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Reasoning about Adaptive Dynamical Systems in the Analysis of Eating Regulation Disorders

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Abstract

To analyse a subject's mental processes, psychotherapists often face nontrivial properties of adaptive dynamical systems. Analysis of dynamical systems usually is performed using mathematical techniques. Such an analysis is not precisely the type of reasoning performed in psychotherapy practice. In this paper it is shown how practical reasoning about dynamic properties of adaptive dynamical systems within psychotherapy can be described using dynamical logical methods and a high-level language to describe dynamics.

Introduction

Within the context of psychotherapy often types of human behaviour and development are addressed that are highly complex, dynamic and adaptive. Recently it has been suggested that the Dynamical Systems Theory (DST) could be an adequate tool for psychotherapists to describe and analyse such behaviours; e.g., (Kupper and Hoffmann, 1996; Levine, 1996; Tschacher, Scheier, and Grawe, 1998; Warren and Sprott, 2002). DST is a relatively new approach to describe the dynamics of cognitive processes; e.g., (Port and Gelder, 1995). Dynamical Systems Theory, which subsumes connectionist modelling, is able to model the temporal aspects of events taking place on a continuous time scale, such as, for example, recognition time, response time, and time involved in motor patterns and locomotion.

However, application of the DST approach in the practice of psychotherapy is not at all straightforward, and much remains to be done. A therapist's reasoning usually is performed in an informal, intuitive, partly conscious manner. Explanation of (at least parts) of this reasoning may take place in a qualitative, logical manner. In contrast, DST requires quantitative mathematical modelling, and analysis of dynamic properties is based on quantitative techniques from mathematics. This contrast between 'qualitative, logical' and 'quantitative, mathematical' makes it very difficult, if not impossible to use the DST approach as it is to adequately describe the manner in which reasoning about such an adaptive dynamical system in therapy practice takes place, or can take place in a systematic manner.

Within the areas of Computer Science and Artificial Intelligence recently alternative techniques have been developed to analyse the dynamics of phenomena using logical means. Examples are dynamic and temporal logic, and event and situation calculus; e.g., (Eck, et al. 2001; Kowalski and Sergot, 1986; Reiter, 2001). These logical techniques allow to consider and relate states of a process at different points in time. The form of these relations can cover qualitative aspects, but also quantitative aspects. As an example, Kupper and Hoffmann (1996) propose Kinetic Logic to stay close to the nature of reasoning in practice.

This paper illustrates the usefulness of such an alternative approach for the analysis and formalisation of adaptive dynamical systems. It addresses the use of adaptive dynamical systems in psychotherapy practice, in particular for the first phase of eating regulation disorders; e.g., (Beument et al., 1987; Garner and Garfinkel, 1985). In Delfos (2002), an adaptive dynamical model that describes normal functioning of eating regulation under varying metabolism levels is used as a basis for classification of eating regulation disorders, and of diagnosis and treatment within a therapy. Reasoning about the dynamic properties of this model (and disturbances of them) is performed in an intuitive, conceptual but informal manner.

In this paper, first this model is formalised in a high-level executable format, and some simulations are shown, both for wellfunctioning situations and for different types of malfunctioning situations that correspond to the first phase of well-known disorders such as anorexia (nervosa), obesitas, and bulimia. Next, as part of our analysis a number of relevant dynamic properties of this dynamical system are identified and formalised at different levels of aggregation: both for the regulation as a whole and for separate parts of the adaptive system. Using a software environment that has been developed, these properties have been checked for a number of simulation traces. Moreover, it is shown how these dynamic properties logically relate to each other, i.e., which properties at the lower level of aggregation together imply given properties at the higher level. Such logical relationships are especially important for the diagnosis of a malfunctioning system.

