Computational Modeling and Analysis of the Role of Physical Activity in Mood Regulation and Depression

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Abstract. Physical activity is often considered an important factor in handling mood regulation and depression. This paper presents a computational model of this role of physical activity in mood regulation. It is shown on the one hand how a developing depression can go hand in hand with a low level of physical activity, and on the other hand, how Exercise Therapy is able to reverse this pattern and make the depression disappear. Simulation results are presented, and properties are formally verified against these simulation runs.

Keywords: Mood and emotions, physical activity, depression, personal assistant agent

1 Introduction

Avoiding negative moods may be a nontrivial challenge faced by a human organism. In the richer countries the number of persons struggling with longer periods of negative moods, like in a depression, is relatively high, and is expected to increase further (cf. [23]). To avoid or to recover from a negative mood requires mechanisms for mood regulation. Within neurological literature, mechanisms are investigated by which mood regulation takes place; for example, [9, 21]. In particular, also dysfunctioning of these mechanisms in persons in a depression is analyzed, for example in [1, 2, 19, 22, 24]. A specific area that receives more attention recently is the way in which brain functioning interacts with the amount of physical activity of a person; for example, it has been shown that a substantial level of physical activity has a positive effect on mood and brain plasticity; e.g., [8, 11, 12]. Indeed, it is known that physical exercise may be an effective way for humans to improve mood (cf. [4, 8]). In particular, this has been studied for the case of mood regulation mechanisms in depressions, among others by using an animal model for human learned helplessness; e.g., [15, 16, 17, 18, 25]. It turns out that the extent of learned helplessness can substantially decrease when more physical activity is undertaken. It has been shown that persons who perform a substantial amount of physical exercise suffer from depression less frequently (cf. [14]); therapies based upon physical exercise are reported, for example in (cf. [8, 13]) and are found to be probably effective (for meta-analyses e.g. [20, 10]).

Computational models of mechanisms for mood regulation are rather rare; one example is [6]. Such a model can be used to analyse how, and to which extent different therapies can achieve a desired effect, as was shown in [7]. However, physical activity and its effect on mood and depression is not addressed this model. In this paper, inspired by the literature on the relevant biological mechanisms, a computational model is presented which models the role of physical exercise in mood regulation; the presented model subsumes the model described in [6] as well. Moreover, a therapy which is based upon performing physical exercise has also been integrated in the model to show how the principles and the workings of these therapies can be simulated and analyzed using the model. Example simulations that have been performed are presented to illustrate the functioning of the model, and the results have been analyzed by verifying particular desired properties against the simulation traces that have been generated.

This paper is organized as follows. In Section 2 the model for mood regulation and depression as taken from [6] is explained in more detail. The connection with physical exercise is introduced into the model in Section 3. Section 4 presents simulation results, whereas Section 5 verifies that these results indeed comply with existing theories within clinical psychology. Finally, Section 6 is a discussion.

2 A Model for the Role of Physical Activity in Mood Regulation

In this section it is discussed how the role of physical activity in mood regulation can be modeled computationally. In order to model the role of the physical activity, four states are distinguished, and the causal relationships between them and with other states in the mood regulation process are described. Among the represented relevant aspects are, for example, the impulse to undertake physical activity, the effect of physical activity on physical state, and the effect of physical state on mood, as indicated in the literature. These states and causal relationships are combined with other states and relationships in a mood regulation process. The latter types of states and relationships have been adopted from an existing mood regulation model based on psychological and neurological literature, in which physical activity and states were not covered (cf. [6]). Furthermore, in Section 3 the main effects of interventions by Exercise Therapy upon mood and depression are modeled in order to simulate and analyze effects of such a therapy.

Figure 1 shows an overview of the relevant states within the model and the relations between the states. In the figure, the states and lines that are depicted in grey represent states from the original model from [6]. States and dashed lines in black have been added to model the points of impact of the interventions as described in [7]. The thick black states and solid black lines represent the additional physical states.

