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PSI: A Computational Architecture of Cognition, Motivation, and Emotion

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This article describes PSI theory, which is a formalized computational architecture of human psychological processes. In contrast to other existing theories, PSI theory not only models cognitive, but also motivational and emotional processes and their interactions. The article starts with a brief overview of the theory showing the connections between its different parts. We then discuss the theory's components in greater detail. Key constructs and processes are the five basic human needs, the satisfaction of needs using the cognitive system, including perception, schemas in memory, planning, and action. Furthermore, emotions are defined and the role of emotions in cognitive and motivational processes is elaborated, referring to a specific example. The neural basis of the PSI theory is also highlighted referring to the "quad structure," to specific brain areas, and to thinking as scanning in a neural network. Finally, some evidence for the validity of the theory is provided.

Keywords: PSI, cognitive architecture, computational theory, modeling, cognition, motivation, emotion, complex problem solving, dynamic decision making

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Forty-five years ago, Herb Simon (1967, p. 29) argued for the study of emotional and motivational influences on cognition: "Since in actual human behavior motive and emotion are major influences on the course of cognitive behavior, a general theory of thinking and problem solving must incorporate such influences."

Over the last several decades, impressive advances have been made in the formulation and modeling of human psychological processes. Human problem solving, for example, has been modeled in Newell's architecture SOAR (States, Operators, And Results; Newell, 1987; Newell & Simon, 1972; Rosenbloom, Laird, Newell, & McCarl, 1991); memory processes and performance have been modeled in Anderson's ACT-R theory (Adaptive Control of Thought – Rational, Anderson, 1990; Anderson & Lebiere, 2003); emotional processes have been modeled (see, e.g., Fellous & Arbib, 2005; O'Rorke & Ortony, 1994; Ortony, Clore, & Collins, 1988); and motivational processes have been modeled in a few architectures (Sun, 2009; EMIB of Michaud, 2002). Yet, the modeled theories focus primarily on either cognition *or* emotion *or* motivation. The goal of the current article is to discuss the interaction of cognitive, motivational, and emotional processes in the PSI architecture. In each section of this article, we will first discuss how other computational architectures—and we will focus primarily on the probably most widely known architectures ACT-R, SOAR, and connectionist models—view motivation or cognition or emotion, before we describe how these processes are implemented in PSI.

The PSI theory (Dörner, 1999), named after the Greek letter 'Ψ,' which is often used as an abbreviation for "Psychology," also addresses cognitive processes, but relates those to motivational and emotional processes, because those three processes always interact (e.g., when feeling duped, Vohs, Baumeister, & Chin, 2007). In our program modeling motivation, emotion, and cognition, PSI is conceptualized as an agent that actively learns how to adapt to a certain environment and to act in this environment following its own goals.

A theory can be described on three levels with different degrees of abstraction according to Dennett (1971, see Bach, 2009, p. viii): the physical level, which describes the physical-material make-up of the theory; the design level, which describes how the theory is designed regarding components, purpose, and functions; and the most abstract intentional level, which describes cognitive core concepts and content of the theory such as intentions and beliefs. The PSI theory encompasses all three levels, and thus is described on these differing degrees. The physical level includes only neurons and neural connections, which form the material-physical basis in PSI.[1] At the design level, the structure and processes of the PSI theory are specified and formalized.[2] With regard to the intentional level, PSI theory explains behavior in terms of motivations and intentions, emotions, perception, memory and sche-

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[1] Unfortunately and because of space limitations, we cannot show the neural representations of the discussed parts of the theory in this article in detail, except the section "Thinking as Scanning Process in the PSI Neural Network" (see for details Dörner et al., 2002, or Hämmer & Künzel's graphical neural simulator, DAS, 2003).

[2] A copy of the PSI program is available and can be downloaded (Dörner & Gerdes, 2004).

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mas, planning and problem solving, action-regulation, language, self-reflection, and so forth. In this article, we will primarily focus on the intentional level and outline the different content areas simulated in PSI and, more importantly, how they are related to each other and how they interact with each other in one common framework.

Overview: The Interaction of Motivation, Emotion, and Cognition in PSI

The core processes of PSI are motivation, perception, cognition, and action (see Dörner, 1999; Güss, 2001). Figure 1 shows the data structures and entities of PSI. More specifically, these involve needs in the hypothalamus, selection of a motive in the thalamus, perception of the situation in the environment and processing in the cortex, protocol memory in the hippocampus, long-term memory including model of the world in the cortex, and search for behavior programs to satisfy needs.[3] If behavior programs exist to satisfy needs, then they will be activated; if not, PSI will engage in planning. Planning occurs primarily in the prefrontal cortex.

Motivation

Motivational processes result from demands, which are represented in the hypothalamus and parts of the limbic system (arousal) in the lower part of Figure 1. The figure shows several "tanks." These tanks have inflow and outflow and different levels of "liquid" representing the degree to which needs are satisfied. If the tank is full, there is no demand. If the tank is not full, then there is a need, which is strongest when the tank is empty. PSI has five groups of needs: the existential needs (hunger, thirst, and pain avoidance); sexuality and the social need for affiliation (Crosier, Webster, & Dillon, 2012 on evolution and social networks); and two cognitive needs related to information and knowledge—the need for certainty related to unpredictability of the environment, and the need for competence related to inefficacy or incapability of coping with problems (Dörner, 2003). The need for competence is satisfied when PSI changes either an aspect of itself or its environment. The existential needs and the need for affiliation can also be found in Maslow's hierarchy of needs (Maslow, 1954).

The strength of a need is dependent on consumption, for example losing water as a result of perspiration or simply metabolism (thirst), or the information that something unexpected has happened (uncertainty), or that an intended action did not have the expected effect (lowers competence). This information increases the needs for water, certainty, and competence. One of these needs becomes the dominant need, which influences planning and actions—at least for a short time as interruptions and multitasking are quite frequent in human behavior, which is explained through the processes described in the following sections (see also Salvucci & Taatgen, 2011, on multitasking simulated in ACT-R).

The need that becomes the dominant motive is dependent on the expectancy–value principle.[4] Value represents the strength of the current need: the stronger the need, the higher the value. Expectancy refers to the estimated likelihood that a need will be satisfied in the current situation or near future and therefore is dependent on previous experiences. If one passes a mountain spring, the expectancy of satisfying the thirst motive is very high. If either value or expectancy are 0, the strength of the motive becomes 0 because of the multiplicative relationship of the two factors.

Even though one motive and its related goals guide PSI's behavior, PSI has other concurring motives and goals. Goals are situations that allow the reduction of demands, for example the just-described mountain spring, which allows the reduction of thirst. These are normally represented in the breadth of PSI's expectation horizon. If opportunities arise to satisfy another need, it might supersede the current motive and guide further actions. Opportunities can easily lead to interruptions of the current behavior, for example, the interruption of grading exams to drink from a coffee mug because thirst became the dominant motive for a short time. However, the stronger the current motive, the stronger the selection threshold along with the related inhibition of other motives (see below), and, therefore, the stronger the concentration on the current motive. Not only opportunities, but dangers, too, can lead to interruptions of the current behavior.