Modelling Approach

The domain of reasoning about dynamical systems in psychotherapy requires an abstract modelling form yet showing the essential dynamic properties. A high-level language is needed to characterise and formalise dynamic properties of such a dynamical system. To this end the

Temporal Trace Language TTL is used as a tool; for previous applications of this language to the analysis of (cognitive) processes, see (Jonker and Treur, 2002; Jonker and Treur, 2003a,b; Jonker, Treur, and Vries, 2002). Using this language, dynamic properties can be expresed in informal, semi-formal, or formal format. Moreover to perform simulations, models are desired that can be formalised and are computationally easy to handle. These executable models are based on the socalled '*leads to*' format which is defined as a sublanguage of TTL; for a previous application of this format for simulation of cognitive processes, see (Jonker, Treur, and Wijngaards, 2003). The Temporal Trace Language TTL is briefly defined as follows.

A *state ontology* is a specification (in order-sorted logic) of a vocabulary to describe a state of a process. A state for ontology Ont is an assignment of truth-values true or false to the set At(Ont) of ground atoms expressed in terms of Ont. The *set of all possible states* for state ontology Ont is denoted by STATES(Ont). The set of *state properties* STATPROP(Ont) for state ontology Ont is the set of all propositions over ground atoms from At(Ont). A fixed *time frame* T is assumed which is linearly ordered, for example the natural or real numbers. A *trace* $\mathcal{T}$ over a state ontology Ont and time frame T is a mapping $\mathcal{T}$: T → STATES(Ont), i.e., a sequence of states $\mathcal{T}_t$ (t ∈ T) in STATES(Ont). The set of all traces over state ontology Ont is denoted by TRACES(Ont). The set of *dynamic properties* DYNPROP(Ont) is the set of temporal statements that can be formulated with respect to traces based on the state ontology Ont in the following manner.

These states can be related to state properties via the formally defined satisfaction relation $\models$, comparable to the Holds-predicate in the Situation Calculus; cf. (Reiter, 2001): state($\mathcal{T}$, t) $\models$ p denotes that state property p holds in trace $\mathcal{T}$ at time t. Based on these statements, dynamic properties can be formulated , using quantifiers over time and the usual first-order logical connectives ¬ (not), & (and), ∨ (or), ⇒ (implies), ∀ (for all), ∃ (there exists); to be more formal: formulae in a sorted first-order predicate logic with sorts T for time points, Traces for traces and F for state formulae.

To model direct temporal dependencies between two state properties, the simpler 'leads to' format is used. This is an executable format defined as follows. Let α and β be state properties. Informally, α leads to β means:

> *if state property α holds for a certain time interval, then after some delay state property β will hold for a certain time interval.*

More formally, β *follows* α in trace $\mathcal{T}$, or $\alpha \twoheadrightarrow_{e,\,f,\,g,\,h} \beta$ holds for $\mathcal{T}$ with time delay interval [e, f] and duration parameters g and h if

$$\forall t1{:}\quad \forall t \in [t1 - g,\, t1) : \text{state}(\mathcal{T}, t) \models \alpha \;\Rightarrow$$
$$\exists d \in [e, f]\; \forall t \in [t1 + d,\, t1 + d + h) \;:\; \text{state}(\mathcal{T}, t) \models \beta$$

Conversely, the state property β *originates from* state property α in trace $\mathcal{T}$, or $\alpha \bullet\!\!-_{e,\,f,\,g,\,h} \beta$ holds in $\mathcal{T}$, with time delay in [e, f] and duration parameters g and h if

$$\forall t2{:}\quad \forall t \in [t2,\, t2 + h) \;: \text{state}(\mathcal{T}, t) \models \beta \Rightarrow$$
$$\exists d \in [e, f]\; \forall t \in [t2 - d - g,\, t2 - d) \;\; \text{state}(\mathcal{T}, t) \models \alpha$$

If both $\alpha \twoheadrightarrow_{e,f,g,h} \beta$, and $\alpha \bullet\!\!-_{e,f,g,h} \beta$ hold in trace $\mathcal{T}$, then α *leads to* β in trace $\mathcal{T}$; this is denoted by: $\alpha \bullet\!\!\twoheadrightarrow_{e,f,g,h} \beta$.

Local properties

Local properties are dynamic properties of the basic mechanisms in the dynamical model. Based on these properties the global properties of the system emerge; they together entail these global properties. Moreover, local properties are specified in an exectable 'leads to' format, useful to simulate the system; for simplicity, below the parameters e, f, g, and h have been left out. The first two properties characterise when a stimulus to eat is generated, based on an internal eat norm N that is maintained.

