An Agent Model for Analysis of Human Performance Quality

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Abstract — **A human's performance in a complex task is highly dependent on the demands of the task, in the sense that highly demanding situations will often cause a degradation of performance. To maintain performance quality usually extra effort has to be contributed. However, the resources for such extra effort available to the human are limited. In this paper an agent model is proposed in which different types of relations between effort, task demands and performance quality can be used to analyse the human's performance quality. It is illustrated how a support agent incorporating this model can support a human based on different performance criteria. The agent model thus allows to build agent applications that provide optimal support depending on a specific situation and goal of the task.**

Human Performance, Agent Model, Support Agent

I. Introduction

When humans have to work in circumstances where demands of the task are high, performance can easily degrade. An example of such a situation is Air Traffic Control, where operators constantly have to pay attention to many items on the screen. A degradation of performance in such circumstances is highly undesired, as errors can have disastrous consequences. In these cases, automated assistance is required in order to maintain a good performance quality. For this purpose, intelligent agents can be designed that support humans and intervene before performance degrades.

For the design of such an intelligent support agent, it is important that human performance over a given time interval can be analysed. A human's performance depends on a person's functional state (e.g., stress, exhaustion; cf.[1]), but also on the demands of the specific task. Earlier models have been designed that allow to determine performance, based on the human's functional state and on the demands of the task ([2], [3]). These models are either very specific to a person, or very specific to the task.

In this paper a general human agent model is introduced to analyse human performance quality, based on a specific relation between performance (degradation), (increasing) task demands, and effort contributed. In earlier research it was found that the task demands over a given time interval have a major effect on the performance quality [4]. The human agent model describes how (a limited amount of) extra power (i.e., effort) can be contributed to maintain a specific performance quality when task demands increase.

The model can be specialised for a task at hand by incorporating a specific degradation curve describing how for a given level of contributed power the performance quality degrades as a function of task demands. Two illustrative specialisations of the human agent model are discussed, based on two different types of degradation curves.

The agent model for human performance can be integrated in a software agent supporting the human. This software agent takes as input certain performance requirements and the (expected) demands of a specific task over time. Taking this into account, the software agent uses the human agent model to analyse whether and how the performance quality requirements can be fulfilled and determines the required power for subsequent time intervals to achieve this.

First, in Section 2 a conceptual background on performance in demanding circumstances is given. After this, in Section 3 the generic human agent model for performance that can be used within an intelligent software agent is introduced, with simulations to illustrate the model in Section 4. Section 5 presents the use of the human agent model within a supporting software agent. Finally, Section 6 concludes the paper with a discussion.

II. On Modeling Human Performance

In research on domains such as aviation and naval warfare, human performance is often represented as part of the human's functional state and is influenced by factors such as fatigue and contributed effort [5]. The relation between (mental or physical) effort contributed and performance is not trivial. In [6] a cognitive energetical framework is suggested, to describe which extra effort is needed for the management of performance when task demand is high. The effort will be extracted from a limited amount of resources available, which contributes to fatigue. Figure 1 shows a graph that is taken from [7], where the relationship between task demands, performance and effort is represented. A similar logistic curve can be seen in [8] where the relation between resources (effort) available for the task and performance is represented. Here, for each task, there exists an amount of resources below which performance on the task degrades. The difference between easy and difficult tasks is shown in the fact that in the former this point is lower (less resources are needed) as compared to the latter.

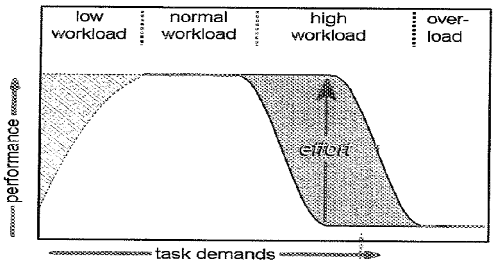

Figure 1 Hypothetical relation between task demands, effort and performance. Adapted from [7]

There are few applications of performance models that are based on the human's functional state. Often, such models are related to specific concepts like attention or decision making (e.g., [9], [10]). Although such concepts can be useful, for a supporting software agent it is also important that overall performance can be analysed in relation to (expected) task demand and effort. In [2] a model is presented where performance estimation is based on factors like the effort a person generates, the person's motivation and several personal characteristics. This model does provide a good representation of a person's functional state, however it is very complex and may not be easily applicable to all types of tasks. In particular, the model assumes a fixed relation between task demands and performance.