Perception

Perception is, to a great extent, determined by motivation. PSI perceives the environment according to hypotheses (see Hypercept-process in Dörner, 1999). These hypotheses allow the recognition of objects by comparing them with existing sensor schemas and also allow the recognition of events by comparing those with existing event schemas.[5] Hypotheses originate in long-term memory and are triggered by motivational information and previous experiences.

The perceptual process in PSI is a top-down and bottom-up process; Bottom-up because it is driven by characteristics of environmental stimuli; top-down because it is driven by hypotheses, which are a result of identification of parts of a schema stored in PSI's long-term memory (e.g., a chair is identified, therefore a table is expected to be nearby). If stimuli do not behave according to the hypotheses, or stimuli show characteristics that are incongruent with the hypotheses, or expected events do not happen, then the need for certainty arises in PSI. If uncertainty reduction becomes the actual motive, PSI starts to explore the stimuli to reduce this uncertainty by creating more accurate or more detailed (or both) schemas of these stimuli.

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[3] The relevant brain areas are discussed here only in general terms, and we are aware that these brain areas have multiple functions.

[4] The expectancy–value theory was developed to explain the selection of a decision alternative. According to the expectancy–value theory, the action alternative among several possibilities is selected which has the biggest product of value and likelihood of success. Adapting the theory to PSI, one among several needs in the hypothalamus is selected and becomes the dominant motive in the thalamus according to the product of strength and likelihood of success. This principle goes back to Tolman (1932), who speaks of expectancies, action–consequence contingencies, and the belief–value matrix. The theory was also part of Lewin's field theory in form of attractive or repulsive valences and forces in the field (1938) and was further developed (Feather, 1982; Vroom, 1964) and applied, for example, in the field of achievement motivation (e.g., Eccles, 2005).

[5] See also Förster and Dannenberg's GLOMOsys (2010) for the relationship of global versus local perceptual processing and the primacy of global processing.

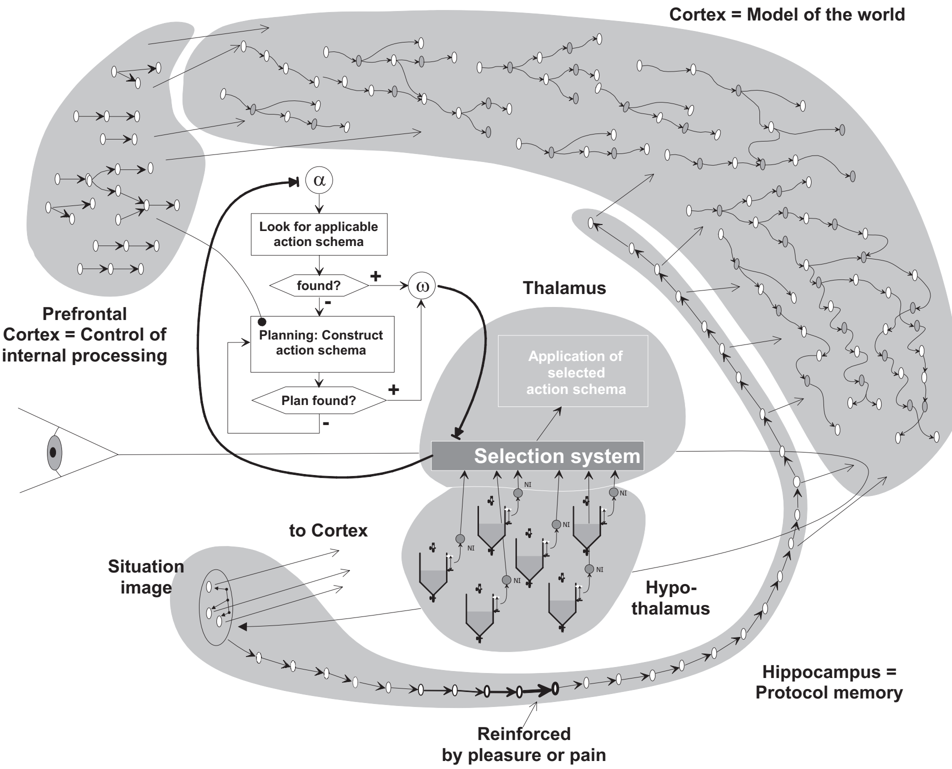

Figure 1. PSI architecture: Data and data processing in PSI and the related brain areas.

Problem Solving and Action Regulation

The current motive activates several internal processes that ultimately serve in reaching a goal and thereby satisfying the need. First, PSI scans the environment for possible goals and searches for known action sequences—represented as sensor-motor coordinations—that can lead PSI from the current situation to the goal. If those goals and action sequences do not exist, PSI starts to develop new plans. Planning refers to the creation of a new possible sequence of operations that could lead to the goal.

If PSI reaches a goal, the need is satisfied, the successful plan is stored (or reinforced) in long-term memory in an abstract form for future use, and the next need guides further actions. If, however, planning was not successful, that is, either a possible sequence could not be created or the developed plan could not be carried out, then PSI acts according to a trial-and-error maxim. PSI targets objects in the environment that it has not dealt with or that it does not know very well and tries to manipulate those objects to reach the goal. If these trial-and-error actions are not successful, PSI extends the trial-and-error principle to all possible objects. If these actions are not successful, PSI leaves the current situation. By that time, the general level of the competence in PSI is extremely low. General competence is a floating average of all successes and failures adjusted by need-specific weights. General competence is extremely important for the regulation of behavior, especially as it is responsible for most emotions (see below).

Emotion

Feeling distressed leads us to the emotions represented in PSI. Emotions guide memory processes, planning, and actions in PSI. They are represented as three parameters of information processing regulating internal processes, and they are represented additionally as behavior tendencies informing the person how to react to the outside world. Ultimately, emotions allow PSI to adapt to the current needs. The three parameters are resolution level, selection threshold, and activation.

Resolution level can be understood as the breadth and width of associations. If the resolution is deep and wide, then PSI has many ideas to choose from as it retrieves more information from long-term memory; if it is short and narrow, then PSI has few ideas to cull from the little information retrieved from long-term memory. In other words, if the resolution level is high during perceptual processes, then PSI compares environment and memory schemas very precisely; if the resolution level is low, then PSI perceives the environment superficially. There are specific uses for both levels. In a dangerous situation, for example, a low resolution level allows a quick scanning of the environment and a quick memory search facilitating quick action. If the resolution is high during planning, then PSI considers side- and long-range effects of possible actions and plans more elaborately. If the resolution level is low, then PSI develops only short-term plans.

