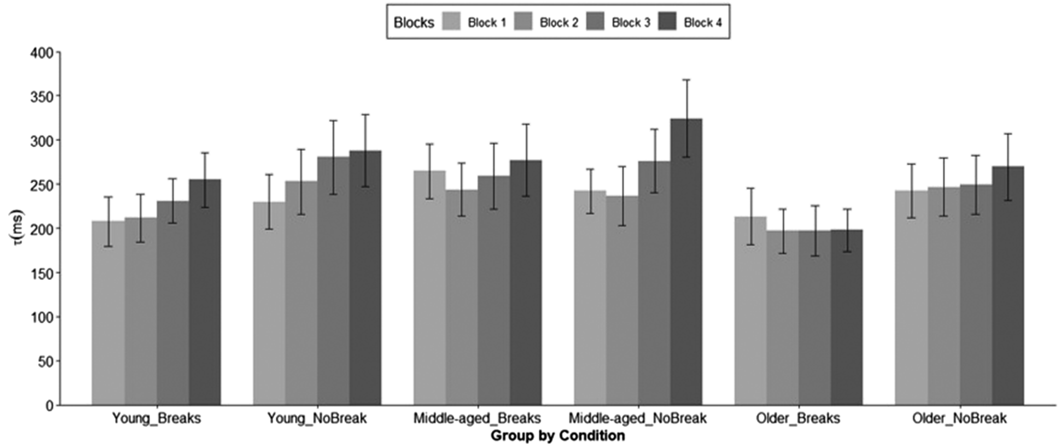

FIGURE 6 Illustration of the ex-Gaussian parameter τ in each subgroup as a function of block

management would allow authorities to develop necessary interventions in organizational settings dealing with different aging workforces.

In this study, cognitive fatigue was induced in a long-lasting paradigm (i.e., a 160-min Stroop task) in which fatigue-related decrements were objectivized by changes in the ex-Gaussian parameter τ—changes in extreme RTs—with Time-on-Task. Changes in subjective scales based on the ([Before–After]/Before) indices did not differ between the six subgroups. However, looking at ratings Before versus After (*t*-tests) showed benefits of Breaks on subjective feelings in young (less sleepiness, demotivation, and fatigue) and middle-aged people (less sleepiness and fatigue), but not in older people (similar profile of Before–After changes in the two conditions). Regarding objective performances, τ values on the entire task were higher for Incongruent items than for Congruent and Neutral items in each age group. However, τ increased with Time-on-Task for Neutral items but not for the other item types. Young and middle-aged people increased their τ values with Time-on-Task while older people did not. Participants in the NoBreak condition showed τ increase with Time-on-Task while those in the Breaks condition kept their parameter constant.

As the ex-Gaussian parameters are not frequently used in the literature, and very few in the context of aging, we will first briefly discuss Stroop and aging effects. Regarding Item effects, τ values associated with Incongruent items were globally higher than that associated with both Congruent and Neutral items (see also Gilsoul et al., 2021, for similar results). This result was expected because Incongruent items tax more on executive resources to solve interference, leading to a classical increase in response times as compared with other items (Heathcote et al., 1991; MacLeod & MacDonald, 2000). Given that τ does not represent the mean but the overall skewness of the distribution, this result suggests that classical increases in RTs during interference resolution could be attributed to a thickening of the right tail of the distribution, representing increases in extreme RTs. This result is also in agreement with authors that linked τ with executive control processes (Brewer, 2011; Unsworth et al., 2010).

In agreement with Gilsoul et al. (2021), there was no significant age Group effect on τ while Time-on-Task (Block effect) did influence τ, confirming that cognitive fatigue induced by Time-on-Task is likely to influence the density of extreme RTs (i.e., the decision component of a response) while aging is not. In our previous study, we also observed that the Group variable had a significant effect on the μ parameter, showing that age-related decrements are more likely to occur on the transduction-motor component of the response. This is in agreement with studies showing age-related decreases in motor speed but not in decisional-related speed (Eckert et al., 2010; Falkenstein et al., 2006; Roggeveen et al., 2007; Yordanova et al., 2004).

We observed a Group by Item interaction, but post hoc tests did not show a different Item effect on τ as a function of the age groups. Instead, all three groups showed the same pattern, namely, higher τ values for Incongruent as compared with the other item types. According to the inhibitory decline hypothesis (Hasher & Zacks, 1988), healthy aging particularly triggers decreases in inhibition. Therefore, we could have expected a greater age-related increase in τ parameter for Incongruent items as compared with other items. However, older people globally showed lower τ values than the other age groups, what may explain the lack of significant age-related increase in τ values for Incongruent items as compared with the other groups. This finding is in agreement with our previous study (Gilsoul et al., 2021), which did not show larger τ values for Incongruent items in older as compared with other age groups. It is also in agreement with the proposal that Stroop-related interference effect is not systematically exacerbated with advancing age (see Rey-Mermet & Gade, 2018, for a meta-analysis).

