A Quantitative Model of Listening Related Fatigue

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Abstract— **Listening related fatigue is a common difficulty, especially for people with hearing loss. To reduce this negative impacts on their daily life, we have to understand the origins and the development of this fatigue. For this reason we developed a quantitative model of cognitive fatigue. We consider the development and course of fatigue, using a Simulink model including factors like internal and external demand, the discrepancy between expected and actual performance and the relation to reward. Besides, control and base motivation act as influencing factors on actual motivation. The functions changing according to the design of the fixed parameters are demanded effort, exerted effort, distress and fatigue. Fatigue acts as an additional input on motivation. Our focus lies mostly on listening-related fatigue. This type of fatigue occurs in difficult listening situations, especially in individuals with hearing loss. This model can be applied of a wide range of listening situations and provides a good basis for further research in this field.**

I. INTRODUCTION

Fatigue is a common phenomenon experienced by everyone at some point. It can be subjectively felt as tiredness, weariness, as an unfocused mental state or as an uncomfortable bodily state [7]. A field of fatigue attracting more and more attention is the listening-related fatigue, affecting mostly individuals with hearing loss. It is a type of cognitive fatigue, which occurs after cognitive or mental exertion and after long periods of attention, e.g., listening. Especially in noisy situations listening can be an extreme demanding, cognitive task for hearing impaired patients [5]. This increased "listening effort" may lead to mental fatigue and to a high need for recovery [4], [15], [10], [12]. The experienced fatigue can lead to difficulties with attention, concentration, memory or clear thinking [8]. It has a great negative impact on the patient's daily routine and quality of life. There already exist a few models dealing with effort, like the 'Compensatory control model' [6] or the 'Capacity model of attention' [13]. In those models the part of fatigue is mentioned but it is not their focus of interest. Furthermore, there is no quantitative evaluation of the important parameters in those models. In our model the following factors influence the behaviour of fatigue:

Effort:
Effort can be defined as the conscious investment of resources to overcome obstacles to reach a goal [13]. The investment of those resourves leads to fatigue, as everyone has been confronted with such a situation at some point. Demanding listening situations can lead to a high invested effort, e.g., "listening effort", as well. Especially individuals with hearing loss experience this "listening effort". However, the source of this cognitive fatigue is not yet clarified completely. Not getting fatigued during cognitive effort is strongly affected by motivation. Although an effortful task can be motivating, for example to overcome boredom [18]. However, in many cases the time on task plays an important role for the origin of fatigue [1].

Motivation and Reward:
A severe fatigue can be described as a profound lack of motivation to complete or to start a task. Therefore, motivation has a major impact on fatigue [7]. Hockey [7] argues that fatigue has an adaptive function, serving the management of motivation and that fatigue is not the inability to do work, but a lack of desire to work. This means that fatigue could also be described as the absence of motivation. Motivation is often linked to reward. Reward is closely related to effort. The effort budget would only be increased if the reward is great enough to justify the invested effort. Reward is not always something material or monetary, if a task is of personal interest, this can be rewarding as well. The emerging question related to reward would be: 'Is the reward worth increasing my effort budget to complete this task?' [13].

Control:
Controllability means that individuals can control their work activities and the amount of effort they invest into a task [7]. If an individual controls his or her work, the activity gives no or less rise to fatigue. If activities are self-initiated or comply with the personal goals no fatigue occurs as well. A flow state, a state of alertness and energy even if the task requires a high amount of effort, can arise[7].

Distress:
There are two different types of stress to distinguish. The first one is the so called eustress, a positive stress related to excitement, elation or joy [16]. If we hear the word stress we mostly refer to the distress, a negative stress related to panic, avoidance or flight [16]. So called stressors (trigger of stress) can be physical threats, tight deadlines, conflicts, loss or any kind of external or internal stimulation that triggers the stress response [16]. Still, a certain stress level is not just a disadvantage in life. According to the Yerkes-Dodson Law, a certain amount of stress is needed to elicit the best performance [9]. An increased effort, not resulting in a better

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performance, can also lead to a high distress.

