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Human cognitive and motor processing time in the aging workforce: An objective parameters-based model

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Abstract In the digital society, recent studies showed that individuals have to perform tasks based on the information gathered by a huge amount of data and effectively use them to express their cognitive and motor abilities. The cognitive task is considered a job with prevalent cognitive demand; on the contrary, a motor task is a job with a prevalent physical need. The model allows evaluating motor (MT) and/or cognitive (CT) performance time based on the individual parameters (i.e., age, sex, and state of health). The effectiveness of the model on a numerical case study is tested. The work conducted proved that it is possible to predict a general motor-cognitive task's processing time based on objective parameters allowing to take account of the difference between individuals of different ages and sex.

Keywords: Human performance; Performance Time; Aging; Cognitive-motor task; Cognitive-motor information processing time.

1 Introduction

The fourth industrial revolution introduced a new paradigm (Wichmann et al. 2019). The increasing adoption of innovative devices (Qin et al. 2016; ElMaraghy et al. 2012) has changed the tasks to be performed by the operators. An increasing mental effort is required to manage the new innovative devices. Although there is no 'pure' cognitive or physical task in a real work environment, in this paper, a ‘cognitive’ task is considered a task with a prevalent cognitive demand; similarly, a ‘physical’ task is considered a task with prevalent motor demand.

In scientific literature, the approaches adopted to evaluate the workload for physical and cognitive tasks are based on 'subjective' and 'objective' perspectives. The 'subjective' approach includes the NASA-Task Load Index (TLX) (Hart & Staveland 1988), the subjective workload assessment techniques (SWAT)(Reid et al. 1988), and other techniques where subjects are asked to evaluate the workload of a task based on the dimensions of time load, mental effort load, and psychological stress load. The 'objective' approaches are based on the worker's physiological response engaged in a specific task. In this category are included evaluation related to physiologic parameters as aerobic capacity, heart rate (HR), blood pressure, body temperature, electromyogram (EMG), pupillary dilation, and so on.

If, on the one hand, the tasks to be performed by the operators are changing, on the other hand, the average age of the workers, as well as the share between women and men in the work environment, is undergoing a radical change. In 2050, around half of workers will be aged over 50 in developed countries, and the presence of older workers in production and operative roles will have an impact on economic growth and manufacturing efficiency (UNFPA 2012; European Agency for Safety and Health at Work; Dupont Claire; Benin Alice; Belgi & Milieu 2016). Generally, an individual achieves the full cognitive and physical capacity at the age of 30 years, starting a progressive physiologic decline. Consistently to this aspect, recent studies proved that individual of age from 45 to 64 years have a cognitive and physical capacity reduced of 20-25% if compared to full cognitive and physical capacity.

Cardiovascular and musculoskeletal systems, body structure, and some important sensory systems reflect the change in a physical work capacity. The maximal oxygen consumption (VO_2max) shows a linear decline with age among individuals of both sexes.

According to Fredericks et al., the maximum metabolic energy expenditure rate (VO_{2max}), or aerobic capacity, is a prominent objective workload measurement for both physical and cognitive tasks (Fredericks et al. 2005).

The work conducted is an extension of the model developed by Digiesi et al. (Digiesi et al. 2020); the aim is to provide a model that allows evaluating motor (MT) and/or cognitive (CT) performance time based on the individual parameters (i.e., age, sex, and state of health). Consistently with the purpose of the presented work, the model allowed to estimate MT and CT, starting from the information processing time needed by an individual to process the information under cognitive and ($T_{p,c}$) and motor ($T_{p,m}$) perspective, and considering the information content of the specific task, expressed in bits. In work conducted, the processing times are strongly related to age, sex, and state of the individual's health, while the information content of the task depends on the complexity in terms of cognitive and motor demand of the task to be performed. Two different numerical case studies have been conducted; for each of them, MT and CT's values have been identified. The analysis led to a redesign of the task to fit the specific worker's characteristics.

The paper is organized as follows: In Section 2, the phenomenon of aging and its influence on maximal aerobic capacity is presented. In Section 3, the data on VO_{2max}, available date in the scientific literature for different age and sex, are considered and applied to assess the cognitive and motor processing time of individuals. The model is tested in numerical cases (Section 4). Discussion on research findings can be found in Section 5. Finally, the summary and conclusions are in Section 6.

2 Aging phenomenon and its influence on maximal aerobic capacity

Nowadays, worker well-being has a prominent interest since modern welfare states prolong working life by increasing the statutory retirement age (van de Berg et al. 2008). High percentages of workers over 60 years are employed in countries like Spain (22%), Japan (31%), Germany (26%), and Finland (25%), and others, due to the lack of young personnel (World Health Organisation 2013).