We found a significant Block by Item interaction showing that τ increased with Time-on-Task for Neutral items but remained constant for the other items while we predicted Interfering items to be the most prone to suffer from fatigue effect. A tentative explanation to this larger susceptibility to fatigue for Neutral items relates to the higher predictability of the Neutral versus the unpredictability of the other item types. Given the addition of Buffer items (see Section 2), *crosses-like* items appeared one item out of two from the participant's point of view, leading to the predictability of Neutral items as compared with the other ones. Cognitive fatigue may result from cognitive overload associated with task difficulty or cognitive underload associated with monotony (Hancock & Desmond, 2000; May & Baldwin, 2009). Therefore, the greater predictability and monotony of Neutral items may have led people into a cognitive underload state (May & Baldwin, 2009) and the "easy and boring" apprehension of Neutral items may have induced task-disengagement because of weariness and motivation drop (Boksem & Tops, 2008).

There was also an almost significant Group by Block interaction. Young and Middle-aged groups were shown to increase their τ parameter with Time-on-Task, which is in agreement with studies showing fatigue effects in young (Boksem et al., 2005, 2006; Hopstaken et al., 2015a, 2015b; Hopstaken et al., 2016; Kato et al., 2009; Lorist, 2008; Lorist et al., 2000; Lorist et al., 2005; Lorist et al., 2009; van der Linden et al., 2003) and the few studies in middle-aged (de Jong et al., 2018; Klaassen et al., 2014; Klaassen et al., 2016). Given the duration of our task, Time-on-Task effect in our Young group can be explained by the fact they suffer from task monotony and boredom when performing a long-lasting repetitive task (Arnau et al., 2017; Terentjeviene et al., 2018; Wascher et al., 2016). It is more difficult to explain the very reason of Time-on-Task effect at midlife as there are very few fatigue-related studies in that population. In 2018, de Jong et al. proposed that cognitive fatigue in that population led to a general decrease in processing speed. Klaassen et al. (2014) interpreted the decline in performance in middle-aged people by a lower level of cerebral compensatory resources (CRUNCH hypothesis; Reuter-Lorenz & Cappell, 2008) in situation of cognitive fatigue as compared with young people. We tentatively propose this population have challenging lives and great responsibilities, likely inducing a less optimal daily cognitive state.

By contrast, the Older group did not increase its τ parameter with Time-on-Task. This invariance of τ in older people was already found in Gilsoul et al. (2021) and is in agreement with studies showing that fatigue effects are not exacerbated in elderly at a behavioral level (Terentjeviene et al., 2018) and that older people are able to manage task monotony and declining motivation (Wascher et al., 2016). Anticipating on the next paragraph, as older people did not show τ increase with Time-on-Task, it may also explain why they seemed to have similar increase in subjective feelings for the NoBreak and Breaks conditions. However, if older people did not show behavioral decrements with Time-on-Task, it is possible that age-related differences in fatigue effect still exist at the cerebral level. For example, Arnau et al. (2017) did not find behavioral difference between young and older people performing a fatiguing task. However, older people showed larger frontal theta power that was attributed to compensatory processes counteracting resource depletion with increasing Time-on-Task. By contrast, young people had a saturation in occipital alpha, which was interpreted as management of task monotony. Therefore, it remains the possibility that the preserved performance under cognitive fatigue in older people is due to parallel cerebral compensatory mechanisms (Cabeza, 2002; Park & Reuter-Lorenz, 2009; Reuter-Lorenz & Cappell, 2008).