A second modulation parameter closely related to resolution level is the selection threshold. If the selection threshold is high, PSI is concentrated solely on the current motive and other needs have little chance to become dominant. Opportunities and dangers are overlooked. If the selection threshold is low, PSI can be easily distracted and switches effortlessly between motives.

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The selection threshold is dependent on the third modulation parameter: general activation.[6] High activation is a result of a low competence level and leads to greater readiness for action. The higher the general activation, the higher the selection threshold, that is, the concentration on the current motive, and the lower the resolution level of perception and planning. This is especially important in dangerous situations when quick action is necessary at the cost of deliberation and energy conservation.

Besides the modulation parameters, behavior tendencies are a part of emotions regulating how the person reacts to the outside world. Examples of behavior tendencies are flight, aggression, or exploration. They result from the five needs, especially from the constellation of the competence and certainty needs. Low competence paired with low certainty, for example, will result in flight tendency. Medium to high competence paired with low certainty will result in aggression tendency.

One might ask: How are those modulation parameters and behavior tendencies related to emotion? We will clarify our position using an example. What happens when someone gets angry? Anger occurs when someone cannot reach an important or urgent goal. The feeling of general competence is medium and the need for efficiency signal increases. Anger means high activation and being ready for action. The selection threshold is high. The focus is only on the issue that caused the anger. The resolution level of perception and planning becomes very low. The consequence is quick action and risky behavior, perhaps aggression. What specific behavior tendency will be followed depends on the epistemic competence, that is, the specific acquired knowledge for how to deal with problem situations and reach goals. Thus, it is possible to describe anger as a specific combination of the three modulation parameters and specific behavior tendencies.

Memory

Perception occurs through sensor schemas, which identify and categorize objects in the environment, and through sensory-motor schemas, which categorize events. Actions are executed through motor schemas that are learned or genetically predetermined. A schema is a framework or organized setting influenced by previous experiences within which novel information can be interpreted (Bartlett, 1932).

Memory is created in PSI through a continuous protocol of perceptions and actions (see protocol chain in hippocampus in Figure 1). The head of the protocol chain is the image of the current situation and the actions that were performed. This protocol memory decays relatively fast, that is, PSI forgets the immediate past rather quickly if it is not reinforced. Whereas the protocol memory forgets relatively quickly, the decay of memory content in long-term memory is rather slow. Content of the protocol memory is reinforced when it is related to the creation or satisfaction of needs. When needs are satisfied, competence increases and PSI experiences pleasure; when needs arise, PSI feels discomfort. "Experiencing pleasure" means that PSI has a high degree of competence and hence has a positive expectation horizon. "Everything can be mastered." These appetitive or aversive reinforced memory contents are like islands in PSI's memory that together build its long-term memory.

This short overview discussed the various psychological systems and processes in PSI. Perception, needs and motivation, memory, learning, emotions, planning, and action regulation are all related to each other and are all brought together in PSI. We have shown how needs give rise to motives, which are related to the formulation of goals that PSI tries to achieve with different methods, such as trial-and-error or planning. Our assumption is that only the combination of all processes helps us to understand the human mind and behavior. Isolated models about human thought or human motivation cannot provide the whole picture.

Motivation

Motivation in Other Architectures

Probably the two most widely known cognitive architectures are SOAR (e.g., Newell, 1987) and ACT-R (e.g., Anderson & Lebiere, 2003). Both architectures provide models for how humans perform tasks. ACT-R does not have a motivational system, yet it has a goal module which keeps track of current goals. This goal module is linked to an intentional module in version ACT-R 5.0 and in version ACT-R 6.0. Yet this intentional module is not identified in both versions. The goal module is related to motivation, because it can direct further information processing such as whether during a math task more information should be retrieved or the math equation should be transformed.

Also SOAR models do not incorporate motivation. Like ACT-R, however, SOAR has goals that become activated when decisions are unsuccessful. When SOAR cannot select a problem-solving alternative or when there are several alternatives that seem equally promising then SOAR generates a goal to solve this impasse (Rosenbloom et al., 1991). The goal might be divided into subgoals which represent subtasks to be performed.

One architecture, CLARION, implemented motivations recently and described their important role in information processing (Sun, 2009). Although CLARION consists of several subsystems, we focus here solely on the motivational subsystem. According to Sun adding motivations in a cognitive architecture would help explaining where goals originate. Ultimately implementing motivations in an agent would allow addressing fundamental issues of survival such as sustainability, acting purposefully, maintaining focus, and adapting to a situation (Sun, 2009, p. 91).

Each subsystem in CLARION is divided in implicit and explicit representations. The motivational subsystem MS is divided in implicit drives and explicit goal structures. (The explicit goal structures can be found in ACT-R and SOAR as well). The implicit part of the MS consists of basic drives, needs, desires, intrinsic motives. Sun calls them all "drives," defined as "internally felt needs of all kinds that likely may lead to corresponding behaviors" (Sun, 2009, p. 93). Explicit goals are more long-lasting and allow persistence in actions. Thus the goal to "find food" could be based on the internal drive "being hungry."

The implicit drives are further divided in low-level primary drives, high-level primary drives, and secondary drives. Sun (2009, p. 94) distinguished SIX low-level primary drives: "food, water, sleep, avoiding physical dangers, reproduction, and avoid-

[6] General activation originates in the ascending reticular activating system (ARAS), which is partly located in the nuclei of the thalamus and the afferent and efferent connections to the cortex.

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ing unpleasant stimuli." He also adds several other drives such as "physical exercise, avoiding boredom, and so on." Sun mentions 11 high-level primary drives, mostly social drives, "affiliation and belongingness, recognition and achievement, dominance and power, autonomy, deference, similance, fairness, honor, nurturance, conservation, and curiosity" based on Murray (1938) and Reiss (2004). Secondary drives are acquired and changeable partly through conditioning and partly "through externally given instructions" (Sun, 2009, p. 97). As we will show, PSI also refers to needs and goals, but does not use the explicit/implicit distinction and only assumes five groups of needs.