The aging phenomenon is a multifactorial process, and genetic and environmental factors determine its intensity. Aging can be defined as the accumulation of various deleterious changes appearing in cells and tissues with advancing age responsible for the increased risk of disease and death (Harman 2003). The Evolutionary Theory defines the aging phenomenon as reducing reaction, poor quality homeostasis, and more prevalent pathologic events resulting from different stressors (Rubin 2002). It defines environmental factors that negatively affect the mitochondrial structure of DNA (Sacher 1982). These diseases affect the frequency and intensity of physical tasks that an individual can perform (Garber et al. 2011). The most common occupational diseases are represented by musculoskeletal disorders (WMSDs) related to the work (almost 40% of the whole occupational diseases) since, in Europe, about 30% of jobs involve incorrect work postures, handling of heavy materials, or repetitive work (Ilmarinen 2012).

In 2005, a study conducted by Fredericks et al. highlighted that the responding of the human cardiovascular system is similar in case of cognitive and physical workload (Fredericks et al. 2005).

Physical stress implies a strength and energy demand on the human body. In contrast, psychological stress implies a mental workload demand on the human body. In both cases, the cardiovascular system responds in similar ways to meet the muscles' metabolic needs when it is subject to physical or mental stressed. Therefore, the effects and the consequences on the cardiovascular system of cognitive or physical workload are quite similar (Govindaraju 1997).

A good cardiovascular function is related to a good aerobic capacity; the product of the maximal cardiac output and the difference of oxygen concentration between venous and arterial blood is the maximal aerobic capacity. Aerobic capacity represents the vascular system's oxygen-carrying capacity to the muscles (Ihász et al. 2016). Maximal aerobic capacity is measured by maximal oxygen consumption (VO_{2max}), decreasing with advancing age (Buskirk & Hodgson 1987). The VO_{2max} decreasing contributes to reducing physiological functional capacity observed with the subject aging (Hagberg 1994).

Two complementary studies investigated the age-related declines in maximal aerobic capacity in subjects regularly exercising versus sedentary, both sexes (Fitzgerald et al. 1997; Wilson & Tanaka 2000).

In both studies, a reduction of VO_{2max} related to the age of workers it is shown. The decreasing maximal aerobic capacity leads to a reduction in physiological functional capacity that influences the independence and quality of life of the individual (Asogwa et al. 1993). Moreover, the reduction in cognitive function with advancing age is affected by an age-related decline in VO_{2max} (Van Boxtel et al. 1997).

Although several studies have been focused on physical abilities and their impact on older workers' health and well-being, the current work-organization in most EU companies considers only marginally the sex and the age of the workers. In many cases, the physical workload between younger and older workers is very similar (Ilmarinen 2002). Moreover, the literature review conducted showed that if there are available studies on the workload evaluation for the motor task, on the other hand, the evaluation of the workload for the cognitive task is less investigated (Fisher et al. 2017).

3 An objective parameters-based model for age- and sex-dependent consumption of oxygen

According to Fit law (Fitts 1954) the MT-value linearly depends on the information processing time under motor perspective and the information content (I_m) required to perform the motor task, according to equation 1. Similarly, Hick's law (Hick 1952) proved that CT depends on the information processing time under cognitive perspective and the information volume (I_c) required to process the cognitive task (equation 2).

$$MT = T_{p,m}(VO_{2max}) \times I_m \qquad (1)$$

$$CT = SRT + T_{p,c}(VO_{2max}) \times I_c \qquad (2)$$

Where the Simple Response Time (SRT) reflects the time takes to interpret a stimulus, get information from memory, initiate a muscle response, etc. In other words, it is given from the sum of all-time delays not associated with decision-making; generally, it is estimated as the 30%-40% of the cognitive time (equation 3)

$$SRT = (0.3 \div 0.4)CT \qquad (3)$$

$T_{p,m}(VO_{2max})$ and $T_{p,c}(VO_{2max})$ expressed in [ms/bit], represent the information processing time under motor and cognitive perspective, evaluated considering the maximum O_2 consumption air, given from equations 4 and 5, respectively (Digiesi et al. 2020). Both T_p-parameters are strongly related to the values assumed to VO_{2max} evaluated for sex, age, and state of health of the considered worker.