II. The Model of Fatigue

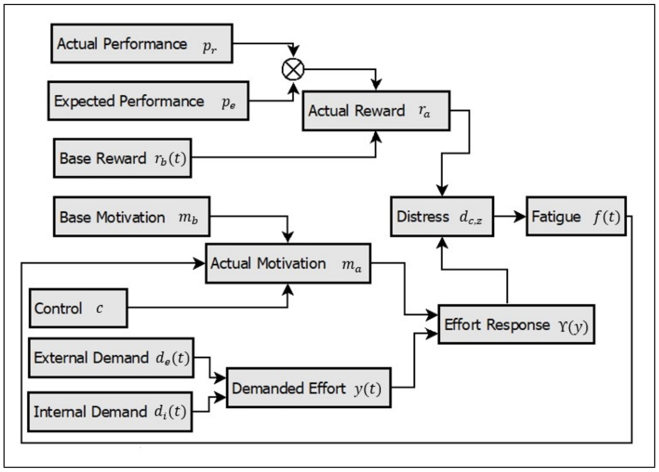

Fig. 1. Proposed model of fatigue. Actual performance, expected performance and base reward are influencing the actual reward, which is an input of distress, as well as the effort response. Base motivation, control and fatigue (included in the feedback-loop) act as inputs for actual motivation, which is an input for the demanded-exerted effort response, next to the demanded effort, consisting of the internal and external demand.

Fig. 1 shows the proposed model. It includes fixed input variables: the actual and expected performance, base reward, base motivation, control, internal and external demand. Other parameters, changing according to the values of the input parameters, are the actual reward, actual motivation, demanded effort, effort response, distress and fatigue. Fatigue acts as an input parameter for the actual motivation and regulates it down, if fatigue is increasing.

Demanded Effort:
There are two kinds of demand on processing resources which can be distinguished according to their sources in listening tasks. Some sources require attention to phenomena that lie outside the listener, while other sources require attention in a more central way [17]. This means there is a kind of demand that directs attention on external information and a type that focuses on internal information. Here we talk about external and internal demand. The external or perceptual demand is related to the selection and modulation of streams coming through the auditory system [17]. The internal or central demand requires more central attention, like working or long-term memory [17], [3], [2]. Because the two types of demand have different capacities, they can be modeled as independent dimensions of the overall demand [14]. To model independence the concept of orthogonality is used. The external and internal demand are quantified by the nonnegative real numbers $d_e(t)$ and $d_i(t)$, which depend on the duration of the simulation t. However, for the actual simulation the internal and external demand are not time dependent, but this could be changed depending on the task being modeled. The duration is $1200 sec$ for the simulations shown in Fig. 3. The overall demand $y(t)$ can then be represented by the vector $\vec{d}(t) = (d_e(t), d_i(t))^T$. The demanded overall effort can thus be modeled as the Euclidean norm of the overall demand $\vec{d}$ [17].

$$y(t) = \vec{d}(t) = \sqrt{d_i(t)^2 + d_e(t)^2} \quad (1)$$

Actual Motivation and Control:
The actual motivation $m_a(f(t))$ is a multiplication of base motivation m_b, control c and occurred fatigue $f(t)$ in the interval t, which is the duration of the measurement. Since it is assumed, that motivation falls with increasing fatigue, motivation is just a kind of inverse of the occurring fatigue. The base motivation is a scalar, which reflects the subject's willingness to complete the task. In our case the base motivation is a constant with the value one, because it is assumed that the subjects are always willing to complete the task conscientiously. In future work this base motivation can be changed to a variable, depending on the real willingness of the subject to complete the demanded task. The control, the subject has over the tasks or over the invested effort is also a constant, according to the low control a subject has in laboratory measurement situations. If the model is used to predict different situations, like more real life situations, this can be changed in the range between zero and one.