There was an almost significant Condition by Block interaction showing that participants allocated to the NoBreak condition increased their τ parameter with Time-on-Task while participants in the Breaks condition were able to keep their τ parameter stable along the task. This result suggests that offering people the possibility to have short breaks prevent them to show increase in extreme RTs with the time they spend on the task. This finding is in agreement with the resource depletion hypothesis according to which cognitive fatigue arises from the exhaustion of available cognitive resources allocated to a specific process. It is also in agreement with the ERM (Meijman & Mulder, 1998) proposing that breaks restore energy levels that were depleted during high work demands by temporarily interrupting task engagement. As a consequence, rest breaks allow to maintain performance and to relieve fatigue (Meijman & Mulder, 1998). This finding is important in preventing errors or accident due to slowed decision with cognitive fatigue. More crucially, the Group by Block by Condition was not significant, meaning that all three age groups benefited from breaks to the same extent. This result is of great relevance to inform the schedules of organizational settings. Given nowadays policies regarding employment, people are sometimes required to work in particular condition (flexible hours, retirement age extension, etc.). However, people's cognitive efficiency (in our case, the time allocated to decision process) may be preserved at any age on a long duration provided that periodic rest moments are granted. *T*-tests performed on subjective scales also suggest that the two groups (Young and Middle-aged) who increased their τ parameter with Time-on-Task benefited from breaks in terms of subjective feelings. The only scale that was still rated higher after as compared with before the task in the presence of breaks was the VAS for effort. This suggests that granting rest breaks allows maintaining sleepiness, motivation, and fatigue but that effort deployment is still perceived. If the energy depletion hypothesis explains cognitive fatigue to some extent (i.e., rest breaks allowed maintaining performance and subjective feelings of sleepiness, motivation, and fatigue), it does not explain why breaks did not stabilize subjective effort.

Therefore, we propose that other factors such as motivation or goal-relevance are good candidates to explain fatigue effects. According to the Compensatory Control Model (CCM; Hockey, 2011, 2013), when discrepancy between task goal and performance is perceived, effort control is needed to increase or stabilize the effort allocated to the task. It is particularly the case for imposed goals that are low valued by the individual as compared with more personal and meaningful goals. In the case of low-valued goals, increasing effort will enable maintaining task goal and performance while *only* stabilizing effort will result in lower performance or even a change in task goals (e.g., stopping). Therefore, we assume that maintaining goal and performance in our low meaningful 160-min Stroop task needed to increase (and not only stabilize) the effort budget allocated to the task, what may explain the increase in subjective effort rating even in the presence of breaks. Related to this motivational hypothesis, the monotonous feature of our task may have induced boredom in some participants. In this regard, the distinction between cognitive fatigue and boredom has raised debate among researchers for a while. As soon as in 1937, Myers differentiated between cognitive fatigue and boredom but considered that these two feelings may affect performance in a similar way. Barmack (1937) proposed that boredom developed in task situations under low intrinsic motivation and represents a state of conflict between remaining in the situation and wanting to get away from it. This state of conflict was assumed to be partially relieved by a state of disengagement or withdrawal. Hence, a very important result of this study was that rest breaks relieved people from cognitive demands and maintained performance stable in time but further studies are needed to disentangle between cognitive fatigue and boredom.

Results assessing changes in subjective scores throughout the five assessment times globally indicated that subjective feelings increased from the beginning of the experiment and the first break but remained stable afterwards. These results further suggest that breaks are also beneficial for subjective feelings. In agreement with our results, rest breaks have been found to reduce subjective fatigue and increase vigor both directly after the break (Hunter & Wu, 2016; Zacher et al., 2014) and at the end of a work episode (Engelmann et al., 2011). Likewise, work breaks in organizations have been associated with increased well-being (de Bloom et al., 2015) and higher daily work engagement (Kühnel et al., 2017). However, these “on-line” assessments were only carried out on participants belonging to the Breaks condition because we did not want to create artifact breaks in the NoBreak condition by proposing such intermediate measures, which limits the conclusions about the impact of breaks on subjective feelings.

Future perspectives

Our study proposed “rest” breaks but did not differentiate between different types of breaks. For example, some authors proposed that any types of diverting activity, which may be physical or cognitive, would help relieve fatigue (Mathiassen et al., 2014). Other authors investigated the difference between rest, physical, and relaxing breaks (Blasche et al., 2018). According to the Attention Restoration Theory (ART; Kaplan, 1995; Kaplan & Kaplan, 1989), natural scenes and biological movement are beneficial for attention restoration (Herzog et al., 1997; Kaplan, 1995). More precisely, direct (actively controlled) attention and effortless (passively controlled) attention are considered distinct systems, with the active one being prone to fatigue and depletion (Kaplan, 1995). One way to facilitate the recovery of actively controlled attention resources is to engage the effortless (passively controlled) attention system by presenting people with natural scenes or natural movement (Berto, 2005; Herzog et al., 1997). Using this perspective, studies have compared the influence of different types of breaks such as looking at a green (natural) versus concrete rooftop (Lee et al., 2015) or looking at dog (natural) versus robots videos (Finkbeiner et al., 2016) and found higher benefits from breaks including natural stimuli at both performance (Lee et al., 2015) and well-being levels (Finkbeiner et al., 2016).