In the next section, a generic human agent model is introduced to describe and analyse performance in relation to task demands and effort. The relation between the concepts (effort, performance and task demands) within any specialisation of this human agent model can be adjusted based on the nature of the task (in both cognitive and physical tasks). As this human agent model can be used in different situations and for different types of tasks, this allows for a high extent of flexibility and optimal use within a supporting software agent.

III. An Agent Model for Human Performance

In this section a generic human agent model is introduced describing the relationship between task demand, effort, and performance quality. As an illustration, two specialisations of this generic model are discussed for different performance degradation curves.

A. *Effort, task demands and performance*

For the generic human agent model that is to be used by the supporting software agent, an agent model is proposed that assumes a decrease of performance quality *PQ* when the value of task demand *TD* is above a specific boundary according to some specific degradation curve. When the value of task demand is below that boundary, performance is always *1*. Furthermore, based on the idea of the cognitive energetical framework (cf. [6]), degradation of *PQ* can be compensated by the contribution of extra effort (in this paper effort is referred to as power *P*).

The generic human agent model describes how *TD*, *P* and *PQ* have a mutual dependency.

For example, any given task demand *TD* and exerted power *P* result in a certain performance quality *PQ*. Or, any required performance quality *PQ* and available power *P* indicate a certain task demand *TD* that is feasible. How these dependencies exactly are may strongly depend on the task at hand. For example, a task such as cycling may strongly depend on the headwind as a task demand, and for a given level of power contributed the speed (as performance quality) may gradually become lower with higher task demands (gradual degradation curve). However, other tasks may involve strongly interconnected subtasks, so that a gradually lower performance quality is hardly possible (steep degradation curve). Therefore for a general setup of the human agent model it is reasonable to assume that some dependencies are available, but may be different for different tasks.

In the generic human agent model the following three variables with real values ≥ 0 that have some mutual dependency are considered:

task demand	*TD*
performance quality	*PQ*
(required) power	*P*

In a symmetric manner their dependency can be described implicitly by one equation

$$f(TD, PQ, P) = 0$$

The following monotonicity relations are assumed:

If $f(TD_1, PQ_1, P_1) = 0$ and $f(TD_2, PQ_2, P_2) = 0$ then

$$TD_1 \leq TD_2 \ \&\ PQ_1 \leq PQ_2 \Rightarrow P_1 \leq P_2$$
$$TD_1 \leq TD_2 \ \&\ P_1 \leq P_2 \Rightarrow PQ_1 \leq PQ_2$$
$$PQ_1 \leq PQ_2 \ \&\ P_1 \leq P_2 \Rightarrow TD_1 \leq TD_2$$

From these relationships it follows that for any two values of two of the variables there is only (at most) one value of the third variable so that the equation holds, i.e., each variable has a functional dependence of the other two. For example, from $f(TD, PQ, P_1) = 0$ and $f(TD, PQ, P_2) = 0$ by monotonicity it follows both $P_1 \leq P_2$ and $P_2 \leq P_1$, so $P_1 = P_2$. When the monotonicity relations are assumed strict (with < instead of $\leq$), then also by the Implicit Function Theorem from Calculus it follows that each of the variables can be described in an explicit manner by a function of the other two. Therefore, as an alternative for the implicit description, their dependency can be described explicitly by any of the following three functions

$$P = p(PQ, TD)$$
$$PQ = pq(P, TD)$$
$$TD = td(PQ, P)$$

The following relations hold:

$f(TD, PQ, p(PQ, TD)) = 0$	for all *TD* and *PQ*
$f(TD, pq(P, TD), P) = 0$	for all *TD* and *P*
$f(td(PQ, P), PQ, P) = 0$	for all *PQ* and *P*

Moreover six inverse or commutation relations hold for these functions, such as $p(pq(P, TD), TD) = P$.

A special class of relations between P, PQ and TD is when for a given performance quality PQ the power P needed to cope with task demand TD is a linear function of TD, expressed as a relation of the form

$$P = p(PQ, TD) = g(PQ)\, TD + h(PQ) \quad \text{or}$$
$$\partial P/\partial TD = g(PQ)$$

Next two specific relations between power, task demands and performance quality are discussed. Both considered relations are of the above form, in which the P needed is a linear function of TD.