Motivation in PSI

The tanks. Figure 2 shows several tanks, which symbolize the different needs of PSI. Each tank has an inflow and outflow and a certain level. A tank empties over time by consumption, which is dependent on basal metabolism and the activity of the organism. The tank level has a certain target value (set point) that should be maintained. As Figure 2 shows, however, the levels are currently below the set points, because the outflow was faster than the inflow. The deviation from the target value (set point) is called demand. If there is a signaled set point deviation, a need arises.[7] The extent of the need is shown as activity of the need-indicator (NI) of every tank. That means, "liquid" has to flow into the tank to again reach the set point. If a basic need arises, for example internal sensors signal a lack of glucose, PSI might start looking for food to satisfy this need. These tanks implement the basic homeostasis principle of motivation. Homeostasis means to maintain this balance in an agent in light of environmental influences.[8]

The pleasure–displeasure center. A signaled demand is called a need. A strong need sends a displeasure signal; once a need is satisfied, a pleasure signal is sent (similar to negative and positive reinforcement). The satisfaction or the increase of a need are registered in the competence tank and in the specific need tank. Pleasure happens as the competence tank is filled and displeasure occurs when the tank level drops below the set point. The purpose of this tank is to signal an evaluation of positive or harmful events related to the demands. Pleasure allows the strengthening of an association between need and successful action. This is important for the future. Whenever the need arises, the newly connected action can be activated and the need will be satisfied. Displeasure is related to situations that increase needs, for example a hot stove which, when touched, results in pain, or a snarling dog who might bite. The system can learn through displeasure what situations should be avoided.

Goals. A need indicates that something has to be done. A motive is a need plus a goal (situation, object) an organism should strive for to satisfy the need. Goals and the paths that lead to them can be learned. Goals are represented as sensor schemas in long-term memory. A goal can be related to either appetitive situations, and therefore a decrease in the need, or avoidance of aversive situations because they are related to an increase of the need.[9] For example, the thirst need becomes a motive when PSI sets a goal to reach (for instance) a mountain spring. Needs are used to identify objects and situations such as mountain springs or Fanta bottles. PSI associates goals to specific needs. The sensor schemas that represent goals are related to tank inflow; those schemas that represent danger or situations that should be avoided are related to tank outflow. Multiple goals are possible; we call them goal-amalgams. So for instance love could be defined as an amalgam of the need for affiliation, the need for sexuality, and the need for certainty ("He or she understands me!").

Thus, we have briefly described a system that has demands, needs, and motives and how those are related to memory. Differences are measured between current and target values, and ways are found to reduce this difference in order to reach the set point.

The motivational system. Human beings have different needs. Energy and water and other existential needs, such as pain avoidance, are important for the basic functioning of the body. Additionally there is the need of sexuality. There is the need for affiliation, to belong to a social group or network (for negative consequences of loneliness, see Cacioppo et al., 2000). Certain signals can satisfy the need for affiliation, such as smiling, embracing, or talking to each other. These are called "signals of legitimacy" (Boulding, 1978, p. 173). They indicate that an organism is accepted as a member of a group and can expect help and assistance. The last two needs are cognitive needs, the need for certainty and the need for competence. These two needs play a central role in emotions, as we will see. Certainty refers to predictability of the course of events and the effects of one's own actions. The "certainty tank" is filled by accomplished predictions and is emptied by events that are new or unexpected. If a need for certainty arises, PSI tries to explore the situation to better explain the unexpected event. This helps PSI to make future events more predictable.

The need for competence indicates the extent to which the organism feels capable of solving problems. The tank is filled through efficiency signals, for example every satisfaction of another need, the filling up of other tanks. When we eat well, sleep well, get enough L-signals (legitimacy-signals), then we feel competent, that is, we feel strong. A direct efficiency signal occurs as the result of solving a problem, for example the mastery of a difficult Mozart sonata without making a mistake or winning a chess game. The tank level lowers through inefficiency signals, for example, experiencing pain, making many mistakes performing the Mozart sonata, or losing a chess game.

This competence tank is very important because it tells PSI at any given moment whether it should dare to do something or not; it "tells" PSI how to act by setting behavior tendencies (we get

[7] It is necessary to distinguish between the demand and a need. The need is not necessarily identical to the demand, but can be defined as the sum of the demands over a certain time period.

[8] Feedback loops are relatively simple systems, but they can easily become more complex (see Bischof, 1968, 1995, on feedback loops, cybernetics, and psychology). We can, for example, explain human temperature regulation through a feedback loop with not only one, but three control factors, referred to as a cascade control. If body heat increases, first, vasodilation occurs, that is, the arteries and veins are enlarged to allow more blood flow in the body periphery. This allows a release of heat that leads to a decline of body heat. If the body heat is still not reaching the target value, then another mechanism occurs. The body starts to perspire. Perspiration evaporates on the skin and the overall body heat declines. If this second process is not enough to reach the target value of body temperature, a third mechanism could happen: an increase in heart rate, which again would increase the blood flow through the blood vessels.

[9] Lewin (1938) speaks in his topological and vectorial theory of attractive or repulsive valence of objects in the life space that either direct the person toward them or away from them.

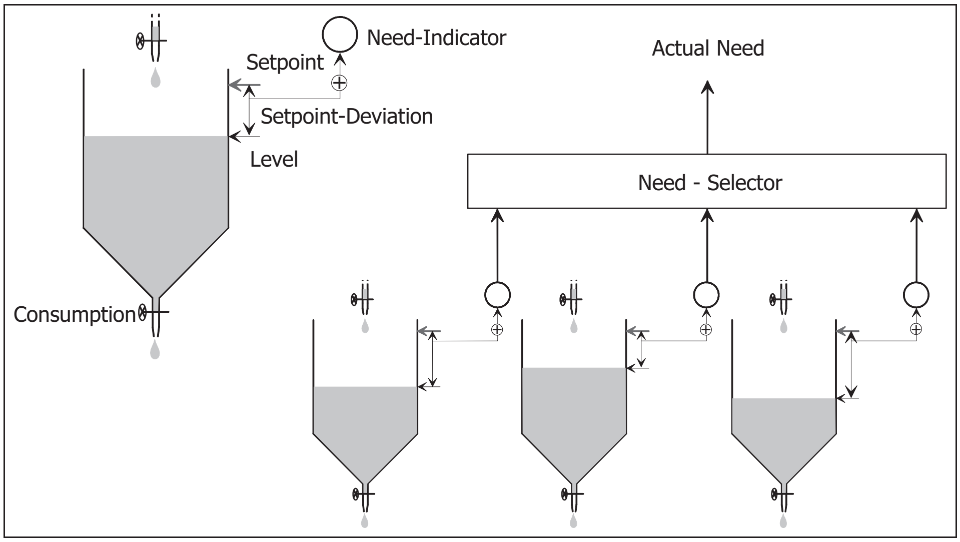

Figure 2. Needs and motive selection.

back to this point when we talk in more detail about emotions). If the competence tank is quite full, PSI is self-confident and might engage in more risky enterprises; it would not matter if the tank level dropped a bit. It might try to play a difficult Mozart sonata. If the level of the competence tank is already relatively low, PSI would not want to risk more drainage but, rather, would engage in actions that could lead to success and therefore a filling of the tank, for example playing Beethoven's relatively easy "Für Elise" or washing the dishes.

All these needs are represented in tanks (see Figure 2): the existential needs (hunger, thirst, pain avoidance, sleep), and the needs for sexuality and affiliation (need for group binding), certainty (need for predictability), and competence (need for mastery). Also, several needs might be active simultaneously. While walking one might become hungry (existential need) and, at the same time, wonder about a strange looking sculpture (certainty).

