Effect of Different Fatigue Levels on Work Quality in an Experimental Cognitive Task

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Abstract

This paper investigates the relationship between physical fatigue and quality by testing the effect of different operator fatigue levels to their accuracy when performing a cognitive task. Groups of participants performed a cognitive task at different levels of fatigue, measured by desired heart rates of 80, 105, 130 and 155 beats per minute (bpm). Heart rates other than 80 bpm were achieved by asking the participants to ride a static bicycle. The cognitive task was filling a beaker with water to a desired volume, that is 200 ml. The outcome volumes of the filled up beakers were measured, compared to the desired volume, and then analyzed with regression to six functions, each of which, the mean squared error (MSE) was computed. The function with the smallest SME is chosen as the best fit function. Our experiment shows that the relationship between quality and physical fatigue best fits in an exponential function.

Keywords: physical fatigue, quality, heart rate, cognitive task.

1. Introduction

The manufacturing industry is related closely to the quality of the products. Widely noted as being of strategic importance in manufacturing (Kolus et al., 2018), quality refers to the extent to which the production processes are executed without deviations from the required specification (Yung et al., 2020). The effectiveness of an inspection task is important to ensure product quality and customer satisfaction (Lin et al., 2001). Manufacturing industries need to generate products without defects or deviation. In industries with manual operations, the need to improve quality has led to a focus on human factors in production engineering (Yung et al., 2020).

Manual operation in production processes can demand continuous and monotonous physical activities causing physical fatigue that may lead to the decrease of product quality. Fatigue is a decrease of performance or a subjective feeling that comes from prolonged and stressful tasks (Milosevic, 1997). According to Yung et al. (2020), fatigue can be generally classified as cognitive/mental/central fatigue, physical/neuromuscular/peripheral fatigue, and perceptual/visual fatigue. Physical fatigue involves the inability to maintain physical performance, and may be related to metabolic disturbance, failure of neuromuscular transmission, and changes that affect the myosin-actin complex, and may lead to the decrease of productivity and quality. Additionally, physical fatigue has a higher contribution to quality decline than other fatigue types (Hammarskjöld and Harms-Ringdahl, 1992, Yung et al., 2020).

The literature shows that there is a positive relationship between visual fatigue and the number of defect products (Lin et al., 2010) and that visual fatigue problem in inspection for a certain period time can reduce product quality (Lin et al., 2014). Although fatigue has been proven to have negative impact to quality (Hammarskjöld and Harms-Ringdahl, 1992), how the relationship occurs has not been studied. The relationship between fatigue and quality needs to be explained in a mathematical function, similar to the relationship between learning and performance

(Wright, 1936). By identifying the mathematical function between fatigue and quality, a better decision in production scheduling can be made, as in Kurniawan et al. (2020), who considered learning and forgetting in a flow shop batch scheduling model. Therefore, the aim of this paper is to investigate a mathematical function that explains the relationship between physical fatigue and quality by testing the effect of different operator fatigue levels to their accuracy when performing a cognitive task.

2. Literature Review

Fatigue is one of elements that influence physical activities. Ream and Richardson (1996) defined fatigue as an unpleasant subjective symptom or a body sensation ranged from tiredness to exhaustion that occurs incessantly and can interfere with an individual's ability to work in normal capacities. Similarly, Lal and Craig (2001) defined fatigue as a deprivation of efficiency or a reluctance in doing tasks. Additionally, Philip et al. (2005) stated that fatigue is a gradual change of condition or an accumulation of monotonous activity that related with deprivation of doing task and involved in the appearance of inefficient performance.