1) Proportional degradation curve

The first of the two relations used is a proportional relation; it is based on the following assumptions:

- performance PQ (below 1) is proportional with power P (for fixed task demand TD)
- task demand TD is proportional with needed power P (for fixed performance quality PQ)

Under these assumptions the equation for power P needed performance quality PQ and task demand TD can be expressed by

$$P - \alpha\, PQ * TD = 0$$

Where α is a parameter value between 0 and 1. Moreover, clearly the power P needed can be explicitly expressed in PQ and TD by the function

$$p(PQ, TD) = \alpha PQ * TD$$

So, in this case

$$\partial P/\partial TD = \alpha\, PQ$$

This specialisation is of the linear type

$$p(PQ, TD) = g(PQ)\, TD + h(PQ)$$

with

$$g(PQ) = \alpha\, PQ$$
$$h(PQ) = 0$$
$$\partial P/\partial TD = \alpha\, PQ$$

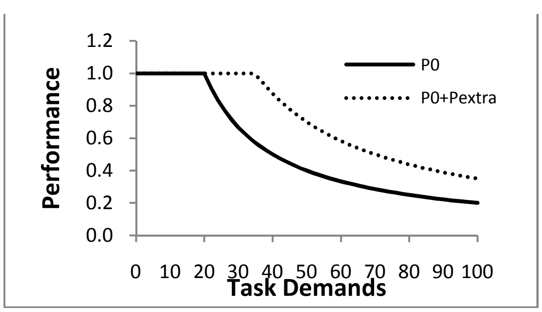

Figure 2 Proportional degradation curve

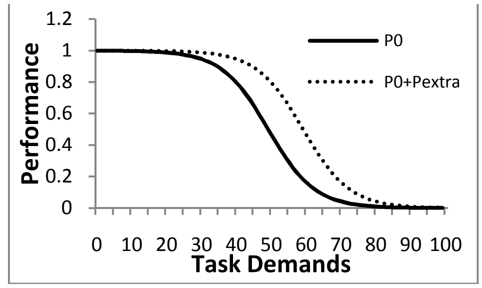

Figure 3 Logistic degradation curve

Alternatively, the performance quality PQ can be expressed explicitly in the power P and the task demand TD by:

$$pq(P, TD) = P/\alpha TD$$

As the performance quality PQ is taken ≤ 1, the degradation curve depicted in Figure 2 (solid line) actually is of the form $pq(P, TD) = min(1, P/\alpha TD)$. The value of α here is 1.

2) Logisitic degradation curve

For the logistic case the performance PQ depends on task demand TD and power P in a logistic manner, according to the equation

$$PQ = 1 - 1/(1+e^{-\sigma(TD - P)})$$

with σ a steepness parameter. So,

$$pq(P, TD) = 1 - 1/(1+e^{-\sigma(TD - P)})$$

This degradation curve is shown in Figure 3 (solid line). Alternatively the function $p(PQ, TD)$ expressing the power P explicitly in PQ and TD can be determined:

$$PQ = 1 - 1/(1+e^{-\sigma(TD - P)})$$
$$1/(1+e^{-\sigma(TD - P)}) = 1 - PQ$$
$$e^{-\sigma(TD - P)} = 1/(1 - PQ) - 1 = PQ/(1 - PQ)$$
$$-\sigma(TD - P) = log(PQ/(1 - PQ))$$
$$P = TD + (1/\sigma)\, log(PQ/(1 - PQ))$$

So, the function $p(PQ, TD)$ can be defined by:

$$p(PQ, TD) = TD + (1/\sigma)\, log(PQ/(1 - PQ))$$
$$= TD - (1/\sigma)\, log((1 - PQ)/PQ)$$
$$= TD - (1/\sigma)\, log(1/PQ - 1)$$

It turns out that also this specialisation is of type

$$p(PQ, TD) = g(PQ)\, TD + h(PQ)$$

with

$$g(PQ) = 1$$
$$h(PQ) = -(1/\sigma)\, log(1/PQ - 1)$$
$$\partial P/\partial TD = 1$$

B. Effect of extra effort

When extra effort is provided the degradation curve between the task demands and the performance quality will be shifted. The effect of additional effort for the two discussed specializations is explained below.