$$m_a(f(t)) = m_b \cdot c \cdot \left(\frac{-f(t)}{10} + 1 \right) \quad (2)$$

Actual Reward
For the simulations we present in this paper we use a certain base reward curve as example, shown in Fig. 2. The reward is rising quickly at the beginning of the measurement and stays constant for a while. This constant reward can occur in a rewarding task, like in a flow state. Distress stays constant as well, because the task is a rewarding one [7]. The decline of the reward can be elicited by demotivating comments, worse performance or other internal or external factors. It will be a part of the future development of this model to change the shape of the reward curve in relation to different parts of the model e.g., motivation or ongoing performance. The actual reward r_a is just a scaled version of the base reward r_b, regarding the discrepancy between expected performance p_e of the subject (a subjective variable) and real performance p_r.

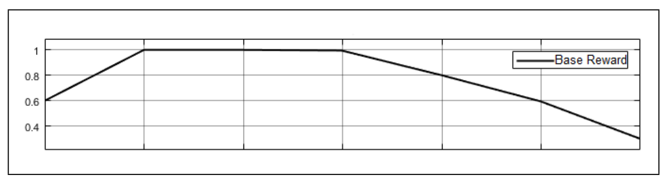

Fig. 2. The curve of the base reward, used in the presented simulations. It rises at the beginning of the simulation, e.g., due to personal interest of the subject for the task, and declines at the end of the simulation e.g., according to demotivating comments or decreasing performance.

$$r_a(r_b(t)) = \frac{p_r}{p_e} \cdot r_b(t) \quad (3)$$

According to Equ. 3, reward is higher if the performance is better than expected, and smaller if it is the other way around. The expectation-performance ratio can be easily modified by