The first type of fatigue is cognitive fatigue, which appears as a decrease in the ability of human to process information caused mental workload (Yung et al., 2020). It may also appear as an inability to keep attention on a particular activity or to stay perform in a particular task. Decrease in quality or performance that comes from a vigilance decline may occur due to inability to cope an increasing task demands. The second type of fatigue is physical fatigue, which includes failure to keep performance in physical tasks, and may be related to metabolic disruption, neuromuscular failure or changes affecting the myosin-actin complex. Physical fatigue can also be related to disturbance in central nervous system changes, and supra-spinal areas, spinal areas and muscle afferent system can deteriorate (Behm, 2004) and brings out further failure of body functions. Physical fatigue also causes the decline in human body strength (Vøllestad, 1997), deterioration in the ability to control motoric coordination (Gates and Dingwell, 2008), and reduction in proprioception (Björklund et al., 2000). These fatigue effects may further reduce work productivity and quality (Hammarskjöld and Harms-Ringdahl, 1992). The third type of fatigue is visual fatigue, which appears as a deterioration in the ability to perceive or perform visually, or an increasing visual soreness. Visual fatigue is not a mental workload, but rather an effect of long visual tasks causing a decline in insight level. Work performance may be interfered due to oculomotor strain and struggles in compliance and confluence (Ukai and Howarth, 2008).

Quality has been generally noted as being strategic importance in manufacturing (Das et al., 2008). There were four frequent types of quality measure identified in Kolus et al. (2018), i.e., number of defects, percentage of defects, frequency of quality deficiencies per task, and human error rate. In Figure 1, Kolus et al. (2018) described a theoretical framework regarding how human factor and human effect (fatigue) influence quality. The scheme showed that when human experiences fatigue, the production quality will be affected.

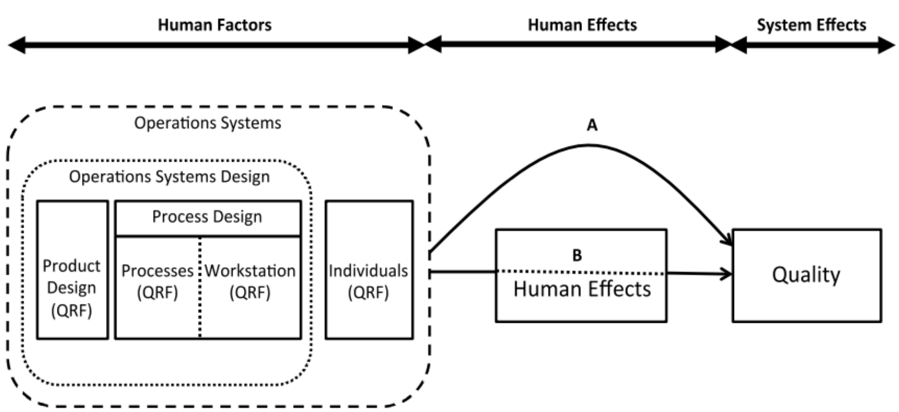

Figure 1. Framework Human Factor and Human Effect Influence on Quality Performance (Kolus et al., 2018)

3. Methodology

The aim of this paper is to identify a mathematical function that explains the relationship between physical fatigue and quality by testing the effect of different operator fatigue levels to their accuracy when performing a cognitive task. Fourteen participants aged 21 to 23 years participated in this study. Their bodyweight range was between 52 and 72 kg, and their condition during experiment was controllable. Each participant was required to do a task, that is filling water to a beaker to a desired volume, 200 ml, under four condition groups, i.e. no-fatigue (80 bpm), light fatigue (105 bpm), middle fatigue (130 bpm) and heavy fatigue (155 bpm). Participants were supposed to achieve light, middle and heavy fatigue conditions by riding a static bicycle. Although the desired heart rates at each condition were specific, participant's actual heart rates were measured before and after performing each task. Apparatus used in this experiment were a static bicycle, a digital weight scale, beakers (4 pieces), one unit of Mi Band Smart Watch, application work environment measurements (BLE Thermo-Hygrometer, LUX Light, Sound meter-Decibel meter), participant data forms, investigator data forms, a water container, papers and stationaries.

Our experiment was conducted under strict restrictions due to the COVID-19 pandemic. Only four participants per day performed the experiment in 5 consecutive days, each started at 8 am. Participants were required to fill personal data before observation, and working environments including exposure, noise, temperature and humidity were measured every day. Participants and investigators were obliged to wear face masks and keep their distances at all time during the experiment, except the participant that being observed, who was allowed to take off his/her mask because they needed to perform physical activities.