1) Extra effort for the proportional case

If the power P is composed of the basic power P_0 (not contributing extra effort) and extra power $\Delta P = P_{extra}$, then the graph for P is compared to the one for P_0 as shown in Figure 2 (dotted line). When $\Delta TD = TD_{shift}$ is the difference for the horizontal TD axis, then this can be determined as follows with $TD^* = TD + TD_{shift}$:

$$\alpha P_0/TD = PQ = \alpha P/TD^* = \alpha (P_0 + P_{extra})/TD^*$$
$$(P_0 + P_{extra})TD = P_0 TD^* = P_0 (TD + TD_{shift})$$

So, the shift TD_{shift} in the horizontal direction is over the following distance:

$$TD_{shift} = (P_{extra}/P_0)\, TD$$

This is independent of PQ; it is a translation of the graph over a distance proportional to TD. Similarly the shift PQ_{shift} in vertical direction for $TD^* = TD$ can be determined: from $PQ^* = (P_0 + P_{extra})/TD^*$ and $PQ = P_0/TD$ it follows that

$$PQ_{shift} = (P_{extra}/P_0)\, PQ$$

2) Extra effort for the logistic case

For the logistic case, from

$$P_0 + P_{extra} = TD_0 + TD_{shift} + (1/\sigma) \log(PQ/(1 - PQ))$$
$$P_0 = TD_0 + (1/\sigma) \log(PQ/(1 - PQ))$$

it follows that

$$TD_{shift} = P_{extra}$$

This means that the curve of PQ against TD for $P = P_0 + P_{extra}$ (dotted line in Figure 3) can be obtained by a (uniform) translation of the graph of PQ against TD for P_0 in the horizontal direction by P_{extra}.

C. Exhaustion

Within the literature on exercise and sports the notion of critical power CP plays an important role. This is the maximal level of power that can be sustained over longer periods without becoming exhausted, assuming no prior exercising. It is an asymptote of the hyperbolic power-duration curve defined by $(P - CP).t = M$ that (as shown in various experiments) models the relationship between a constantly generated power P (above the critical power CP) and the time t that this can be sustained; e.g., [11], [12]. Here M is the total amount of work that can be spent above the critical power (the available stored resources). Often it is assumed that this critical power CP is a constant that is not affected by prior exercising, and is a capacity to provide (sustainable) power based on aerobic processes. Power generated above this critical power is assumed to be based on (nonsustainable) anaerobic processes, that exploit an available fixed reservoir or budget M of stored basic resources, which is one of the parameters of the hyperbolic power-duration curve (in the literature sometimes indicated by W').

Multiple choices can be made regarding exhaustion and power, depending on the nature of the task. For example, in some tasks a maximum power may be assumed to exist and it is impossible to contribute a power beyond this value. Or, in other tasks, in addition to the extra power that is contributed, the degradation curve can be influenced by the extent of exhaustion. For the current paper only a maximum amount of exhaustion is assumed (comparable to the available stored resources: M). When exhaustion reaches this maximum, no more extra power can be contributed. In the human agent model power affects exhaustion according to:

$$Ex(t+\Delta t) = Ex(t) + (P_{extra}(t) - \varepsilon * Ex(t) * Rec(t)) * \Delta t$$

with

$$Rec(t) = \max(PQ\_for\_P_0(t) - PQ(t), 0)$$

In this case, there can also be recovery (indicated by *Rec*), when no extra power is contributed. More specifically, when PQ at a specific point in time is low as compared to the maximum PQ without contribution of extra power, recovery will be higher than zero. In all other cases, recovery is zero.

IV. Simulation Results

To illustrate the model, two example simulations are shown for both the proportional and the logistic case, where PQ is estimated for an interval of 15 time units. Task demands are taken equal over time, for the first simulation *15* and for the second *25*. Power is generated at random at each time point. The parameters used are as follows: $\sigma=0.15$, $P_0=21$, $\varepsilon=1$, *Exhaustion Budget=50.* No extra power can be contributed if this will lead to exceeding the exhaustion budget. In this case recovery of *0.2* has been chosen: the PQ is *0.2* lower as compared to a maximum PQ that can be achieved by power P_0 only.

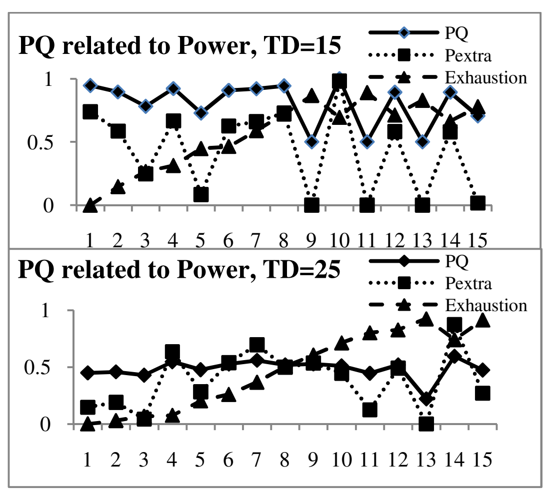

Figure 4a, b; Performance, power and exhaustion for task demands of 15 (a) and 25 (b): proportional case

A. Simulations for the proportional case

Figure 4a and 4b show the results (PQ, extra power P_{extra}, and Ex, all scaled between *0* and *1*), of the first simulation.