These five needs seem to be sufficient to explain human behavior.[10] But what about other needs? Stern (1958), for example, came up with a list of 30 needs in his activity index, and Reiss (2004) found 16 basic motives (see also Sun, 2009). And are there no needs for discovering the world's beauty? No need to lose oneself in deep admiration for Monet's impressionist water lilies or to listen devotedly to Dvorak's Symphony No. Nine "From the New World"? Is there no need to fall in love? We postulate that all of these and other complex human motivations can be explained through the above mentioned five basic needs, respectively by amalgams of motives (for detailed discussion about how love is based on the five needs, see Dörner, 1999). Observing a painting or listening to music is related especially to the need of uncertainty reduction. The process involves discovering parts of the painting or the melody and how these parts are related to other parts. It involves relating these impressions to associations in one's memory, for example, one's own experiences with water lilies, swimming in ponds, or embracing a loved one. Sure, this process can take time and become quite complex, but it is basically a dynamic process to reduce uncertainty further resulting in an increase in competence.

Motive selection. Organisms are "multistable systems" as Ashby (1960, p. 16) called them, meaning that they have to care for multiple feedback loops. Which need should be cared for first: food or water? To resolve such conflicts, one need becomes the dominant motive according to the expectancy–value principle. *Expectancy* stands for the estimated likelihood of success. The *value* of a motive stands for the extent of set point deviation (strength of need). If the hunger is very strong, the value of its satisfaction is very high. If one knows where to buy something to eat, the expectancy of success is very high. A fast-food place, for example, is a goal situation in which the respective tank can be refilled.

Such known situations or actions to reach goals make up the specific competence (also called epistemic competence). They are stored in long-term memory. If no knowledge is stored on how to satisfy the need—and often we are confronted with problems for which we do not know solutions—the likelihood for success is measured through general competence (also called heuristic competence), a reliance on heuristics, activities, and exploration to deal with novel situations. General competence can be understood as self-confidence and as a floating average over efficiency and inefficiency signals. General competence also influences motive

[10] Similar categories of needs/drives have been postulated, for example, by Sun (2002, 2009): the low-level primary drives get-food, get-water, avoid-danger, get-sleep, reproduce and a set of avoid saturation drives; the high-level primary drives belongingness, esteem, self-actualization; and derived secondary drives acquired through conditioning or externally set drives such as to conform. The low level primary drives are also part of PSI, where saturation is implemented in the form of feedback loops. High-level drives—although different ones—are represented in PSI in the needs for affiliation, certainty, and competence. The derived secondary drives are represented in PSI in the form of goals. Reiss (2004) came up with a list of 16 human motives analyzing more than 20,000 surveys. Those can also be summarized in our five basic needs: existential needs (eating, physical activity, tranquility), sexuality (romance), affiliation (acceptance, honor, social contact, family), certainty (order, savings, curiosity, idealism), and competence (power, status, independence, vengeance).

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selection through estimated likelihood of success even if a specific solution is known.

An additional factor that influences motive selection is urgency. Not reaching a goal within a given time would constitute an aversive goal. Urgency is a result of an estimation of how much time is needed to reach the goal measured against how much time is available to reach the goal. Of course, urgency is very high when the time available is just as much as the time estimated to be needed. Urgency is very low when the time needed is either less or much more than the time available.

To summarize, the motive strength to satisfy a demand *d* can be calculated mathematically as follows:

Motive Strength = Expectancy × Value.

Weighted Motive strength = $\text{Weight}_d \times (\text{general competence} + \text{specific competence}_d) \times (\text{need}_d + \text{urgency}_d)$.

Let's assume a range between 0 and 1 for expectation and value. Thus, the maximum range of the product can be also between 0 and 1 because of the multiplicative relationship of the two to three factors. This product is the motive strength. One could also add specific weights to the needs, because it seems plausible that existential needs, for example pain avoidance, should receive higher weights and become more easily dominant than, for example, the need for certainty. Multiplying these need-specific weights with expectation and value would result in weighted motive strengths. If two needs arise, the one with the higher product will be selected and guide further action.

The selection of the motive that governs behavior is continually recalculated so that another motive can take over control any moment. Parallel processing (Bechtel & Abrahamsen, 2002; McClelland, 1985) of demands and needs is always happening in PSI and allows for another motive to take over. However, a continuous change between motives would lead to oscillating behavior, that is, a started action would be easily and frequently interrupted. To avoid such oscillations, we added the parameter "selection threshold." It determines when a motivation can be changed by inhibiting the nonguiding motives. To put it another way, the selection threshold puts weights on other motives. If a certain motive controls behavior, it is not enough for another motive just to be stronger than the hitherto governing motive. It should be stronger than the motive strength of the governing motive *plus* the selection threshold. The selection threshold makes PSI more persistent and efficient in following its current goal. It makes PSI more focused. Thus, the number of oscillations can be reduced.

Problem Solving and Action Regulation

Problem Solving in Other Architectures

We refer in our following discussions primarily to Ritter et al. (2003) and their comparison of ACT-R and SOAR. Human behavior is reduced in both ACT-R and SOAR to problem solving. Both ACT-R and SOAR are based on production rules which are "if–then" statements that specify which actions are taken under which conditions.

SOAR explicitly is a theory on problem solving. SOAR was developed to explain primarily heuristics and procedures in problem solving in difficult tasks and bottom-up learning (Laird, Rosenbloom, & Newell, 1986). SOAR may have several goals at a time arranged in a stack. Moving from initial to goal state through the problem space requires often certain subgoals. These subgoals are organized in a hierarchy in SOAR. SOAR is relatively flexible and able to remove or solve these intermediate subgoals. When solving problems, SOAR follows a decision cycle (see Rosenbloom et al., 1991, for details). SOAR moves between states and attempts to change the states through productions. When no productions can fire, either the state is changed or an operator is selected. If an operator cannot be selected (e.g., perhaps because of conflicting operators), a subgoal is created to choose the next operator or to find or generate information that would allow another operator to be executed.

ACT-R implies problem solving through its assumption of behavior being goal-directed. Problem solving requires moving from an initial state to a goal state. ACT-R has only one possible goal state with potential subgoals. These subgoals are organized in a hierarchy in ACT-R as well. In ACT-R, these subgoals must be satisfied in a serial manner. Thus ACT-R is less flexible than SOAR. Problem solving in ACT-R means movement between states in the problem space by firing productions. These productions can directly change the state and the goal. Simplified, the probability of the expected gain relative to the competitors expected gains determines which production rule is chosen in a given situation (see Lovett, 1998, for details). Problem solving in PSI differs from problem solving in SOAR and ACT-R.