Moreover, our task assessed the effect of breaks on a laboratory-like protocol: a 160-min task with short breaks that were imposed every 40 min. This study does not directly reflect real work conditions. Nevertheless, inhibitory and cognitive control processes as well as sustained attention capacities that were required in our cognitive task are implied in a large panel of cognitive abilities (e.g., abstract reasoning and verbal abilities) known to predict job performance (e.g., Lang et al., 2010). Moreover, our study is one of the sole studies to directly investigate the age effect in the context of breaks during a cognitively fatiguing task. We propose future studies should be aimed at reproducing this type of design in real situations and varying different parameters (i.e., the type of breaks, the length of breaks, and imposed vs. deliberated breaks) in order to find what is the most beneficial for working people as a function of their age.

Limitations

There is a limitation in this study regarding the recruitment process. Indeed, most of the participants in the NoBreak condition were included in our previous publication (Gilsoul et al., 2021). Therefore, we cannot exclude that a random effect attached to this reused sample may explain part of the results. However, we replicated the main effects of Group, Block, and Item (i.e., independently of the two Conditions) on τ with a sample twice as large as the first study. These later results are reassuring but further studies need to replicate ours with a completely new set of participants.

CONCLUSION: HOW THIS STUDY INFORMS SCHEDULES IN ORGANIZATIONAL SETTINGS?

Results of the present study show that young and middle-aged people do suffer from cognitive fatigue when they have to perform a cognitive task on a long-lasting duration. Cognitive fatigue appeared in terms of decreased speed as well as in terms of subjective feelings (mainly fatigue and sleepiness). However, when allowed to take short breaks at regular intervals, these two age groups were able to maintain their speed to the same level as in the beginning of the task but also to maintain their subjective feelings of fatigue, sleepiness, and motivation stable along the task. Consequently, our results are in partial agreement with the energy depletion hypothesis according to which humans become fatigued after a period of work because their cognitive resources are depleted but can be restored by temporarily disengaging from the task at hand (Hockey, 2013). We propose it is important and more productive for organizational settings to let their employees shift their attention away from work demands as short as 5 min on a regular basis in order to quickly replenish cognitive resources and to prevent slowdown in speed processing. This will also contribute to a global well-being of workers that will feel more energized and more motivated until the end of the work day. By doing so, it is also likely that work errors or accidents can be reduced to a certain extent but futures studies are needed to test this variable more specifically. Regarding the older, this age group did not show reduced speed in the NoBreak condition, which we explained by a better resistance to task monotony and boredom in this population. However, we also proposed they could intensively resort to cerebral compensatory processes that were not assessed in this study. Moreover, older people increased in fatigue, sleepiness, and effort even in the presence of breaks. Therefore, it is likely that on a longer task duration resembling that of a real work day, older people would progressively reduce their performance if they are not allowed to rest periodically. Hence, our study tends to show that short break allowance on a regular basis would be beneficial at any age to maintain positive outcomes, including performance and general well-being. Finally, the fact that the effort measure was rated higher after as compared with before the task for all age groups even in the Breaks condition can be explained by the very monotonous and low-valued nature of our task. We thus propose that energy depletion, which is relieved by breaks, was not the only factor explaining fatigue installation in our study. Other processes such as goal-relevance or goal-meaningfulness are also at play to explain effort deployment in the context of long-lasting fatiguing tasks. We propose future studies should reproduce this kind of design in more ecological experiments using tasks resembling those required in organizations, including an assessment of task relevance for working people.

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CONFLICT OF INTEREST

None.

ETHICS STATEMENT

All participants gave their informed consent to participate, and the study was approved by the Ethics Committee of the Faculty of Psychology, Speech and Langage Therapy, and Educational Sciences of the University of Liège and was in accordance with the Declaration of Helsinki (1964).

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ENDNOTES

[1] The study started in the very beginning by the recruitment of participants to be included in the NoBreak condition. Afterwards, the recruitment for both conditions (NoBreak and Breaks) was done in parallel with a pseudo-random allocation to one or the other condition in an attempt to balance participants as much as possible in terms of demographic data. See supporting information for more details.

[2] Negative priming effect appears when the required answer is the one that had to be inhibited on the previous item. Classically, participants take more time to respond to a target that had to be inhibited in the previous trial than when the two consecutive trials are unrelated (Tipper, 1985). In a Stroop task, C, N, or I trials may be answered more slowly just because they follow a negative probe. In our case, the addition of B items after each I item eliminated any negative priming effect.

[3] Normality assumption on the distribution of the scores of difference (score After − score Before) were tested for each scale. If the assumption of normality on these scores of difference was respected, we resorted to Student's t-test for paired sample (denoted t in Table 3); if not, we resorted to the nonparametric Wilcoxon signed-rank tests for paired samples (denoted T in Table 3).

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