After some time, the exhaustion budget will be exceeded (for example when *TD* is *15* at time point 9 and 11). The choice is made to let *PQ* decrease, which will allow recovery and decreases exhaustion at the next point in time. Note that in this case the extra power is *0*. The graph shows that power increases *PQ*, but also increases exhaustion, which can result in an unavoidable decrease of *PQ* later on.

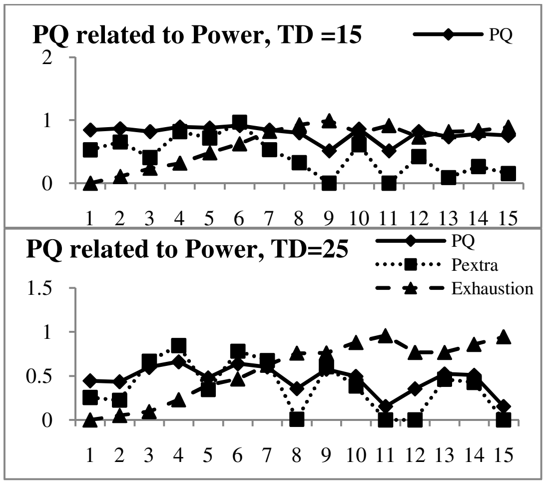

Figure 5 a, b; Performance, power and exhaustion for task demands of 15 (a) and 25 (b): logistic case

B. *Simulations for the logistic case*

As in the proportional case, Figure 5a and b show simulation results for equal Task Demands of 15 and 25. Exhaustion increases faster when *TD* is 15 as compared to a *TD* of 25, as P_{extra} (randomly generated) is higher. In both cases, the relation shows that the higher the P_{extra}, the higher the *PQ*.

V. Using the Human Agent Model within a Supporting Software Agent

In this section it will be discussed how the introduced human agent model can be used within a software agent supporting the human.

A. *Possible requirements on performance*

The generic human agent model presented above can be used within a supporting software agent in a number of ways. The way in which it is applied depends on the scenario, the task, and the circumstances in which a task has to be performed. The presented generic human agent model can be specialised using specific choices

As discussed above, a first criterion is the relation between the task demands and the performance (the *degradation curve*) for a specific task. Currently two different types of degradation curves have been presented, but it is possible to use any other curve within the human agent model.

A second choice concerns the *distribution of the task demands* over time. For example, they can be fixed, increasing, decreasing, or fluctuating during different periods of the task.

The other choices for the specialisation of the human agent model relate to the goals of the supporting software agent. One goal related choice is the *requirement on the performance goals*. There can be several possible goals related to the performance, for example:

- In each time interval the highest performance possible.
- Maintaining at least some minimal performance quality during the whole period of the task (i.e., no periods with very low performance). This can be relevant when performing monitoring tasks. A variation of this type of goal is when the minimal performance requirements differ for different periods during the execution of the task (e.g., a maximal performance during the last period, or some minimum requirement during another period);
- Achieving a maximal cumulative performance (i.e., some periods with low performance are not problematic if the cumulative performance is higher). When involved in a competition this can be a relevant goal.
- Maintaining a stable performance quality during the complete time of the task.

Note that these requirements often assume that the power is distributed as efficient as possible, thus, the total possible exhaustion is spent during the complete duration of the task.

Another goal-related choice is the type of *intervention action* of the software agent, especially if the goals may not be met:

- an advice on an effort distribution to achieve the maximal possible performance quality over time;
- a prediction of the length of the period that the requirements are achievable.

In the examples presented below, it is illustrated how the choices can be made to obtain a specific type of analysis based on the specialised human agent model.

B. *Maintenance of Performance Quality*

First it is discussed how a certain performance quality can be maintained.

1) *Situation Description*

As first example, a person is considered that has to perform a Naval Warfare task (e.g. identify incoming contacts as enemy or ally). In such a task, it is important that the person achieves at least some minimum required performance quality *PQ*. However, if the task demands are too high, it might not be possible to maintain this level for an unlimited time. Based on the human agent model, the supporting software agent will analyse how long the required *PQ* can be maintained (the time it takes before the exhaustion budget is finished) given the task demands. By using this information, the support system can provide support to the human performing the task, for example by task allocation to another person or an another agent.