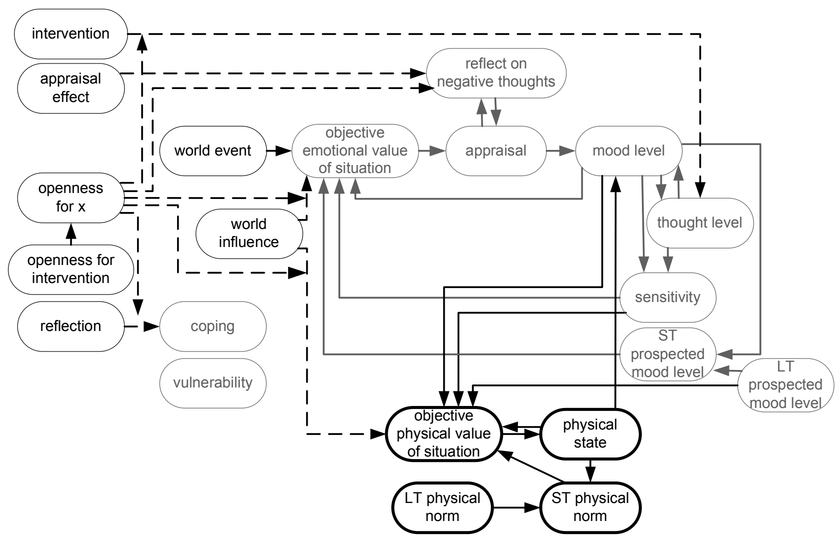

Fig 1. Model for mood and depression (grey states and lines indicate the original model [6], dashed lines and black states indicate intervention influences from [18], the thick black states represent the additional physical characteristics).

States directly related to physical action. In order to model the role of physical activity of a person, four states are introduced. First, the *physical state* of a human is used, which expresses a combination of physical properties that are influenced by exercise: endorphin, monoamine and cortisol levels [12]. Exercise itself is represented in *objective physical value of situation*, the value of the current physical situation the human is in. The *long term physical norm* (or *LT physical norm*) expresses what physical state the human is striving for in the long term, whereas the *short term physical norm (or ST physical norm*) represents the goal for physical state on the shorter term. Each state is represented by a number in the interval [*0,1*].

States not directly related to physical action. In addition to these states representing aspects of the processes directly related to physical activity, a number of other states relevant for mood regulation are used, adopted from the existing model in [6]. The *mood level* represents the current mood of the human, whereas *thoughts level* the current level of thoughts (i.e. the positivism of the thoughts). The state *objective emotional value of situation* represents the value of the situation a human is in (without any influence of the current state of mind of the human). The state *appraisal* represents the current judgment of the situation given the current state of mind (e.g. when you are feeling down, a pleasant situation might no longer be considered pleasant). The *long term prospected mood level* expresses what mood level the human is striving for in the long term, whereas the *short term prospected mood level* represents the goal for mood on the shorter term (in case you are feeling very bad, your short term goal will not be to feel excellent immediately, but to feel somewhat better). The *sensitivity* indicates the ability to select situations in order to bring the *mood level* to the *short term prospected mood level*. *Coping* expresses the ability of a human to deal with negative moods and situations, whereas *vulnerability* expresses how vulnerable the human is for getting depressed. Finally, *world event* indicates an external situation which is imposed on the human (e.g., losing your job). In addition to the states mentioned above, in [7] a number of states have been added to the model in [6] that relate to therapeutical interventions. First, a state representing the intervention (i.e., *intervention*) expressing that an intervention is taking place. The state *reflection on negative thoughts* expresses the therapeutic effect that the human is made aware of negative thinking about situations whereas the *appraisal effect* models the immediate effect on the appraisal of the situation. The *world influences* state is used to represent the impact of a therapy aiming to improve the *objective emotional value of situation* and possibly the *objective physical value of situation*. The *openness for intervention* is a state indicating how open the human is for therapy in general, which is made more specific for each specific influence of the therapy in the state *openness for X*. Finally, *reflection* represents the ability to reflect on the relationships between various states, and as a result learn something for the future.

Dynamics directly related to physical activity. The states as explained above are causally related, as indicated by the arrows in Figure 1. These influences have been mathematically modeled. The *physical state* is regulated towards the *long-term physical norm* by choosing physical situations (*opvs*) that help increase or decrease the physical state towards the *short-term physical norm*. The long-term physical norm *lt_physnorm* is considered a personal characteristic. The *ST physical norm* is determined as follows: *physical state* can have an increasing or a decreasing influence, the *LT physical norm* has a regulating function.

$$st\_physnorm(t+\Delta t) = st\_physnorm(t) + (vulnerability \cdot (phys\_state(t)-lt\_physnorm) + coping \cdot (lt\_physnorm-st\_physnorm(t))) \cdot \Delta t$$