Problem Solving in PSI

Problem solving and action regulation in PSI follows a modified Rasmussen ladder (1983). It can be explained in the following example: I am currently driving and would like to reach a store where I can buy a sandwich.

Automatisms. A set point deviation is found in the hunger/existential needs tank and the organism tries to reduce it to reach the set point again. The first step to satisfy the hunger need is to search in long-term memory for automatisms (for details on neural regulation of hunger and the role of schemas, see also Shin, Zheng, & Berthoud, 2009). These are schemas, learned routine behavior patterns that lead from current to goal situation. Such schemas are also called scripts (Schank & Abelson, 1988). Sometimes those automatisms have to be slightly adapted to the novel situation. When we drive a new car, for example, the windshield wiper might work differently than the one in the old car. Pressing it forward might now activate the wiper of the rear window instead of the windshield wiper. The turn-on-windshield-wiper automatism has to be slightly adjusted so the lever will be moved upward instead of pressed forward. The search and execution of such automatisms often happens without deliberate control, for example turning on the windshield wiper while driving the car. Automatisms amount to probably more than 90% of daily human behaviors (our estimation).

So, then, returning to the hunger need: Is there an existing path from the current situation on the road to the goal situation—the store? How can I reach the store where I can buy a sandwich? The automatism must encompass the way from situation image to goal. The situation image consists of pointers, which point to sensor schemas that are used to perceive the objects of the current situation. The situation image might consist, for example, of one's car, a street crossing, and a street name. If there is an existing path from situation image to goal in long-term memory, then the goal can be reached. The rise of a need must therefore be linked to a search for an existing path to a goal. The likelihood of success can be calculated by searching for such paths.

Planning. The second step is planning. When no routines can be found, for example, because of being new in a city, then one might engage in planning (Güss, 2000). The organism relies here on its general ability to construct a new chain of actions to approach a goal (see also Sun & Sessions, 2000). The hungry person has to develop a plan for how to reach a store. The person might look for a gas station and either buy a sandwich there or ask for directions to a nearby fast-food place or restaurant. Often, there are endless options to create a plan and certain strategies help to narrow down the planning space. One such strategy is the general problem solver (GPS, Newell & Simon, 1972), specifically one of the implemented algorithms, called hill climbing which attempts to reduce the distance between current situation and goal situation at any point during the planning process. The distance could be geographical or it could be the number of features between current and goal situation.

Exploration. If no automatism exists and planning is not successful, the person might fall back on the third stage: exploration, answering the question, What can be done? Part of this exploration is trial and error to explore the environment in more detail, such as by focusing on novel objects in the environment. For our hungry person, this could mean driving around and looking for something that looks like a restaurant or grocery store. The acquired more-detailed knowledge about the environment and its objects can then be incorporated in future plans. Another form of exploration is self-reflection. The hungry person could have an internal dialogue: "Ok, I have not found a restaurant yet. What was wrong with my knowledge about the environment? What was wrong with my heuristics?" (The existing implementations of the PSI theory, however. do not contain self-reflection.)

Through automatisms, planning, exploration including trial-and-error, and self-reflection, the organism tries to reach a goal. Then, a suitable final consummatory response is activated, which normally alters the state of the motivation system.

Memory

Memory and Learning in Other Architectures

Both SOAR and ACT-R have a declarative (facts) and procedural (rules) memory—although represented differently (see Ritter et al., 2003). Memory is unlimited. Declarative memory can be manipulated by either adding new items or by changing existing ones. Procedural memory does not change, but new rules can be added in both architectures.

Declarative knowledge is represented in schema-like structures building chunks of information (programmed as pointer-structures). Procedural knowledge is represented in the form of production rules such as "IF . . . is the goal, THEN set as a subgoal to . . .".

Learning in SOAR involves the creation of new rules whenever a subgoal is solved. Learning involves only production memory. When the same situation is encountered again, the new production fires and no now subgoal needs to be set. The new production can include information about which operator to select or how to implement the operator. This information also refers to long-term declarative memory, because all memory is represented in SOAR only as a result of production memory.

In ACT-R, learning involves both procedural and declarative memory. When rules fire, they become stronger. Thus, declarative memories also strengthen when they are used. In ACT-R one production is selected, the one with the highest expected value of gain. This value results from the production's probability of success, its cost, and the value of the current goal. The production with the highest expected gain is selected when there are several other competing productions. If the production was applied successfully, its probability increases; also leading to a strengthening of the declarative memory which constitutes the condition of the specific production. The more often an item in declarative memory is activated, the higher will become the associated base-level activation for this item. The more strongly the item is associated with other items being used, the higher will be the chance for this item to have its activation raised. Memory of facts and rules is conceptualized differently in PSI with the core being an "action schema."

Memory and Learning in PSI

The world in the mind: long-term memory and schemas. The basic unit of action is an action schema. It consists of a sensor input schema, a motor schema, and a sensor output schema. Such sensor-motor-sensor schema combinations are also called triplets because they consist of three parts (Klix, 1992). An action-schema is a realization of what Miller, Galanter, and Pribram (1960) called a TOTE-unit: *T*est (whether conditions are given), *O*perate (execute action), *T*est (whether expectation is met), and *E*xit (or continue). When we start a car, we use such an action schema: Perception of an ignition is the input schema. Putting the key in the ignition and turning the key is the motor schema (which might consist of several sensor-motor subschemas) and hearing the noise of the motor is the sensor output schema (see Figure 3). The sound of the motor is the expected result.

A sensor schema consists of a sequence of structural and "elementary" nodes (see Figure 3). The sequence of elements consists, for example, of horizontal, vertical, and diagonal lines, which are the sensors. Such lines are organized in a certain form and order. A simple picture of a house, for example, consists of diagonal, vertical, and horizontal lines. To organize those elements into a structure, we need the structure sequence. It consists of pointers to *xy*-coordinates. To go from one vertical line to the diagonal line, one has to go a number of units *x* to the right and units *y* upward. One could imagine those *x*/*y* units as activations of the eye muscles (Dörner et al., 2002, pp. 50–52).

Sensor schemas can become quite complex, for example when perceiving a face. Then the sequences are organized hierarchically from basic horizontal, vertical, and diagonal lines, to the sequences that scan the nose or the right eyebrow, to the highest level, which combines all those sequences into the face sequence. Each element of this sequence would point to the starting element of the sequences, which represent the parts of the face (nose, eyebrow, etc.). Thus, sensor schemas are not images or pictures of an outside world object, but rather a hierarchical description of how to recognize things or how to construct images (e.g., a chair on top of a table).