Two scenarios are simulated. In scenario 1, task demands are first *15*, then *8* and *15* again from t=30. In scenario 2 task demands are *15* at all points in time. For both scenarios the required PQ is 0.8. The simulation settings for this situation are as follows:

$$\sigma=0.15,\ P_0=21,\ \alpha=0.5,\ \varepsilon=1,\ \text{Exhaustion Budget} = 50$$

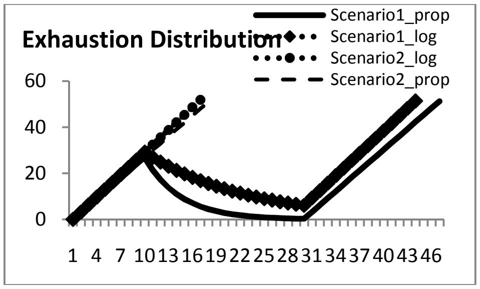

Figure 6 Exhaustion for scenario 1 and 2.

2) Analysis

To analyse how long it is possible to maintain a specific performance quality, the supporting software agent will determine the extra power that has to be contributed for the given task demands. For the logistic case this is:

$$P_{extra}(t) = TD(t)+(1/\sigma)*log(PQ/(1-PQ)) - P_0$$

and for the proportional case:

$$P_{extra}(t) = PQ/\alpha*TD(t) - P_0$$

The amount P_{extra} will add to the exhaustion according to a simulation of the difference equation for exhaustion by the software agent:

$$Ex(t+\Delta t) = Ex(t) + (P_{extra}(t) - \varepsilon*Ex(t)*Rec(t))*\Delta t$$

with $P_{extra}(t)$ replaced by one of the alternative formulae above. If the exhaustion budget of 50 will be exceeded by $Ex(t)$ at the next point in time, the required PQ cannot be achieved anymore.

3) Simulation results

Table 1 presents the final time points for both scenario 1 and 2. Scenario 1 allows for recovery when task demands are 8.

TABLE I. DURATION OF THE MAINTENANCE OF REQUIRED PQ

Scenario	End time Log. case	End time Prop. case
1	$t=43$	$t=45$
2	$t=16$	$t=17$

This is also shown in Figure 6, where exhaustion decreases from $t=10$. As a consequence, in scenario 1 the person can maintain the required PQ for a longer period. It can be seen that the period with lower task demands in scenario 1 allows predicting that recovery will take place, resulting in a longer time during which the PQ can be maintained.

C. Maximizing Stable Performance Quality

Next it is discussed how the performance quality that can be maintained can be maximised.

1) Description

In the second example, a demonstration is given of the criterion that PQ at all points in time should be the same. The supporting software agent analyses the maximal value for PQ for a given scenario that can be maintained, as well as the power that is needed in different time intervals to achieve that PQ. For this, an ice (speed) skating case study is used. For a person performing in a speed skating competition it is important to know the maximal performance that can be achieved throughout the entire track. In addition, the Support Agent can provide information on the amount of power that needs to be contributed to obtain that specific performance quality.

For this example, three specific simulations are chosen: 1) short track skating ($t=5$) 2) long track skating ($t=50$) 3) long track skating ($t=50$) with changing task demands. In simulations 1 and 2, task demands are equal at each time point: 20. In scenario 3, task demands change between 25 (high), 20 (middle) and 15 (low). Other simulation settings are equal to the values described in Section V-B-1 for situation 1.

2) Analysis by what-if simulation

One approach for the software agent in order to analyse the highest PQ that can be achieved at all time points, is by what-if simulation of the human agent model. The software agent starts with a PQ of 0.5. To check for this PQ, the necessary extra power at a given point in time is determined as explained in Section V-B-2.

$$P_{extra}(t) = TD(t)+(1/\sigma)*log(PQ/(1-PQ))- P_0$$

or

$$P_0+P_{extra}(t) = PQ/\alpha*TD(t)- P_0$$

The extra power is determined that has to be contributed in order to achieve the PQ. When at any point in time the exhaustion budget is exceeded, the agent decides that the currently assumed PQ cannot be achieved at all time points and it will check for the next (lower) PQ. Otherwise it will try a higher PQ.