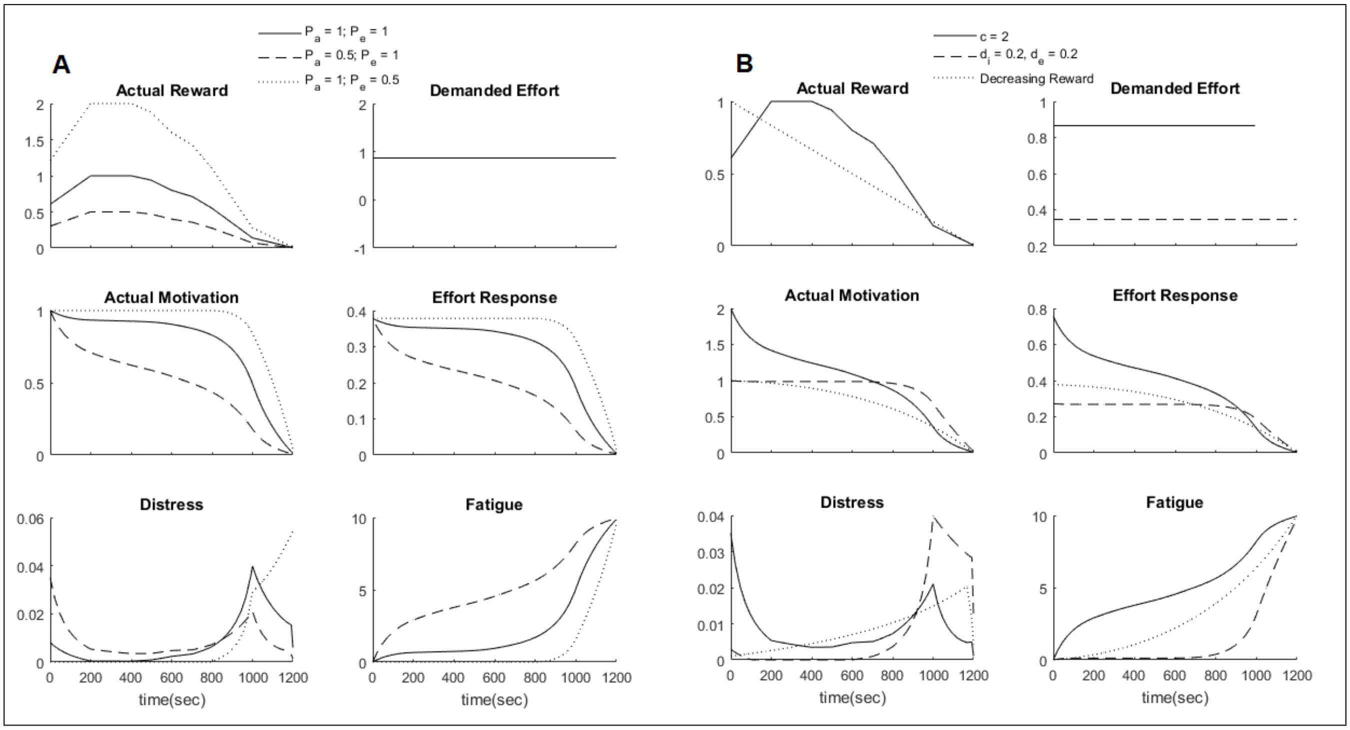

Fig. 3. Results or the simulation about 1200 seconds of the model is shown for six different predictions. For all situations, only the base motivation (m_b) was fixed to a value of 1. **A:** Three different simulations are shown with different values for the expected and actual performance. Control (c) = 1, internal (d_i) = 0.5, external demand (d_e) = 0.5. Simulation A.1 (solid line): actual performance (p_a) = expected performance (p_e). A.2 (dashed line): $p_a = 0.5$ and $p_e = 1$. A.3 (dotted line): $p_a = 1$ and $p_e = 0.5$. **B:** Here $p_a = p_e$ for all predictions. B.1 (solid line): control (c) = 2. B.2 (dashed line): $d_i = d_e = 0.2$, $c = 1$. B.3 (dotted line): The shape of the reward curve is changed. It is continuously decreasing during the measurement.

manipulating the performance feedback.

Effort Response:

The demanded-exerted effort response $\Upsilon_{b,p}(y(t))$ is modeled with the same resource-limiting function as in [17]. This response models the relation between demanded and exerted effort. A resource limiting function is used, because the exerted effort differs from the demanded effort, according to capacity limitations, vigilance and arousal levels [17]. Equation 4 characterizes this resource limiting function. For small demands, the function responds almost linearly and falls quickly after a certain demanded effort threshold is reached. This threshold can be seen as a quitting point, when the subject decides not to spend any further effort into the task [17], or if he or she changes the goal to doing nothing.

$$\Upsilon_{b,p}(y) = m_a(f(t)) \cdot \frac{b^p}{\Gamma\left(1 - y(t)\right)} \cdot y(t)^{p-1} \cdot e^{-b\cdot(1-y(t))} \quad (4)$$

$\Gamma(\cdot)$ is the Γ function and $y(t)$ the demanded effort. The parameters b and p control the steepness and the intensity of the effort response and can be used to adjust motivation or arousal of the subject in a simulation. For a less motivated subject the quitting point (the moment the subject stops investing effort into the task) is reached earlier in contrast to a more highly motivated subject [17]. For the actual version of the model the values $p = 2$ and $b = 2$ are used.

Distress and Fatigue:

It is assumed that distress $d(\Upsilon, r_a)$ is a sigmoid transfer function of the exerted effort-actual reward ratio (see Equ. 5). With a higher ratio, which means high effort-response and low actual reward, distress is rising. It is rising very quickly at a certain ratio and stays then constant. We assume that distress just increases when the subject is under pressure to increase or maintain the performance. This pressure can occur internally or can be exerted by an external source. However, if the subject has reached the quitting point distress does not arise or it decreases rapidly. In this situation the subjects are not under any pressure, because they are no longer interested in the correct execution of the task.