After measuring the initial heart rate, participants were asked to fill water to each beaker up to 200 ml. Four beakers needed to be filled by each participant at each condition. The volumes of the filled-up beakers were determined by weighing the beakers with a digital weight scale (assuming a standard water density of 1 gram/ml), then reduced the scale outcome with the weight of the empty beaker. Quality in this research is measured by deviation, i.e. the difference between the volume of the filled-up beakers and the 200 ml target volume (note that the higher the deviation, the lower the quality).

4. Results and Discussion

A total 14 participants attended the experiment we conducted under strict COVID-19 restrictions, less than our initial plan of a total 20 participants. Although groups 1 to 4 were supposed to have heart rate 80, 105, 120 and 135 bpm respectively, the actual heart rate of participants when starting and finishing the experiment were recorded (see Table 1). We used the average of starting and finishing heart rates for our computations (see Table 2). Fatigue level was extrapolated linearly based on heart rates, i.e. zero for 80 bpm and one for 180 bpm.

Table 1. Heart rate of each participant during experiment

Partici-pant	Group 1		Group 2		Group 3		Group 4	
	Start HR	End HR	Start HR	End HR	Start HR	End HR	Start HR	End HR
1	72	101	99	102	110	71	116	110
2	72	85	90	96	101	103	118	162
3	61	82	82	110	93	137	91	111
4	74	92	84	120	95	122	91	154
5	60	107	89	115	102	139	109	149
6	70	90	92	107	97	129	121	142
7	61	92	85	110	103	120	118	153
8	75	107	89	116	97	81	105	163
9	60	110	104	112	112	130	82	140
10	62	90	96	85	97	130	82	125
11	62	92	98	118	108	129	90	149
12	61	102	80	120	115	150	112	162
13	72	107	90	112	94	105	129	120
14	74	100	87	101	92	140	107	150

Table 2. Average heart rates and fatigue level of participants

Participant	Group 1	Group 2	Group 3	Group 4
1	86.5	100.5	90.5	113.0
2	78.5	93.0	102.0	140.0
3	71.5	96.0	115.0	101.0
4	83.0	102.0	108.5	122.5
5	83.5	102.0	120.5	129.0
6	80.0	99.5	113.0	131.5
7	76.5	97.5	111.5	135.5
8	91.0	102.5	89.0	134.0
9	85.0	108.0	121.0	111.0
10	76.0	90.5	113.5	103.5
11	77.0	108.0	118.5	119.5
12	81.5	100.0	132.5	137.0
13	89.5	101.0	99.5	124.5
14	87.0	94.0	116.0	128.5
Average HR	81.9	99.6	110.8	123.6
Fatigue level (ϕ)	0.019	0.196	0.308	0.436

Each participant conducted four trials at each condition group. Resulted data of each participant at each trial is presented in Table 3 and averaged in Table 4. As the target volume is 200 ml, we use the absolute difference between the average volume and 200 ml as deviation (*D*), the selected variable to represent quality (please note that the higher the deviation, the lower the quality).

Table 3. Four-trial experiment results

Participant	Trial	Group 1	Group 2	Group 3	Group 4
1	1	211	208	211	197
	2	202	205	207	203
	3	216	207	200	213
	4	204	201	202	197
2	1	202	203	204	190
	2	207	211	204	187
	3	203	201	209	192
	4	192	200	212	190
3	1	217	202	211	207
	2	206	203	202	220
	3	209	193	206	232
	4	200	209	203	222
4	1	203	207	203	189
	2	200	205	210	205
	3	207	200	200	192
	4	205	204	207	207
5	1	202	194	209	210
	2	205	201	197	207
	3	200	205	202	188
	4	209	200	200	203
6	1	203	201	197	200
	2	200	204	207	192
	3	200	202	200	204
	4	202	200	201	203
7	1	192	203	194	189
	2	202	200	207	194
	3	200	201	205	204
	4	201	202	201	207