The *objective physical value of situation* (*opvs*) is calculated in two steps. First, the change in *opvs* is *calculated based* on a physical regulation part using *physical state* and *ST physical norm* (*action_p1*) and a *mood* influence part (*action_p2*). When *mood level* is lower than *LT prospected mood level*, the action will have a lower value and therefore the human is less capable of choosing appropriate situations to increase the *physical state*. This models the idea that persons with a depression tend to be less physically active [14].

$$action\_p1 = opvs(t) + sens(t) \cdot (Neg(opvs(t) \cdot (st\_phys\_norm(t)-phys\_state(t))) + Pos((1-opvs(t)) \cdot (st\_phys\_norm(t)-phys\_state(t))))$$

$$action\_p2 = opvs(t) + (1-sens(t)) \cdot (Neg(opvs(t) \cdot (mood(t)-prospmood)) + Pos((1-opvs(t)) \cdot (mood(t)-prospmood)))$$

$$action\_p(t) = w_{phys\_reg} \cdot action\_p1 + w_{mood} \cdot action\_p2$$

Second, the new *opvs* is determined using the action from above and influence from the world to do physical activities (*world influence*).

$$opvs(t+\Delta t) = opvs(t) + ((action\_p(t) + openness(t) \cdot world\_influence\_p(t) \cdot (1- action\_p(t))) - opvs(t)) \cdot \Delta t$$

Physical state is affected by *opvs*. The adaptation factor *adapt_phys* determines the speed with which the *physical state* changes.

$$phys\_state(t+\Delta t) = phys\_state(t) + adapt\_phys \cdot (opvs(t)-phys\_state(t)) \cdot \Delta t$$

Dynamics not directly related to physical activity. Next, a number of relations adopted from the model described in [6] are briefly discussed. The *objective emotional value of situation (oevs)* represents the situation selection mechanism of the human. First, the change in situation as would be selected by the human is determined (referred to as *action* in this case) as an intermediate step:

$$action(t) = oevs(t) + sensitivity(t) \cdot (Neg(oevs(t) \cdot (st\_prosp\_mood(t)-mood(t)) + Pos((1-oevs(t)) \cdot (st\_prosp\_mood(t)-mood(t))))$$

In the equation, the *Neg(X)* evaluates to *0* in case *X* is positive, and *X* in case *X* is negative, and *Pos(X)* evaluates to *X* in case *X* is positive, and *0* in case *X* is negative. The formula expresses that the selected situation is more negative compared to the previous *oevs* in case the *short term prospected mood* is lower than the current mood and more positive in the opposite case. Note that the whole result is multiplied with the *sensitivity*. The *action* in combination with the external influences now determines the new value for *oevs*:

$$oevs(t+\Delta t) = oevs(t) + (world\_event(t) \cdot (action(t) + openness(t) \cdot world\_influence(t) \cdot (1 – action(t))) - oevs(t)) \cdot \Delta t$$

The above equations basically take the value of actions as derived before in combination with the external influences (i.e. *world influence* and *world event*). The second step is that the human starts to judge the situation (i.e. *appraisal*) based upon his/her own state of mind:

$$appraisal(t+\Delta t) = appraisal(t) + \alpha\, (\gamma + openness\_intervention(t) \cdot reflect\_neg\_th(t) - appraisal(t))\, \Delta t$$

where

$$\gamma = (vulnerability \cdot oevs(t) \cdot thoughts(t) + coping \cdot (1 - (1-oevs(t)) \cdot (1-thoughts(t))))$$

The value of *appraisal* is determined by the *thoughts* of the human in combination with the *coping* skills and *vulnerability*. In addition, the intervention related state *reflection on negative thoughts* plays a role (i.e. being aware that you are judging the situation as more negative than a person without a depression) in combination with the openness to this type of intervention. The state *reflection on negative thoughts* is calculated as follows:

$$reflect\_neg\_th(t) = (basic\_reflection(t) + appraisal\_effect(t) \cdot openness\_X(t)) \cdot (1 - appraisal(t))$$

Hence, the value increases based upon the *appraisal effect* of the intervention in combination with the *openness* to this specific part of the intervention. Furthermore, a *basic reflection* is expressed, which is the reflection already present in the beginning. Therapy can also dynamically change this *basic reflection* which can be seen as one of the permanent effects of therapy:

$$basic\_reflection(t+\Delta t) = basic\_reflection(t) + \alpha \cdot intervention(t) \cdot learning\_factor \cdot (1 - basic\_reflection(t))\Delta t$$

The value for *mood* depends on a combination of the current *appraisal*, the *thoughts* and the *objective physical value of situation (opvs)*, whereby a positive influence (i.e. *thoughts*, *appraisal* and *opvs* are higher than *mood*) is determined by the *coping* and the negative influence by the *vulnerability*.