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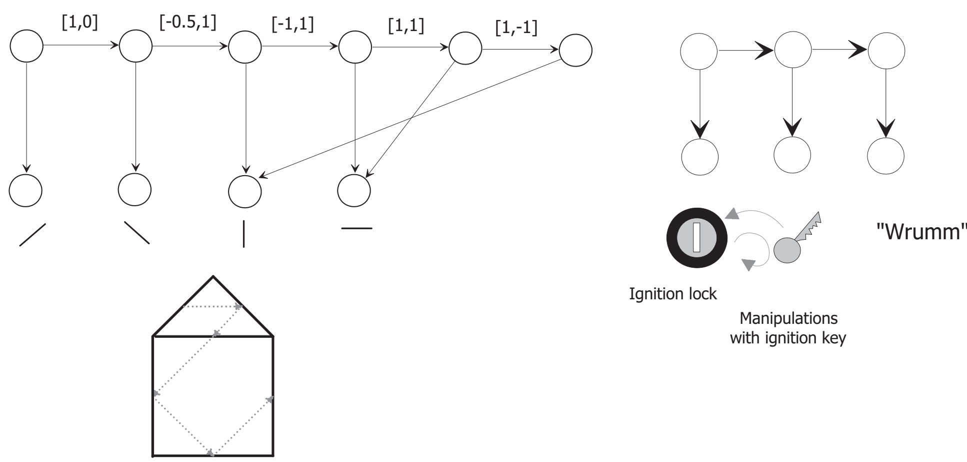

Figure 3. Sensor schema of a house and action schema of starting a car.

Existing sensor schemas are instructions for how to scan the environment. Perception, therefore, can be understood as a scanning process of the environment. It is also possible to create abstract schemas, by including branches of sequences (Dörner, 1999, p. 142). The first possibility is element abstractness. For example, the horse head sensor schema could branch out and either show ears that stand vertically (neither far forward not flat back) or ears pinned back flat against the head. Vertical ears would indicate to the rider that the horse is relaxed. Pinned back ears would indicate to the rider that the horse is angry and might not want to do what it is instructed to do. A skilled rider would have even more horse-ear branches in his schemas.

The second possibility is structural abstractness. For example, a German who had grown up in Germany and who had not seen many Asians would not have specific subschemas about different facial features for Chinese, Japanese, or Thai persons and thus would only have an Asian-face sensor schema. These subschemas, however, can be developed when the person is exposed to many faces of different Asians and starts to develop more specific schemas.

A motor schema (Bach, 2009, calls them effector/action schemas) points to a sequence of muscle activations which in turn can also consist of sequences of muscle movements. Such motor schemas can be relatively simple, but also relatively complex, like a hierarchical algorithm of visiting a restaurant, that is, the restaurant script (Abelson, 1981; Dörner, 1999, p. 106; Schank & Abelson, 1988). Like sensor schemas, motor schemas consist of chains of nodes, and every node stands for an action, which in turn can point to other actions.

To summarize, and coming back to behavior patterns, they consist of a sequence of sensory and motor schemas. All those sensory and motor schemas in their combination make up the worldview. When a motive is followed, this worldview is then searched for a promising path from current situation to goal situation.[11]

Working memory: the protocol chain. The working memory in PSI is conceptualized as a protocol chain (see Figure 1) made up of the following memory content: the image of the current situation, the expectation horizon (which consists of possible expected future events), the remembered past, and the intention memory (Dörner, 1999).

The intention as part of the protocol consists of 10 related parts. The core of the intention memory is the active need and its strength, which is the reported set point deviation. Usually goals, represented in the form of sensor schemas, are related to this need indicating situations that allow a consummatory response. Goals are related to other content in memory, for example, to knowledge of plans on how those goals previously were achieved in the past. The remembered past for the active motive is the protocol of actions and events that took place in the context of the intention execution. The past leads to the current situation and to the current state of the intention. An additional part of the intention memory are incomplete or complete plans for the current goal, that is, sequences of triplets from current goal state to satisfying the need. Further parts of the intention memory are a competence estimate indicating the expectancy of reaching the goal, the estimated time until the goal will be reached, and the urgency of the intention measured through the estimated time available in relation to the time needed (see also Detje, 1999; Dörner, Schaub, Stäudel, & Strohschneider, 1988).

The protocol chain consists of a chain of internodes that point at sensory or motor schemas at different hierarchical levels in the cortex. At any moment, some elements of the cortex become activated, dependent on the perception of the current environment or the behavior program that is being executed. The current situation image is added to the top of the chain. After a while, a new

[11] Our model of human memory does not assume production rules. Production rules are quite common in other cognitive architectures (e.g., Newell, 1973). They usually have the form: if (goal = X and precondition = Y) then Z (Anderson, 1983). Production rules differ from triplets as they always have the goal component already as a part of the conditions (Dörner, 1999, p. 105). Thus, the goal X is mixed with the output of a production rule Z. Additionally, production rules do not have an output schema. This is not a problem for internal processes such as math transformations where the changes usually correspond with the expectations. For real-world events, unlike math tasks, triplet-theory might be advantageous, because actions can have numerous outcomes and not always in the expected direction.

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current situation image is added to the top of the protocol chain, and so forth. Such a protocol memory allows the perception of whole events and the learning of new behavior programs (see Dörner, 1999, pp. 111–112, for more details).

The more time that has passed, the weaker the connections become between neurons in the protocol chain. The decay of the protocol chain is—following evolutionary theory—necessary to make efficient use of neurons. The once coherent string of neurons becomes loose and islands of action sequences or events are stored in memory in the cortex. Particularly those chains that lead to satisfaction of needs remain as islands. This fading of the protocol represents one part of human forgetting (Dörner, 1999, p. 118). (Of course, human forgetting also occurs in long-term memory.) The protocol chain also allows learning by strengthening elements of the protocol and their links to sensory and motor schemas when a need increases or decreases (see Luria as cited in Dörner, 1999, p. 93, for more details).[12]

Cognition in Detail

Thinking in Other Neural Networks

Some of the most widely known computational theories of psychological processes, especially cognitive processes, are connectionist models. Simplified, most connectionist models start with the neuron as elementary unit and simulate psychological processes in neural networks. These neurons can either inhibit each other or activate each other and the degree to which activation and inhibition occurs depends on the weights with which neurons are connected and on the strengths of the inputs and outputs (McClelland & Rumelhart, & the PDP Research Group, 1986). Because these networks follow more parallel and distributed and not only sequential processing, they have been called originally parallel distributed processing models (PDP, Rumelhart & McClelland, 1986).

Connectionist models have been regarded as a revolutionary alternative to the symbol manipulating, production-rule systems, because information stored in memory is reflected in groupings of neurons and their activation and connection patterns rather than as specific facts or events in a specific location. A further advantage of connectionist models is that they mimic the biological basis of psychological processes more accurately than production systems. Learning, for example, is reflected as change in neural connections through experience and simulated for example through Hebbian algorithms (McClelland, Rumelhart, & Hinton, 1986) or backpropagation (see, e.g., Rumelhart, Hinton, & Williams, 1986).