3) Using a mathematical analysis

The result above can not only be achieved via what-if simulation, but also via mathematical analysis. The analysis results in an expression to calculate the maximal stable PQ in a given scenario. Here, analysis is shown for the proportional case and for the logistic case. Assume from the exhaustion budget M at each time point $U(t)$ indicates the used part, and $Rec(t)$ the recovered part. It is assumed that always

$$Rec(t) \leq U(t)$$

so not more than full recovery takes place. Then the remaining budget at t is determined as:

$$Rem(t) = M - U(t) + Rec(t)$$

with $0 \leq Rem(t) \leq M$. Under these assumptions the used part $U(t)$ and the recovery part are determined as

$$U(t) = \int_0^t Pos(P(u) - P_0)du$$
$$Rec(t) = \int_0^t Pos(P_0 - P(u))du$$

From this and the assumptions it follows that

$$Rem(t) = M - U(t) + Rec(t)$$
$$= M - \int_0^t Pos(P(u) - P_0)du + \int_0^t Pos(P_0 - P(u))du$$
$$= M - \int_0^t (P(u) - P_0)du = M - \int_0^t P(u)du + P_0 * t$$

From $0 \leq Rem(t) \leq M$ it follows that

$$0 \leq M - \int_0^t P(u)du + P_0 * t \leq M$$
$$-M - P_0 * t \leq - \int_0^t P(u)du \leq M - P_0 * t$$
$$M + P_0 * t \geq \int_0^t P(u)du \geq P_0 * t - M$$
$$P_0 * t - M \leq \int_0^t P(u)du \leq M + P_0 * t$$
$$P_0 - M/t \leq \int_0^t P(u)du/t \leq P_0 + M/t$$

In general the function $P(u)$ is given by

$$P(u) = p(PQ(t), TD(t)).$$

In pinciple, for constant PQ this function can be used to express $\int_0^t P(u)du/t$ in PQ and the function TD over time. Suppose the function P of TD can be described by

$$P = pp(PQ, TD) = g(PQ)\, TD + h(PQ)$$

Then the integral of P from 0 to t can be expressed in the integral of TD as follows:

$$\int_0^t P(u)du = \int_0^t (g(PQ)TD(u) + h(PQ))du$$
$$= g(PQ) \int_0^t TD(u)du + h(PQ)t$$

Therefore the average effort over $[0, t]$ can be expressed in the average task demand over $[0, t]$:

$$\int_0^t P(u)du/t = g(PQ) \int_0^t TD(u)du/t + h(PQ)$$

Then the following inequalities hold:

$$P_0 - M/t \leq g(PQ) \int_0^t TD(u)du/t + h(PQ) \leq P_0 + M/t$$

So, the maximal value of PQ_{max} that can be maintained over the whole period satisfies the equation

$$g(PQ_{max}) \int_0^t TD(u)du/t + h(PQ_{max}) = P_0 + M/t$$

The proportional case
As shown in Section 4.1, for the proportional case it holds

$$p(PQ, TD) = \alpha PQ\,.TD$$

Then for constant PQ the following is obtained:

$$\int_0^t P(u)du = \alpha PQ \int_0^t TD(u)\, du$$

So, for this case the above inequalities provide:

$$P_0 - M/t \leq \alpha PQ \int_0^t TD(u)du/t \leq P_0 + M/t$$
$$\frac{P_0 - M/t}{\alpha \int_0^t TD(u)du/t} \leq PQ \leq \frac{P_0 + M/t}{\alpha \int_0^t TD(u)\, du/t}$$

In particular the maximal PQ possible, expressed in terms of the average task demand over $[0, t]$ is

$$PQ_{max} = \frac{P_0 + M/t}{\alpha \int_0^t TD(u)\, du/t}$$

This formula can be used by the software agent to determine the maximal stable PQ directly, using an estimation of the expected average task demand.

The logistic case
For the logistic case the following is obtained:

$$p(PQ, TD) = TD - (1/\sigma) \log(1/PQ - 1)$$
$$\int_0^t P(u)du = \int_0^t (TD(u) - (1/\sigma) \log(1/PQ - 1))du$$
$$= \int_0^t TD(u)\, du - ((1/\sigma) \log(1/PQ - 1)) * t$$