Thoughts is a bit more complex, and is expressed as follows:

$$thoughts(t+\Delta t) = thoughts(t) + \alpha\,(\zeta + (1 - (thoughts(t) + \zeta)) \cdot intervention(t) \cdot w_{intervention}(t))\Delta t$$

where:

$$\zeta = Pos(coping \cdot (appraisal(t) \cdot w_{appraisal\_thoughts} + mood(t) \cdot w_{mood\_thoughts} - thoughts(t))) - Neg(vulnerability \cdot (appraisal(t) \cdot w_{appraisal\_thoughts} + mood(t) \cdot w_{mood\_thoughts} - thoughts(t)))$$

$$w_{intervention}(t+\Delta t) = w_{intervention}(t) + \alpha\,(openness\_X(t) - w_{intervention}(t))\Delta t$$

This indicates that *thoughts* are positively influenced by the fact that you participate in an intervention (you start thinking a bit more positive about the situation, you are in therapy). The weight of this contribution depends on the *openness* for the intervention at that time point. In addition, the *thoughts* can either be positively influenced due to the higher combination of the levels of *mood* and *appraisal* (again multiplied with the *coping*), or negatively influenced by the same state (whereby the *vulnerability* plays a role). The *sensitivity* is calculated in a similar manner (without the influence of therapy):

$$sensitivity(t+\Delta t) = sensitivity(t) + \alpha\,(Pos(coping \cdot (\eta - sensitivity(t))) - Neg(vulnerability \cdot (\eta - sensitivity(t))))\Delta t$$

where

$$\eta = mood(t) \cdot w_{mood\_sens} + thoughts(t) \cdot w_{thoughts\_sens}$$

The *short term prospected mood* is calculated as follows:

$$st\_prospmood(t+\Delta t) = st\_prospmood(t) + \alpha\,(vulnerability \cdot (mood(t) - lt\_prospmood) + coping \cdot (lt\_prospmood - st\_prospmood(t)))\Delta t$$

Dynamics of mood combining physical and nonphysical effects.
Finally, the *mood level* combines effects from different (physical and non-physical) sides, represented by the concepts defined above. The effect of the physical state models the positive influence of physical exercise on mood [4] and the effectiveness of Exercise Therapy [4, 8, 13, 14, 23 ,24].

$$mood(t+\Delta t) = mood(t) + \alpha\,(Pos(coping \cdot (\varepsilon - mood(t))) - Neg(vulnerability \cdot (\varepsilon - mood(t))))\,\Delta t$$

where

$$\varepsilon = appraisal(t) \cdot w_{appraisal\_mood} + thoughts(t) \cdot w_{thoughts\_mood} + phys\_state(t) \cdot w_{opvs\_mood}$$

3 Modeling Exercise Therapy for Mood Regulation and Depression

Exercise Therapy consists of a structured form of exercise, often prescribed together with another intervention and/or anti-depressant medications. Physical exercise has a positive influence on mood [4] and can therefore aid in the recovery from a depression [8, 13, 14, 20, 10].

Figure 2 shows the mood regulation and depression model with the influences of Exercise Therapy. *Appraisal effect* is shown in light grey, because Exercise Therapy does not influence this concept. Furthermore, arrows from *mood level* and *physical state* to *coping* are added, to represent the learning of coping skills by doing more physical activities.