Participant	Trial	Group 1	Group 2	Group 3	Group 4
8	1	203	202	200	198
	2	191	205	193	200
	3	212	189	182	215
	4	200	202	184	207
9	1	192	197	200	191
	2	202	205	192	196
	3	200	202	194	207
	4	200	200	213	210
10	1	192	201	207	209
	2	197	204	198	205
	3	199	200	201	212
	4	202	197	207	207
11	1	197	196	198	190
	2	200	207	190	197
	3	205	203	192	211
	4	202	201	217	208
12	1	194	202	212	194
	2	207	200	218	196
	3	200	199	202	200
	4	227	203	205	184
13	1	192	200	200	209
	2	198	202	209	194
	3	200	197	197	210
	4	197	192	210	207
14	1	202	200	207	204
	2	204	207	210	194
	3	200	206	204	201
	4	201	203	202	218

Next, the relationship between fatigue level (ϕ) and deviation (D) was investigated by implementing regression. Six functions were considered as candidates for the function relating ϕ and D. To simplify the calculation, non-linear functions were linearized, so only linear regression would be performed for all functions. The function names, the equations and the linearized form of each function are shown in Table 5.

Table 4. Four-trial average of experiment result

Participant	Volume (ml)				Deviation (ml)			
	Group 1	Group 2	Group 3	Group 4	Group 1	Group 2	Group 3	Group 4
1	208.25	205.25	205.00	202.50	8.25	5.25	5.00	2.50
2	201.00	203.75	207.25	189.75	1.00	3.75	7.25	10.25
3	208.00	201.75	205.50	220.25	8.00	1.75	5.50	20.25
4	203.75	204.00	205.00	198.25	3.75	4.00	5.00	1.75
5	204.00	200.00	202.00	202.00	4.00	0.00	2.00	2.00
6	201.25	201.75	201.25	199.75	1.25	1.75	1.25	0.25
7	198.75	201.50	201.75	198.50	1.25	1.50	1.75	1.50
8	201.50	199.50	189.75	205.00	1.50	0.50	10.25	5.00
9	198.50	201.00	199.75	201.00	1.50	1.00	0.25	1.00
10	197.50	200.50	203.25	208.25	2.50	0.50	3.25	8.25
11	201.00	201.75	199.25	201.50	1.00	1.75	0.75	1.50
12	207.00	201.00	209.25	193.50	7.00	1.00	9.25	6.50
13	196.75	197.75	204.00	205.00	3.25	2.25	4.00	5.00
14	201.75	204.00	205.75	204.25	1.75	4.00	5.75	4.25
Deviation average (D)					3.286	2.071	4.375	5.000

Table 5. Function candidates for the relationship between D and ϕ.

No.	Function	Equation	Linearization
1	Linear	$D = A + B\phi$	$D = A + B\phi$
2	Exponential	$D = Ae^{B\phi}$	$\ln D = \ln A + B\phi$
3	Power	$D = A\phi^B$	$\ln D = \ln A + B \ln \phi$
4	Hyperbolic	$D = 1 / (A + B\phi)$	$1/D = A + B\phi$
5	Logarithmic	$D = A + B \ln \phi$	$D = A + B \ln \phi$
6	Exponential power	$D = Ae^{B\sqrt{\phi}}$	$\ln D = \ln A + B\sqrt{\phi}$

Linear regressions were performed using linearized forms in Table 5. The inputs for the regression were D, $\ln D$ or $1/D$ as y values, and ϕ, $\ln \phi$ or $\sqrt{\phi}$ as x values. The outputs were A or $\ln A$ as the constant, and B as the slope. The obtained A and B were then substituted to the original equations in Table 5, resulting the equations in Table 6. These equations were then used to compute forecasted deviations (D') at each fatigue level (ϕ) of each group as calculated in Table 2. For example, substituting $\phi = 0.019$ of group 1 to the linear function $D = 2.498 + 4.492\phi$ results $D' = 2.592$. The mean squared error (MSE) for each function was then computed based on D and D' values. For linear function as an example, the MSE is $[(3.286–2.592)^2 + (2.071–3.467)^2 + (4.375–4.020)^2 + (5–4.653)^2]/4$ which equals to 0.669. The complete equations, the forecasted deviation D' and the MSE of each function are shown in Table 6.

Table 6. Complete equation, forecasted ℓ and MSE.