LP1 (eat-stimulus)

The first local property LP1 expresses that an eat norm N and an intermediate amount eaten E less than this norm together lead to an eat stimulus. Formalisation:

intermediate_amount_eaten(E) and eat_norm(N) and E < N
$\bullet\!\!\twoheadrightarrow$ stimulus(eat)

LP2 (not-eat-stimulus)

Local property LP2 expresses that an eat norm N and an intermediate amount eaten E higher than this norm together lead to an non-eat stimulus. Formalisation:

intermediate_amount_eaten(E) and eat_norm(N) and E ≥ N
$\bullet\!\!\twoheadrightarrow$ stimulus(do_not_eat)

The next three properties characterise the effect of eating

LP3 (increase of amount eaten)

Local property LP3 expresses how an eat stimulus increases an intermediate amount eaten by additional energy d (the energy value of what is eaten). Formalisation:

intermediate_amount_eaten(E) and stimulus(eat)
$\bullet\!\!\twoheadrightarrow$ intermediate_amount_eaten(E+d)

LP4 (stabilizing amount eaten)

Local property LP4 expresses how a non-eat stimulus keeps the intermediate amount eaten the same. Formalisation:

intermediate_amount_eaten(E) and stimulus(do_not_eat)
$\bullet\!\!\twoheadrightarrow$ intermediate_amount_eaten(E)

LP5 (day amount eaten)

Local property LP5 expresses that the day amount eaten is the intermediate amount eaten at the end of the day. Formalisation:

intermediate_amount_eaten(E) and time(24)
$\bullet\!\!\twoheadrightarrow$ day_amount_eaten(E)

Here time counts the hours from 1 to 24 during the day.

LP6 (weight through balance of amount eaten and energy used)

Local property LP6 expresses a simple mechanism of how weight is affected by the day balance of amount eaten and energy used. Here γ is a fraction that specifies how energy leads to weight kilograms. Formalisation:

day_amount_eaten(E1) and day_used_energy(E2) and weight(W)
$\bullet\!\!\twoheadrightarrow$ weight(W + γ * (E1 – E2))

The last local property characterises how the eat norm N is adapted.

LP7 (adaptation of amount to be eaten)

Local property LP7 expresses a simple (logistic) mechanism for the adaptation of the eat norm based on the day amount of energy used. Here α is the adaptation speed, β is the fraction of E that is the limit of the adaptation; normally β = 1. Formalisation:

day_used_energy(E) and eat_norm(N) and time(24)
•→→ eat_norm(N + α * N * (1 - N/βE))

Simulation Examples

A special software environment has been created to enable the simulation of executable models. Based on an input consisting of dynamic properties in 'leads to' format, the software environment generates simulation traces. Examples of such traces can be seen in Figure 1, 3 and 4. Here, time is on the horizontal axis, the state properties are on the vertical axis. A dark box on top of the line indicates that the property is true during that time period, and a lighter box below the line indicates that the property is false. These traces are based on all local properties presented above.