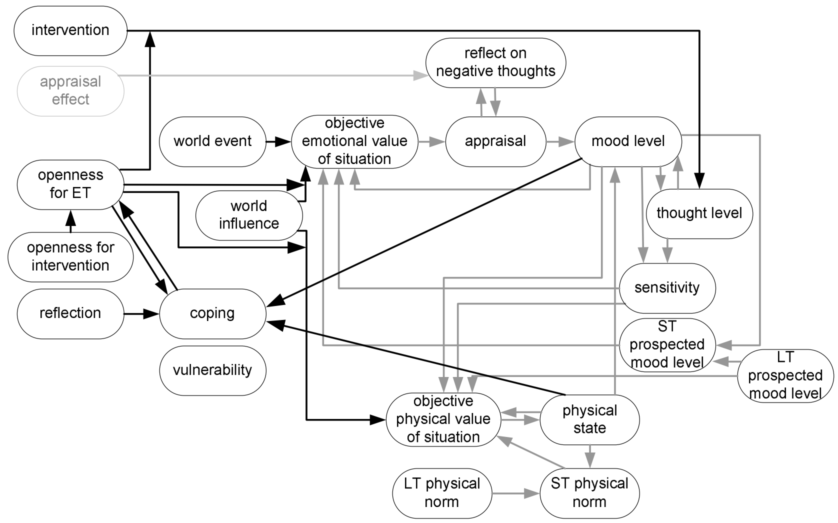

Fig. 2. Computational model for Exercise Therapy.

The intervention influences the human via four states: *thought level*, *objective physical value of situation (opvs)*, *coping* and *openness for ET*. The *thought level* is increased by the fact that the human is participating in an intervention, the formula is explained in Section 2. Second, the choice for a situation with a certain value for physical activeness (*opvs*) is influenced by *world influence*. Again, this effect is described in Section 2. The third effect of the intervention is on *coping skills*: learning the relationship between *mood* and *objective physical value of situation* results in better *coping* (as the human can now better cope with a lower mood since he/she knows that an option is to select more situations with a higher value for physical activeness). This is expressed as follows:

$$coping(t+\Delta t) = coping(t) + \alpha\ reflection(t) \cdot w_{reflection}(t) \cdot (1 - |opvs(t) - mood(t)|\ ) \cdot (1 - coping(t))\ \Delta t$$

where

$$w_{reflection}(t+\Delta t) = w_{reflection}(t) + \alpha\ (openness\_et(t) - w_{reflection}(t))\ \Delta t$$

When there is a moment of reflection in the therapy, the value for *coping* will increase as the difference between the *mood* and *opvs* is perceived small (which makes it easy to see the relationship and improve *coping*). The last effect is that the openness for the specific therapy increases as the coping skills go up (since the human notices that the therapy works). Theta (θ) is an adaptation factor determining the speed with which openness changes.

$$openness\_et(t+\Delta t) = openness\_et(t) + \theta \cdot ((coping(t) - coping(t-\Delta t))/\Delta t) \cdot \Delta t$$

4 Simulation Results

The computational model as described in Section 2 combined with Exercise Therapy (as presented in Section 3) is implemented in Matlab in order to run a number of simulations. For the simulations, three fictional persons are studied which are all susceptible for depression (low coping skills and high vulnerability) and a high openness for intervention. These persons are referred to as person 1, 2, and 3 respectively. The *LT physical norm* is set to low, medium, and high for person 1, 2, and 3 respectively. The values are chosen to show the effect of different physical norms on the mood level and on the influences of the therapy. In all traces, a world event with a very low value occurs at the beginning of the simulation (value 0.1 during 80 hours). For half of the simulations the intervention starts after two weeks of low mood and lasts for ten weeks. In the other half, no intervention is simulated.

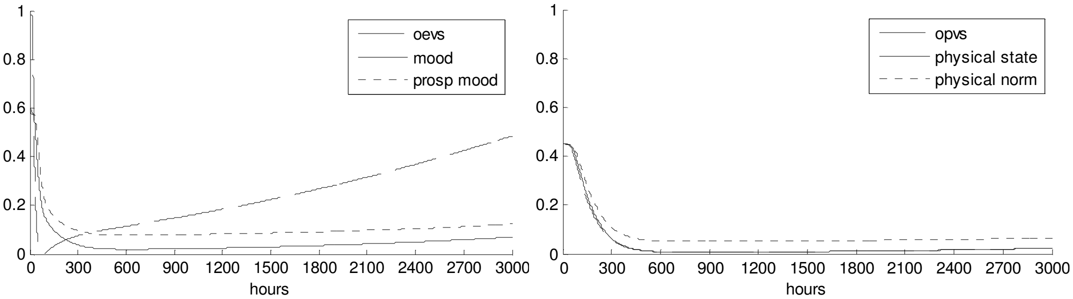

Fig 3. Simulation trace of person 1 (low value for *LT physical norm*) with no intervention. The left panel shows the mood related values; the right panel shows the physical state related values.