No.	Equation	Forecasted deviation (D')				MSE
		Group 1	Group 2	Group 3	Group 4	
1	$D = 2.498 + 4.492\phi$	2.592	3.467	4.020	4.653	0.669
2	$D = 2.557e^{1.301\phi}$	2.621	3.300	3.817	4.510	0.626*
3	$D = 4.132\phi^{0.088}$	2.910	3.578	3.724	3.840	1.045
4	$D = 1 / (0.389 – 0.356\phi)$	2.614	3.130	3.576	4.274	0.684
5	$D = 4.408 + 0.382 \ln \phi$	2.895	3.787	3.959	4.092	1.023
6	$D = 0.2571e^{-0.2693\sqrt{\phi}}$	2.725	3.476	3.801	4.135	0.841

The smallest MSE was given by the exponential function (no. 2), so we use the function $D = 2.557e^{1.301\phi}$ to explain the relationship between D and ϕ in this experiment. The function indicates that the deviation will be 2.557 ml when working at a no-fatigue condition and will be $2.557e^{1.301}$ or 9.392 ml when working at a total-fatigue condition. To generalize these numbers, we need to convert the volume deviation to the percentage of the target volume. Since the target volume in the experiment is 200 ml, the deviation is 1.28% at no-fatigue condition and 4.70% at full-fatigue condition. Figure 2 presents the relationship between fatigue and deviation in percent (please remind that the higher the deviation, the lower the quality).

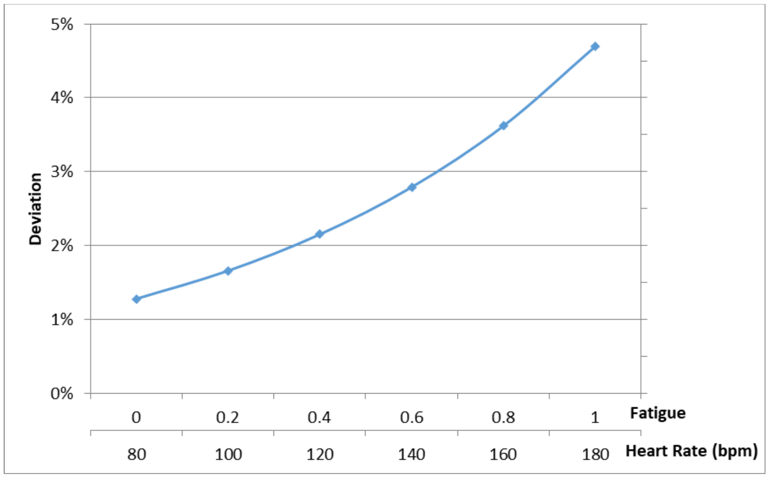

Figure 2. Graphical form of the deviation function to fatigue

From the regression results, we can analyze that the higher the fatigue level of participants, the more deviation from the target they make when doing the task. This finding is consistent with Hammarskjöld and Harms-Ringdahl (1992) and Yung et al. (2020), who stated that physical fatigue decreases quality. However, the exponential function relating fatigue and quality is a new insight obtained from this study. An exponential relationship between fatigue and deviation means that the increase in fatigue accelerates the increase in deviation. In other words, the slope of deviation is steeper at a higher fatigue level. As deviation in inversely related to quality, this urges production managers to keep operator fatigue level low by processing parts in small batches, so products are kept in a good quality. However, small batches implies more batches and more setups are required for production. Therefore, the managerial implication of this research is to find optimal batch sizes that minimize setups while at the same time keep a good quality of the products.

The finding of this paper can be practically implemented by firstly determining the value of A and B constants in a particular company. This can be performed by conducting a measurement similar to the procedure conducted in this experiment. The value of A and B may be different among workers, so the company may need to develop a database regarding to the characteristic of their workers.

5. Concluding Remarks

This research investigates the relationship between quality and physical fatigue by testing the effect of different fatigue levels on participant accuracy when doing a cognitive task. Our experiment shows that quality and fatigue is related in an exponential function. This means that the decrease of quality is faster when the operator fatigue level is higher. The consequence of this finding is to reduce the size of production lots; however, small lots require more setups. Therefore, a future research needs to develop a scheduling model that is capable to find the optimal lot size considering the relationship between quality and fatigue.

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