$$T_{p,c}(VO_{2max}) = \alpha_c(s) + \beta_c(s) \times \left[\frac{K_1}{K_2} - \frac{\left({VO_{2max}+6.3}/{0.14\times10^{-2}}\right)}{K_2}\right] \qquad (4)$$

$$T_{p,m}(VO_{2max}) = \alpha_m(s) + \beta_m(s) \times \left[\frac{K_1}{K_2} - \frac{\left({VO_{2max}+6.3}/{0.14\times10^{-2}}\right)}{K_2}\right] \qquad (5)$$

The Physical Fitness Specialist Certification Manual provides the VO_{2max} range values, expressed in maximum O_2 volume rate (ml/min) per unit mass (kg), for different age clusters (Vivian H. Heyward 2016). The same range, standardized for gender, age, and state of health by the Cooper Institute (http://www.cooperinstitute.org/), is shown for men and women in tables 1 and 2, respectively.

Table 1. Male standardized VO_{2max} values

Age	State of health				
	Very Poor	Poor	Good	Excellent	Superior
20-29	<41.7	41.7	45.4	51.1	>55.4
30-39	<40.5	40.5	44.0	48.3	>54.0
40-49	<38.5	38.5	42.4	46.4	>52.5
50-59	<35.6	35.6	39.2	43.4	>48.9
60-69	<32.3	32.3	35.5	39.5	>45.7
70+	<29.4	29.4	32.3	36.7	>42.1

Table 2. Female standardized VO_{2max} values

Age	State of health				
	Very Poor	Poor	Good	Excellent	Superior
20-29	<36.1	36.1	39.5	43.9	>49.6
30-39	<34.4	34.4	37.8	42.4	>47.4
40-49	<33.0	33.0	36.3	39.7	>45.3
50-59	<30.1	30.1	33.0	36.7	>41.1
60-69	<27.5	27.5	30.0	33.0	>37.8
70+	<25.9	25.9	28.1	30.9	>36.7

Therefore, for an individual in 'Good' state of health by varying the age, it proved a variability of the information processing time in a cognitive task, equal to 2.08% in a male subject, and variability of 29.3% is shown in female subjects. Similarly, for an individual in a 'Good' state of health by varying the age, it proved a variability of $T_{p,m}(VO_{2max})$ equal to 11.47% in a male subject, and variability of 28.72% is shown in female subjects.

Starting to the analytical model already developed by Digiesi et al. (2020) to identify the estimated time required to process one bit of information as a function of age (A) and sex (s) in case of cognitive and physical tasks (equations 6 and 7, respectively), it is possible to define the K-values to be considered in equations 4 and 5.

$$T_{p,c} = \alpha_c(s) + \beta_c(s) \times A \qquad (6)$$

$$T_{p,m} = \alpha_m(s) + \beta_m(s) \times A \qquad (7)$$

The values of $\alpha_c(s)$, $\beta_c(s)$, $\alpha_m(s)$ and $\beta_m(s)$ are constant parameters, dependently on the sex of the worker to be evaluated (table 3).

Table 3. Values of α_c and β_c for each sex, to model processing time in cognitive tasks

Sex	$\alpha_c(s)$ [ms/bit]	$\beta_c(s)$[ms/bit]	$\alpha_m(s)$ [ms/bit]	$\beta_m(s)$ [ms/bit]
male	160.75	1.20	155.33	0.70
female	165.94	1.12	144.55	0.67

According to Fredericks et al. (Fredericks et al. 2005), the myocardial oxygen consumption (VO_2) that represent the aerobic capacity of one individual can be identified for physical and cognitive tasks by the equation showed below (eq. 3):

$$VO_2 = 0.14 \times (RPP \times 10^{-2}) - 6.3 \qquad (8)$$

Where *RPP* is the rate-pressure product given by the Heart Rate (HR) (beats on the minute) and systolic blood pressure (SBP) (mmHg). Increasing the RPP-value increases the VO_2, which means that the metabolic demand needed for the tasks' performance is increasing. The maximal value achieved by RPP corresponds to the individual maximum myocardial aerobic capacity (RPP_{max}). It has been shown that RPP_{max} decreases with age accordingly to the relation showed in equation 9 (Bruce et al. 1974).

$$RPP_{max} = 36400 - 58 \times A \tag{9}$$

Therefore, VO_{2max} has strictly related to RPP_{max} and the age of the worker. Consistently to relations highlighted, the value of VO_{2max} can be estimated fitting the equations 8 and 9, as showed below (eq. 10).

$$VO_{2max} = 0.14 \times ((36400 - 58 \times A) \times 10^{-2}) - 6.3 \tag{10}$$

From which the A-parameter can be expressed as follow (eq. 11):

$$A = \frac{K_1}{K_2} - \frac{{}^{VO_{2max}+6.3}/_{0.14\times10^{-2}}}{K_2} \tag{11}$$

Therefore, the K-values to be considered in $T_{p,m}(VO_{2max})$ and $T_{p,c}(VO_{2max})$ are equal to 36400 (K_1) and 58 (K_2).