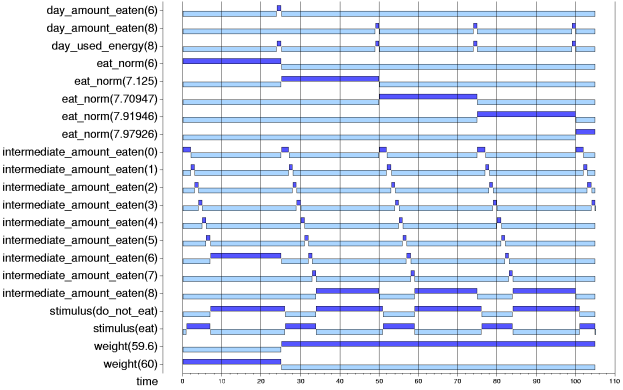

Figure 1 Simulation of a normal pattern

Certain parameters are the same in all three simulations. In the properties LP1 to LP5, the values (0,0,1,1) have been chosen for the timing parameters e, f, g, and h. In the properties LP6 and LP7, these values are (0,0,1,25); moreover, γ = 0.2 in LP6. The initial weight is always 60, the initial eat-norm is always 6, and the amount of energy used on each day remains 8. Thus, we are dealing with situations where initially the eat-norm is too low with respect to the energy used, and should be adapted accordingly. All simulations involve a period of 110 hours (i.e., slightly more than four days). In Figure 1, an example of a normal situation is shown (i.e., no eating regulation disorders are present). To simulate this, in the Norm Adaptation Property (LP7), α = 0.75 and β = 1; As can be seen in the figure, it takes some time before the eat-norm is correctly adapted to the amount of energy used, but in the end they are practically equal. As a consequence, the subject first undereats a little bit (6 units), causing a loss of 0.4 kilogram. However, within the next 24 hours she starts eating more (8 units). Subsequently, the eating pattern stabilizes, and so does the weight (at 59.6 kg).

The simulation of anorexia is based upon the assumption that anorexia in many cases is gen-related (Vink et al., 2001). This means that the signal 'stop eating', in this simulation translated into the 'stimulus(do-not-eat)', comes too early with respect to the amount of energy deployed. Delfos (2002) proposes that as a result of this condition, there exists an unconscious phase of slight underfeeding resulting in not gaining weight proportional to the growth and the risk of hampering growth. This first phase of anorexia, which can cover several years especially prepuberty, consists of a discrepancy between food eaten and energy deployed at an unconscious level; the person is not consciously trying to lose weight.

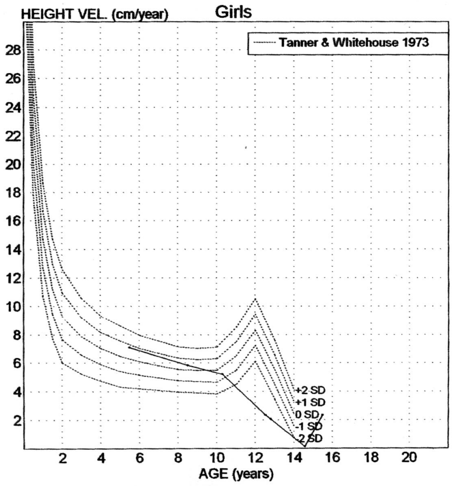

Figure 2 Height velocity pattern for anorexia

In Figure 2 the anorexia process is depicted in height velocity (cm/year). The girl entered the conscious phase of her eating disorder (anorexia) when she was nearly 13 years old. It was then that she began dieting. Within a year she was in a very bad medical condition. The height velocity however shows that the growth was stopped much earlier by a delay of puberty from age 10 on. After entering therapy when 14 years old, the height velocity recovered with the process of gaining weight.

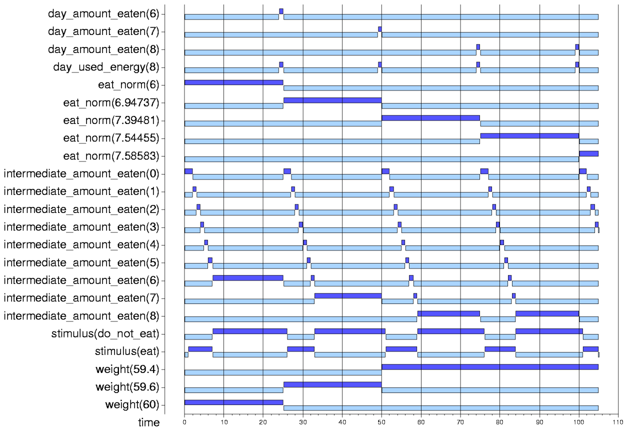

Figure 3 Simulation of the pattern of a person with anorexia

In Figure 3, a simulation of the eating pattern of a person within the first (unconscious) phase of anorexia is shown. To simulate this, in the Norm Adaptation Property, $\alpha = 0.75$ and $\beta = 0.95$. These settings result in an eat norm that converges a little bit to the amount of energy used, but this adaptation is not enough. The picture clearly demonstrates the consequences: the subject continuously eats an amount of food that is too low, compared to what she needs. Therefore, weight drops from 60 to 59.6 to 59.4, and this decreasing trend continues. A simulation of the dynamics of obesitas that has been performed (not shown) provides exactly the opposite pattern. In that case, the simulated subject continuously eats too much and gains weight.