This provides the following inequalities:

$$P_0 - M/t \leq \int_0^t P(u)du/t \leq P_0 + M/t$$
$$P_0 - M/t \leq \int_0^t TD(u)\, du/t - ((1/\sigma) \log(1/PQ - 1)) \leq P_0 + M/t$$
$$P_0 - M/t - \int_0^t TD(u)\, du/t \leq -((1/\sigma) \log(1/PQ - 1)) \leq P_0 + M/t - \int_0^t TD(u)\, du/t$$
$$\sigma (P_0 - M/t - \int_0^t TD(u)\, du/t) \leq -\log(1/PQ - 1) \leq \sigma (P_0 + M/t - \int_0^t TD(u)\, du/t)$$
$$-\sigma (P_0 + M/t - \int_0^t TD(u)\, du/t) \leq \log(1/PQ - 1) \leq -\sigma (P_0 - M/t - \int_0^t TD(u)\, du/t)$$
$$e^{-\sigma (P_0 + M/t - \int_0^t TD(u)\, du/t)} \leq 1/PQ - 1 \leq e^{-\sigma (P_0 - M/t - \int_0^t TD(u)\, du)}$$
$$1 + e^{-\sigma (P_0 + M/t - \int_0^t TD(u)\, du/t)} \leq 1/PQ \leq 1 + e^{-\sigma (P_0 - M/t - \int_0^t TD(u)\, du)}$$
$$\frac{1}{1 + e^{-\sigma (P_0 - M/t - \int_0^t TD(u)\, du)}} \leq PQ \leq \frac{1}{1 + e^{-\sigma (P_0 + M/t - \int_0^t TD(u)\, du/t))}}$$

In particular, for this case the maximal PQ possible, expressed in terms of the average task demand is

$$PQ_{max} = \frac{1}{1 + e^{-\sigma (P_0 + M/t - \int_0^t TD(u)\, du/t)}}$$

4) Results

Table 2 shows the maximum stable *PQ* in all three scenarios, for both the logistic case and the proportional case. Exhaustion (scaled between *0* and *1*) and maximal *PQ* are shown for both the constant task demands (Figure 7) and the variable task demands (Figure 8) long track scenario. As the logistic and the proportional case both showed the same trend, the graphs only display the logistic case.

TABLE II. MAXIMUM EQUAL PERFORMANCE QUALITY

Case	*PQ* logistic	*PQ* proportional
ShortTrack	*0.88*	*0.835*
Long Track, Constant *TD*	*0.57*	*0.55*
Long Track, Variable *TD*	*0.55*	*0.535*

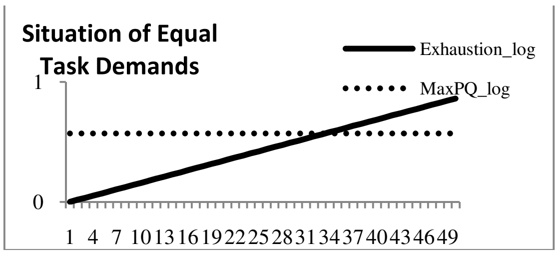

Figure 7 Exhaustion and Performance Quality: Constant Task Demands.

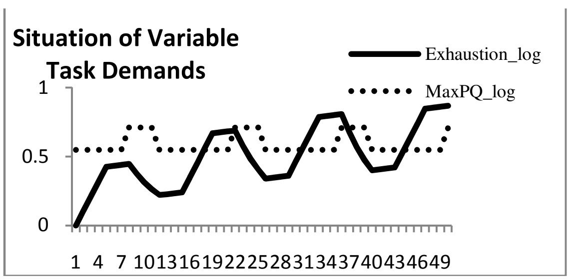

Figure 8 Exhaustion and Performance Quality: changing Task Demands.

In Figure 7 can be seen that exhaustion builds up in a constant manner, as an equal amount of extra power is contributed at each time point. Fluctuation of exhaustion can be seen in Figure 8. Here, at all time points *PQ* is *0.55*. However, when task demands are low, the *PQ* that hypothetically can be achieved without the contribution of extra power is higher. As a consequence there will be recovery, which will cause a decrease in exhaustion.

VI. DISCUSSION

In this paper a generic human agent model to analyse human performance has been presented, based on the idea that performance degrades with increasing task demands according to a specific pattern. From the literature, it becomes clear that the relation between effort and performance is not trivial. The presented human agent model can be used with different types of descriptions of the relation between effort, task demands and performance quality. Two different special cases of degradation curves are distinguished and elaborated in this paper.

The generic human agent model can be used within an intelligent software agent supporting the human. By specialising the generic human agent model with specific choices based on the task and its characteristics, it allows a software agent equipped with the model to reason in a number of ways about the situation and required support for the human. Two example scenarios have shown the applicability of the generic human agent model. One example illustrated how both a heuristic approach and an analytical approach can be used to predict the maximum performance quality given some task demands.

Further research is planned to actually apply the generic human agent model. For a specific task at hand the relationship between power, task demand and performance has to be studied closely. For this purpose, an experiment can be conducted where human subjects perform different tasks. The resulting relation can then be used within the generic human agent model.

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