Summarizing, given the age, sex, and state of the health of the worker to be evaluated, it is possible to identify $T_{p,m}(VO_{2max})$ and $T_{p,c}(VO_{2max})$ considering the constant parameters (i.e., $\alpha_c(s)$, $\beta_c(s)$, $\alpha_m(s)$, $\beta_m(s)$) provided in table 3, the K-values and the VO_{2max} values identified by range standardized (tables 1 and 2) based on the individual parameters of the worker. Concerning the information content of motor (I_m) or cognitive task (I_c) task, expressed in bits, different techniques are available in the literature to quantify both information (Digiesi et al. 2020; Shannon 1948). Therefore, the joint evaluation of these parameters allows to identify the values of MT and CT from equations 1 and 2, respectively.

4 Numerical simulation

A numerical simulation is conducted to evaluate the performance of an operator in a motor and cognitive task. The simulation is divided into two parts; the first part is focused on a motor task; the second is referred to as a cognitive task.

The motor task consists of a straightforward task; an operator has to move a whole arm to reach for something at a distance of 75 cm. The rest of the body is steady; his eyes are focused on the tiny object to be picked. The task is quite easy but required high accuracy. An I_m-value of 0.005 [bit] is estimated for the specific task, different male and female subjects in aged between 20 and 60+ in 'Good' physical state are considered. The MT evaluated for each subject have been compared with the expected time (ET) provided by Methods-Time Measurement, where the time estimated for this task is equal to 0.95 [s]. The results of analysis are showed below (table 5), in the case of ET is higher than MT, a positive value of δ-parameter is showed. On the contrary, for negative values of δ-parameter, the expected time is not enough to perform the task.

Table 4 Comparison between movement time (MT) estimated by the model and expected time (ET) provided by literature (MTM), by varying the age and sex of the operator.

Age	MT [s]		$\delta = ET - MT$	
	Male	Female	Male	Female
20-29	0.76	0.94	0.19	0.01
30-39	0.82	1.00	0.13	-0.05
40-49	0.95	1.13	0	-0.18
50-59	1.10	1.25	-0.15	-0.30
60+	1.23	1.32	-0.28	-0.37

Concerning the cognitive task, a Digit Symbol Substitution Test (DSST) is considered. The DSST was initiated over a century ago as an experimental tool to understand human associative learning requires a subject to match symbols to numbers according to a key located on the top of the page (figure 1). The subject copies the symbol into spaces below a row of numbers (1 to 9). The number of correct symbols within the allowed time constitutes the score (Jaeger 2018).

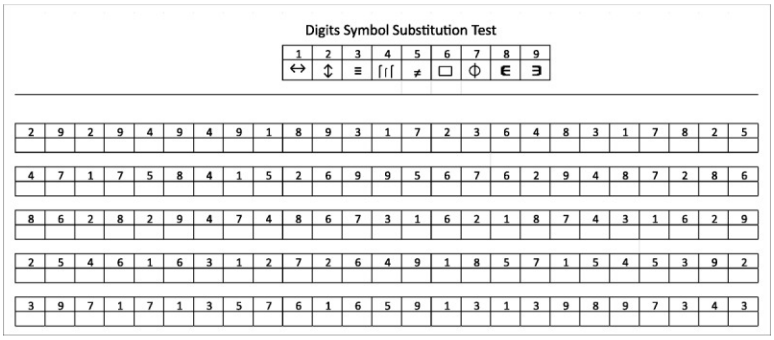

Figure 1. The DSST symbol coding sheet. Figure reprinted from Patel and Kurdi (2015) (Patel & Kurdi 2015)

In the cognitive case study from DSST, the ET is equal to 90 [s] (Rosano et al. 2016), and an I_c-value of 0.31 [bit] is estimated for the specific task. Similar to previous numerical simulation, the results of the analysis are shown below (table 6).

Table 5 Comparison between cognitive time (CT) estimated by the model and expected time (ET) provided by literature (Rosano et al. 2016), by varying the age and sex of the operator.

Age	CT [s]		δ	
	Male	Female	Male	Female
20-29	53.4	81.6	36.6	8.4
30-39	60.8	88.1	29.2	1.9
40-49	75.6	102.4	14.4	-12.4
50-59	92.8	115.3	-2.8	-25.3
60+	107.6	123.6	-17.6	-33.6

The MT and CT values estimated by the model versus age for male and female individuals are shown in figure 2.