As for bulimia there exists two kinds of situations. First the prephase of bulimia, in which the eating disorder exists at an unconscious level, and second the bulimia that evolves from consciously slight underfeeding or anorectic underfeeding that results in compensating urges of excessive eating.

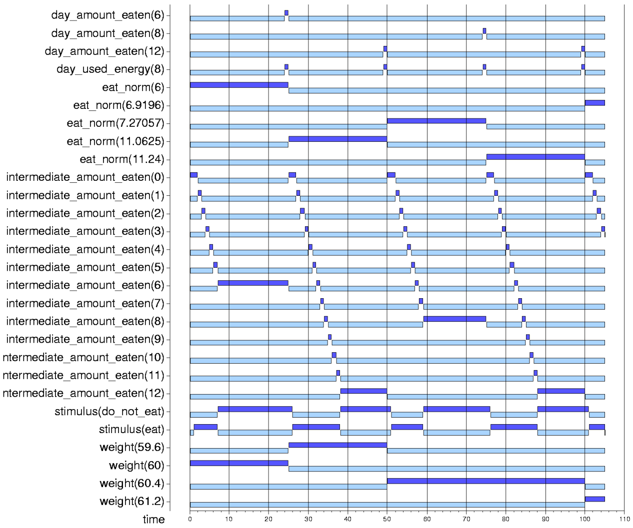

Figure 4 Simulation of the pattern of a person with bulimia

In Figure 4, a simulation of the eating pattern of a person in a prephase for bulimia is shown. To simulate this, in the Norm Adaptation Property, $\alpha = 2.25$ and $\beta = 1.2$. Especially the value of α is very important here, because it makes that the adaptation of the eat norm to the energy use is too sensitive. Thus, a norm that is too low will be increased, but this increment will be too big, so that the new norm is too high. This behavior can be seen in Figure 4, where the eat-norm keeps fluctuating somewhere between 6 and 12. This results in a very irregular eating pattern. Accordingly, the subject's weight fluctuates between 59 and 62. The risk of developing bulimia fully in the form as known in psychotherapy is present, and will become manifest as soon as the subject starts to attempt to correct these fluctuations by conscious decisions.

Analysis of Dynamic Properties of the System

In this section, dynamic properties of the system as a whole are identified (global properties). Moreover, to analyse the behaviour in specific circumstances, some environmental assumptions are expressed. The global dynamic properties can be logically related to the local properties presented above. To structure these relationships, intermediate properties are expressed; see also Figure 5.

Environmental properties

For the adaptive dynamical system, the amount of used energy is an exogenous variable, i.e., this comes from the environment. To be able to do analysis, it is convenient to consider certain simplifying assumptions on the environment. For example, to study limit behaviour, a suitable assumption is that from a certain point of time no changes occur in the used energy (EP2), or to study how the system behaves under one change, a suitable assumption is that only one change occurs in the environment (EP1). The latter type of environment may be used, for example, to study transitions occurring in subjects of around 35 years old, when the metabolism becomes slower, and hence the day amount of used energy will become lower. For each of the properties, first an informal description is given, and next the formal description that has been used for the automated checking software; see Discussion.

EP1(t1, t2, E1, E2) (Transition from one used energy E1 to another used energy E2)

This property EP1 expresses a very simple type of environmental change. First the day amount of used energy is constant at value E1, and next it is constant at (another) value E2. Formalisation:

For all $t < t1$ state(T, t) ⊨ day_used_energy(E1)
& for all $t \geq t2$ state($\mathcal{T}$, t) ⊨ day_used_energy(E2)

EP2(t, E) (Constant amount of used energy E from time t)

Property EP2 expresses that from a certain time point t the day amount of used energy is constant E. Formalisation:

For all $t' \geq t$ state($\mathcal{T}$, t') ⊨ day_used_energy(E)

Global properties

Global properties are dynamic properties of the process as a whole.