Figure 3 shows the simulation trace of person 1 (with a low *LT physical norm*) whereby no intervention is present. The panel on the right shows the values for *objective emotional value for situation*, *mood* and *ST prospected mood level*; the right graph shows the values for *objective physical value for situation*, *physical state* and *ST physical norm*. It can be seen that the person recovers very slowly from the negative event. Figure 4 shows the simulation run where the same person does follow the exercise therapy intervention, this results in a more rapid recovery. In Figure 5 person 3 (with a high *LT physical norm*) is shown, following the same intervention is. This results in a faster recovery compared to the person with a low physical norm.

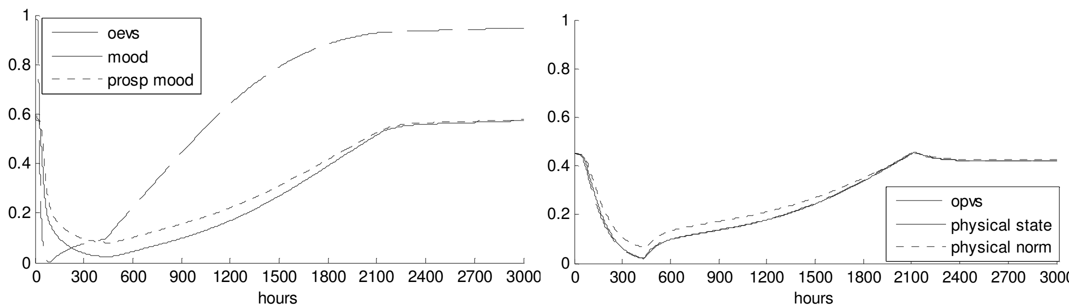

Fig 4. Simulation trace of person 1 (low value for LT physical norm).

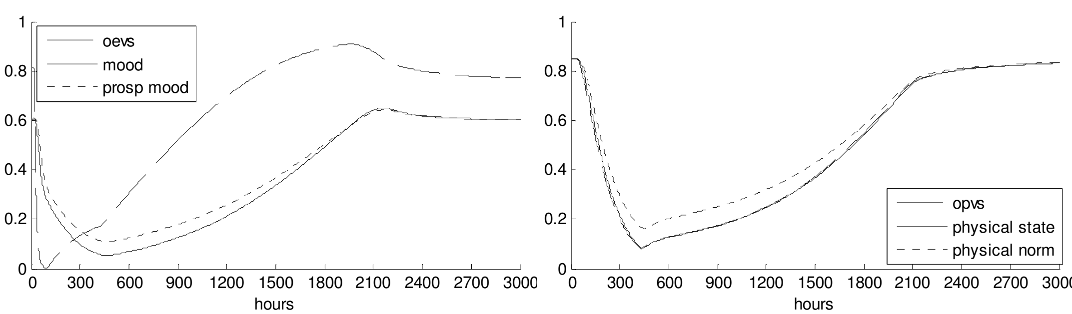

Fig 5. Simulation trace of person 3 (high value for LT physical norm).

5 Dynamic Properties and their Verification

A number of temporal properties that reflect a number of general patterns and characteristics of the process of depression and the treatment have been formulated. The properties were specified in the language TTL [5]. This predicate logical temporal language supports formal specification and analysis of dynamic properties, covering both qualitative and quantitative aspects. TTL is built on atoms referring to *states* of the world, *time points* and *traces*, i.e. trajectories of states over time. In addition, *dynamic properties* are temporal statements that can be formulated with respect to traces based on the state ontology Ont in the following manner. Given a trace γ over state ontology Ont, the state in γ at time point t is denoted by state(γ, t). These states can be related to state properties via the infix predicate |=, where state(γ, t) |= p denotes that state property p holds in trace γ at time t. Based on these statements, dynamic properties can be formulated in a sorted first-order predicate logic, using quantifiers over time and traces and the usual first-order logical connectives such as ¬, ∧, ∨, ⇒, ∀, ∃. For more details, see [5]. Automated tool support is also available that allows for dedicated editing and for verifying whether the properties hold in a set of simulation traces. A number of simulations (thereby considering the different types of persons mentioned in Section 4 in combination with Exercise Therapy or no intervention) have been used as basis for the verification. Some of the properties considered are the following.