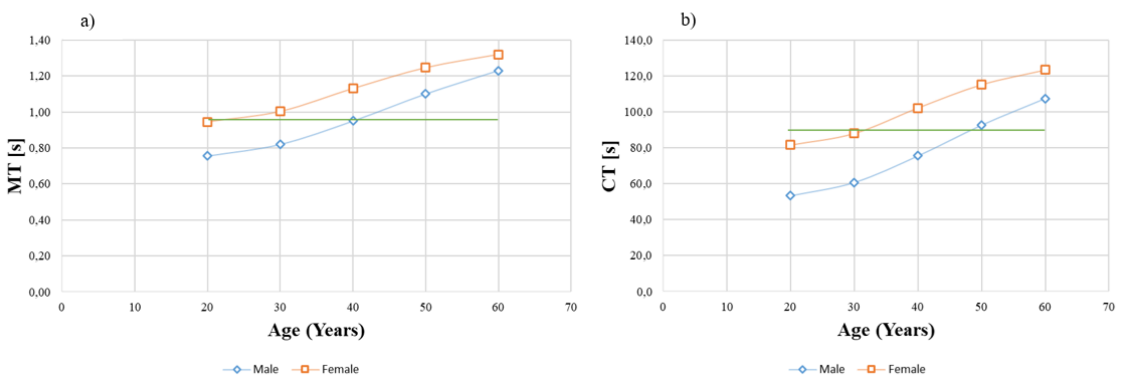

Fig. 2 MT (a) and CT (b) vs age, for male and female individual, compared with expected time (ET) provided by literature.

5 Results Discussion

Starting from the work conducted by Digiesi et al. (Digiesi et al. 2020), a model that allows evaluating motor (MT) and/or cognitive (CT) performance time based on the individual parameters (i.e., age, sex, and state of health) is developed. Consistently with the purpose of the presented work, the model allowed to estimate MT and CT, starting from the information processing time needed by an individual to process the information under cognitive and ($T_{p,c}$) and motor ($T_{p,m}$) perspective, and considering the information content of the specific task, expressed in bits. In work conducted, the processing times are strongly related to age, sex, and state of the individual's health, while the information content of the task depends on the complexity in terms of cognitive and motor demand of the task to be performed.

The results proved the developed model's effectiveness, and the data pursued are consistent with literature data. In the numerical simulation, an optimization problem has been defined to identify the operator suitability in performing cognitive and motor tasks. Tables 5 and 6 show the MT and CT values estimated by the model and the corresponding results of the optimization problem (δ) in motor and cognitive tasks, respectively. It can be observed in both cases that not all individuals are eligible to perform a motor or cognitive task. In particular, the average processing time of the male subjects is lower than female ones; this depends on the higher aerobic capacity of the male subject compared to the female subject. Although MT and CT increasing with age advancing in both sexes, the MT and CT percentage change versus age of the motor and cognitive task in female subjects is lower than male ones, as shown in table 7.

Table 6 Percentage change of MT and CT vs age

Age Class	Motor Task		Cognitive Task	
	Male	Female	Male	Female
20-29	0	0	0	0
30-39	8.57	6.15	13.87	7.94
40-49	15.78	12.75	24.36	16.18
50-59	15.76	10.28	22.64	12.66
60+	11.77	5.90	15.97	7.12

This confirms that the presence of older workers in production and operative roles have an impact on economic growth and manufacturing efficiency.

The result showed are achieved considering individuals in a ‘Good’ state (tables 1 and 2). In real working life, not all the operators might be in good physical condition. For instance, some may follow a proper diet and do exercise; others may not. By identifying the real physical condition of the subject by applying the developed model, it will be possible to obtain the MT and the RT reflecting the physical condition as well as the individual's age and sex.

6 Conclusion e further research

The developed model provides a proven way to determine the MT and the CT of individuals differently aged and sexed engaged in motor and cognitive tasks, respectively. The current model based on VO2max value provides an objective evaluation of information processing time. The variability between T_p values obtained by the proposed model and by the developed model by Digiesi et al. is of the order of 15%, concerning both motor and cognitive tasks.

The model applied to the case study underlines the differences that are in subjects differently aged and sexed. Older individuals show higher motor-cognitive processing time for both sexes; this implies that the time needed to complete a given task is higher than the younger individuals.

Further research should investigate the model applicability in endurance-trained versus sedentary individuals; different values of information processing time should be obtained in individuals of having same-sex and age.

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