GP1(W, m) (Stable weight W, margin m, e.g., 2%)

Property GP1 expresses that fluctuations in weight are limited: within a relative m-interval of weight W. Formalisation:

For all t [state($\mathcal{T}$, t) ⊨ weight(W1) $\Rightarrow$ $-m \leq (W1 - W)/W \leq m$]

GP2(t1, t2, E1, E2, W, m) (Conditional constant weight W with margin m)

Property GP2 states that GP1 holds in environments in which only one change occurs in the day amount of used energy. Formalisation:

EP1(t1, t2, E1, E2) $\Rightarrow$ GP1(W, m)

GP3(t, E, d, e) (Adaptation of day amount eaten)
Property GP3 expresses that if the day amount of used energy is constant E after a time point t, then the day amount of food eaten will be in a relative d-interval of E. Formalisation:

For all t $\mathrm{EP2}(t, E) \Rightarrow \exists t'\ t \leq t' \leq t + e\ \&\ \mathrm{state}(\mathcal{T}, t') \models \mathrm{time}(24)\ \&$
$\forall E1[\mathrm{state}(\mathcal{T}, t') \models \mathrm{day\_amount\_eaten}(E1) \Rightarrow -d \leq (E1 - E)/E \leq d\ ]$

Intermediate properties

Intermediate properties are dynamic properties, normally fulfilled by parts of the dynamical system such that together they entail the global properties.

IP1(t, E, d, e) (Eat norm is adapting to used energy)
Intermediate property IP1 expresses that, if the day amount of used energy is constant after time point t, than, after some time the eat norm will be in a relative d-interval of E. Formalisation:

For all t $\mathrm{EP2}(t, E) \Rightarrow \exists t'\ t \leq t' \leq t + e\ \&\ \mathrm{state}(\mathcal{T}, t') \models \mathrm{time}(24)\ \&$
$[\mathrm{state}(\mathcal{T}, t') \models \mathrm{eat\_norm}(N) \Rightarrow -d \leq (N - E)/E \leq d\ ]$

IP2 (Eat stimuli)
Intermediate property IP2 expresses how the eat norm N and the amount of food eaten together determine whether or not an eat stimulus occurs. It is just the conjunction of LP1 and LP2. Formalisation: LP1 & LP2

IP3 (Day eating accumulation)
Intermediate property IP3 expresses how the day amount of eaten food is generated by following the eat stimuli during the day. Formalisation: LP3 & LP4 & LP5.

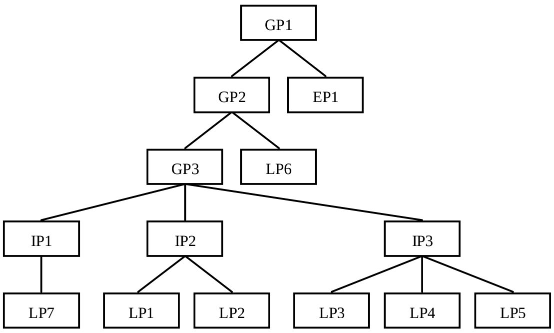

Figure 5 Interlevel relations between the dynamic properties

Interlevel Relationships Between Properties

The dynamic properties as identified in the section above describe the process at different levels of aggregation. The global properties describe the highest aggregation level: of the process as a whole. The local properties presented earlier describe the process at the lowest level of aggregation: the specific basic mechanisms. These properties are logically related in the sense that if a trace satisfies all local properties, then it also satisfies the global properties. To analyse these logical relationships between properties at different aggregation levels more systematically, properties at an intermediate aggregation level have been defined: the intermediate properties. Thus a set of properties at different aggregation levels was obtained that forms a connected set of properties with the following interlevel relationships:

EP1(t1, t2, E1, E2) & GP2(W, m) ⇒ GP1(W, m)
GP3(d, e) & LP6 ⇒ GP2(W, m)
IP1(d, e) & IP2 & IP3 ⇒ GP3(d, e)
LP7 ⇒ IP1(d)
LP1 & LP2 ⇒ IP2
LP3 & LP4 & LP5 ⇒ IP3

These interlevel relationships are graphically depicted by an AND-tree in Figure 5. Here the property at any parent node is implied by the conjunction of the properties at its children nodes.