P1: Effectiveness of Exercise Therapy

Persons that follow exercise therapy are depressed for a shorter period than persons who do not.

∀γ1, γ2:TRACE, ∀ t:TIME
[[state(γ1, t) |= intervention_ET & state(γ2, t) |= not intervention_ET]
⇒ ∃t2:TIME > t, R1,R2 :REAL [R1 < MIN_LEVEL & R2 > MIN_LEVEL &
state(γ2, t2) |= has_value(mood, R1) & state(γ1, t2) |= has_value(mood, R2)]

P2: A higher physical norm results in a shorter depression

Persons that have a higher long term physical norm remain depressed for a shorter period than those with a lower norm.

∀γ1, ∀γ2:TRACE, ∀ R1,R2: REAL, t:TIME
[[state(γ1 t) |= has_value(phys_norm,R1) & state(γ2 t) |= has_value(phys_norm,R2) & R2 < R1)]
⇒ ∃t2:TIME, R3,R4 :REAL [R3 < MIN_LEVEL & R4 > MIN_LEVEL &
state(γ2, t2) |= has_value(mood, R3) & state(γ1, t2) |= has_value(mood, R4)]

P3: Effect of exercise therapy on coping skills

After a person has followed exercise therapy for some time, the coping skills have improved.

∀γ:TRACE, t:TIME, R1:REAL
[[state(γ, t) |= intervention_ET & state(γ, t) |= has_value(coping, R1)]
⇒ ∃t2:TIME > t + MIN_DURATION, R2 :REAL [R2 > R1 + MIN_INCREASE & state(γ, t2) |= has_value(coping, R2)]

P4: Effect of exercise therapy on physical state

After a person has followed exercise therapy for some time, his physical state is higher than the physical state of person that did not follow exercise therapy

∀γ1, γ2:TRACE, ∀ R1,R2: REAL, t1, t2:TIME
[[state(γ1, t1) |= intervention_ET & state(γ2, t1) |= not intervention_ET &
state(γ1, t2) |= has_value(physical_state, PS1) & state(γ2, t2) |= has_value(physical_state, PS2) &
T2 > T1 + MIN_DUR] ⇒ PS1 > PS2]

The first three properties were shown to be satisfied for the simulation traces as described in Section 4. The last one, however, did not satisfy. This can be explained by the fact that the physical norm has a large influence on the physical state in the long run. In other words, a person with a high physical norm can have a higher physical state without following exercise therapy, than a person that did follow exercise therapy but has a lower long term physical norm. For persons with the same level of physical norm, the property does hold.

6 Discussion

The computational model for the role of physical activity in mood regulation and depression introduced here shows a number of encouraging results. It shows how for certain types of persons a depression can develop when physical activity is low or absent. Moreover, it shows that by exploiting Exercise Therapy in order to increase physical activity the depression can disappear. Both types of effects show a gradual, pattern over time. This relates to an interesting discussion in the literature on how positive effects of physical activity can be explained, for example in [25]:

> 'Broadly, there are two possible types of explanation. One is that emotional benefits arise from the accumulation of acute mood improvement caused by the individual sessions of exercise. Accumulation of acute effects has been suggested by mainly anecdotal, single-case, or uncontrolled reports that have suggested that mood deteriorates rapidly when exercise regimes are interrupted (…). However, a theory based entirely on acute emotional effects is implausible because, as was argued above, exercise is likely to be aversive to many people, particularly at the start of training.' ([25], p. 42-43).

> 'The alternative to attributing the stress-reducing effects of exercise to the accumulation of acute effects is to suppose that a long-term process is recruited. One way to distinguish short-term from long-term effects is to study the effects of interruption of regular exercise. Whereas an acute effect should dissipate rapidly, a long-term effect would be expected to persist.' ([25], p.47)

In the model the choice has been made to define a direct impact of the physical state on mood, and not of the physical activity. This physical state accumulates prior physical activity. The result is indeed a longer term effect with some persistence. In this sense the model fulfills the requirements suggested in [25] as alternative explanation. It would also be not difficult to include as well direct effects in the model from physical activity or physical state to sensitivity and/or to coping and vulnerability. However, the fact that the dynamics of the current model already display the longer term effects as indicated in [25] suggests that this is not required.

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