$$d_{c,z}(\Upsilon, r_a(r_b(t))) = \frac{1}{1 + e^{-c\cdot\left(\frac{\Upsilon}{r_a(r_b(t))} - z\right)}} - g \quad (5)$$

The variable $c = 1$ is a scaling parameter and $z = 4$ a shifting parameter. There is a little offset $g = 0.025$, to start the distress at the value zero, when the effort-reward-ration is zero too. This function is regularized, that not every little change in the effort response changes the distress, which would lead to fatigue. To provoke fatigue there has to be a certain amount of distress. Fatigue itself is modelled as the integrated distress. This leads to a ‘time on task effect’, which means that the fatigue is rising over the time on task. It also reflects the effort-reward ratio.

$$f(t) = \int d_{a,b}(\Upsilon, r_a(r_b(t)))dt \quad (6)$$

Fatigue acts as an input for the model and regulates the effort response down, with its direct influence on the actual motivation like in [11]. This feedback loop can be seen in Fig. 1.

III. RESULTS AND DISCUSSION

We simulated different situations, like demanding listening situations, over a 1200 seconds interval. They can be seen in Fig. 3. The demanded effort, actual reward, actual motivation, effort-response, distress and fatigue are pictured. In part 'A' of Fig. 3 the expectation-performance-ratio is changed. Comparing the simulations A.1, A.2 and A.3, we can see that if the individual performs better than expected (A.2), the reward is higher than if the expectations were not fulfilled (A.3) or if performance exactly equals expectations (A.1). We can see the same development for motivation and the effort response. They drop earlier in the simulation if the expectations are not achieved. However, they drop in any case toward the end of the simulation, according to the falling reward. Distress and fatigue show the inverse development than motivation and effort response. The reason for the falling of distress after rising first is the reaching of the quitting point. This point is only reached in prediction A.1 and A.2. If it is reached the subject is not engaged into the task anymore and there is no pressure to fulfil the task correctly. If that is the case distress decreases. For A.3 the motivation is higher over the whole measurement and distress increases at the end, without reaching the quitting point. Fatigue increases towards the end faster for a high motivation, than for the low motivation condition. Part 'B' of Fig. 3 shows in B.1 what happens, when the subject has a higher control. Here, the expectation-performance-ratio has again a value of 1. In comparison to part 'A' motivation and effort response are higher. This shows the effect of control on motivation. If you can choose the goal or the task by yourself, your motivation to complete the task is higher. This leads to a higher exerted effort. Another difference to the simulations in part A is the distress curve. It starts at the same point and rises, according to the reward curve. However, if the control is higher, distress increases not as much as before, according to the higher motivation. B.2 shows the model with the same parameters as in A.1, but with a smaller overall demanded effort. The task to be performed is now a simpler one. Motivation stays high for a long time, and the exerted effort starts with a smaller value as in the other cases. There is no development of fatigue or distress until the ending of the measurement. However, if a task is too easy for a subject boredom can occur, which can be reflected in a worse performance and low motivation [18]. B.3 shows the development of the functions for a different reward. The reward is decreasing continuously. The rapid drop of the reward at the beginning leads to a faster decrease of the motivation, however the effort stays constant for a longer time. Distress increases over the whole simulation, as the reward declines. According to this, fatigue is increasing faster than in the condition before. This suggests that reward has a higher influence on fatigue than the demanded effort does. While this seems like a reasonable assumption, we note that the model currently only works within certain limits of certain parameters, especially base reward. We intend to remove this limitation in future versions of the model.

IV. CONCLUSION

In this paper we presented a first version of a quantitative model of fatigue in the context of effortful listening. The simulations show the hypothesized behaviour of fatigue, motivation, effort and distress. We are currently in the process of developing human experiments to evaluate the different predictions of the model. Additionally there are more parameters we can implement in the model. For example we could expand the feedback loop adding the performance into it. Future versions of the model will be developed in conjunction with experiments to test and refine predictions in human subjects' performance.

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