Diagnostics Based on Failing Analysis

The interlevel relations as depicted in Figure 5 provide a formalisation of a basis for a form of diagnostic reasoning that is sometimes applied in therapy practice. This reasoning runs as follows. Suppose the top level property GP1 fails (*e.g., non-stable weight).* Then due to the logical interlevel relations, one level lower in the tree either EP1 fails (*e.g., strongly fluctuating metabolism*) or GP2 fails. Suppose GP2 fails. Then one level lower either LP6 fails (*e.g., insufficient food uptake by digestion*) or GP3 fails. Suppose GP3 fails. Then either IP2 fails (*e.g., no effect of eatnorm on eating*) or IP3 fails (*e.g., eating no adequate food in the sense of energy-content*) or IP1 fails. Suppose IP1 fails. Then LP7 fails (*e.g., no adequate adaptation mechanism of eat norm to energy use*). Subsequently the type of failure of LP7 can be identified depending on whether weight is systematically too low or decreasing (first phase anorexia), too high or increasing (first phase obesitas) or fluctuating (first phase bulimia).

Discussion

Two software environments have been developed to support the research reported here. First a simulation environment has been used to generate simulation traces as shown. Second, checking software has been used that takes traces and formally specified properties and checks whether a property holds for a trace.

	trace 1	trace 2	trace 3	trace 4	trace 5
EP1	+	+	+	+	+
EP2	+	+	+	+	+
GP1	+	-	-	-	-
GP2	+	-	-	-	-
GP3	+	-	-	+	-
IP1	+	-	-	+	+
IP2	+	+	+	+	+
IP3	+	+	+	+	-
LP1	+	+	+	+	+
LP2	+	+	+	+	+
LP3	+	+	+	+	-
LP4	+	+	+	+	+
LP5	+	+	+	+	+
LP6	+	+	+	-	+
LP7	+	-	-	+	+

Table 1 Results of checking properties against traces

The results for checking the properties on a number of these traces are as depicted in Table 1. The parameters used were as follows: W = 60, E = 8, m = 0.02, d = 0.1 and e = 24. Here the first three traces are those depicted in Figs 1 to 3 respectively (normal, anorexia and bulimia). In traces 2 and 3 the adaptation mechanism is malfunctioning (LP7 is the cause of the problems). Trace 4 shows a pattern in which the eating regulation in principle functions well but there is insufficient food uptake by digestion (LP6 is the cause of the problems), whereas trace 5 shows a pattern in which the response on the eat stimulus is eating food without energetic value (LP3 is the cause of the problems). Notice that indeed for all these traces the interlevel relations of Fig. 5 hold.

In comparison to Executable Temporal Logic (Barringer et al., 1996) our simulation approach has possibilities to incorporate (real or integer) numbers in state properties, and in the timing parameters e, f, g, h. Similarly, our approach to analysis has higher expressivity than approaches in temporal logic such as (Fisher and Wooldridge, 1997). In comparison to Kinetic Logic, in our approach thresholds can be used but are not needed. Moreover, for Kinetic Logic no format is available to express more complex, non-executable dynamic properties as in our language TTL, nor analysis methods for these dynamic properties at different aggregation levels as described above.

The high-level model integrates both medical and psychological aspects of the process, and has proven its value by predicting and explaining many of the patterns observed in psychotherapy practice. A more detailed model based on a set of differential equations for more detailed physiological processes is hard to obtain due to the lack of detailed knowledge (and parameter values) at the physiological level. Furthermore, even if such a model could be constructed, it probably would be so complex that it is hard to handle for simulation and analysis. Moreover, such mathematical techniques are not compatible with the type of reasoning within psychotherapy practice.

Further work is underway to address further phases of eating regulation disorders, especially phases when the subject’s learned behaviour to cope with such a disorder becomes more dominant. One of the aims is to show how, for cases of a malfunctioning system, the types of therapy described in (Delfos, 2002) can lead to a modified dynamical system in which eating regulation is wellfunctioning.

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