It is important to mention that there is not one connectionist model, but there is a multitude of different connectionist models each with different assumptions, focusing on different phenomena (e.g., connectionist models of emotion regulation, Armony, Servan-Schreiber, Cohen, & LeDoux, 1997; or connectionist models of motivation, e.g., Portegys, 2001). It is also important to note that in the literature connectionism is often discussed as contrary to production-rule architectures. The two approaches are not mutually exclusive, however. In fact several researchers simulate processes combining connectionist/neural network assumptions with symbol-manipulating models including production rules (e.g., Marcus, 2001; Schneider & Chein, 2003). In fact, PSI theory also combines connectionist and symbol-manipulating assumptions. PSI incorporates the basic assumptions about neural networks. The neural quad structure, however, we will discuss shortly is unique to PSI theory.

Thinking as Scanning Process in the PSI Neural Network

Coming back to the hunger example, the first step to satisfy the hunger need is to search in long-term memory for automatisms. How could the search for such an automatism work in detail? One possibility is backward scanning. The search would go backward from the goal situation until an element of the situation image or the complete situation image is reached.

This process is realized in PSI using quads (see Figure 4). A quad is a neural unit consisting of one central neuron and four attached neurons pointing forward (por, from Latin porro), backward (ret, from Latin retro), downward (sub, from Latin sub), and upward (sur, from Latin super). If one searches for parts of an object, for example, a search process in the subneurons occurs. During the process of backward scanning from the goal, ret and central neurons of quads would be activated (see for more details on quads, Dörner et al., 2002).[13]

Our hungry person from before has to find a way from current situation to goal situation, for example, from sitting in the car and driving to reaching a place to buy a sandwich. Sandwiches are usually part of a certain context, for example, fast-food places, restaurants, groceries. Therefore, a search has to occur in the sur network, to go upward and find situations or locations that include a sandwich. One would probably reach a sensor schema of either a grocery or a restaurant. Then the search continues backward, through the ret network, until an element of a behavior sequence is found that is part of the situation image. If the search is successful, then a behavior sequence leading to the goal is found and can be executed. If not, then, a new behavior sequence has to be created. This, exactly, is planning. Planning is learning a priori. One adjusts to the demands of a novel situation before the situation actually has happened.

The search process answers questions such as the following: Is the goal part of an existing behavior pattern? Then: Which sensor schema or sensory-motor schema precedes the goal? Then: Is the subschema the current situation image or part of the current situation image?

Emotion

Emotions in Other Architectures

After Picard's seminal book on "Affective computing" (1997), one would expect a multitude of architectures simulating emo-

[12] Bach describes the PSI theory and the specific conceptualization of working memory as follows (2009, p. xiv): "The stakes of the PSI theory lie elsewhere: its propositions are of a qualitative nature. Rather than predicting *how long* it takes and *how likely* it is to retrieve an item from working memory, it addresses *what* an item in working memory *is*: how it is related to inner imagery and to language, the way it is represented, and how it is grounded in interactional contexts.. . . The PSI theory is no model of human performance, it is a blueprint for a mind" [italics are in original].

[13] The use of quads and specific axonal relationships would also explain how meaning can become part of a neural system, and therefore be a possible answer to the so-called "labeling-problem" (Goldblum, 2001).

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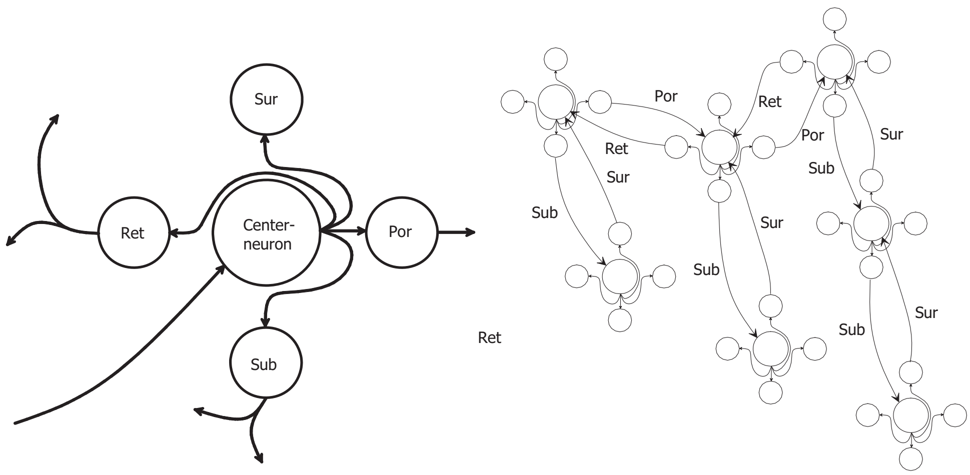

Figure 4. Structure of a quad and a quad network.

tional and cognitive processes. Belavkin (2001, p. 49) summarized, however, the current state of emotions modeled in computerized cognitive architectures.

> We know from our own experience and observation that emotion accompanies any problem solving process, but these computer simulations say nothing about it. It seems that in cognitive science this subject has not yet been studied deeply enough. This is not to claim that cognition and emotion were not considered together at all, but there was not many attempts to study this subject with cognitive architectures such as SOAR or ACT-R.

Some attempts have been made to include emotions into ACT-R, for example. Belavkin (2001) suggests that an emotional problem solver would follow certain heuristics. Positive emotions during problem solving would increase motivation and confidence. Negative emotions could help overcoming barriers during problem solving by, for example, leading to a change in problem-solving direction. Belavkin (2001, p. 56) also linked the overall activation to the strength of the experienced emotion; "For example, frustration corresponds to negative emotion with low activation, while anxiety to negative with high activation." These are thoughtful reflections and some parts are similarly reflected in PSI; however, at this stage, it seems like emotions are added onto the ACT-R system or some parameters are seen as indicators for emotions, yet emotions are not yet an integral part of ACT-R.

Another approach related to emotions is the addition of a physiological module to ACT-R (Dancy, Ritter, & Berry, 2012). This module allows, for example, connecting aversive memory content to physiological parameters and connecting the effects of physiological changes (e.g., during hunger) to cognitive processes. We mention this important work here, because physiological processes are at a core to emotions. In a similar way Damasio (1994) talks about "somatic markers." Somatic markers are created when stimuli are reinforcing in a certain situation and related to a physiological affective state. The markers are then the association between the stimuli and the physiological affective state. They can become influential in complex situations when decisions have to be made. The affective state can "bias" the rational thought process.

Another way to simulate emotions is to create overlays (Ritter et al., 2007). Overlays would modify a set of central parameters and mechanisms in an architecture to represent changes in information processing as a result of situation-specific demands. "For example, an eyeglass overlay would allow more inputs to be passed to the vision processor; a caffeine overlay could increase processing speed by 3% and improve vigilance by 30%" (Ritter et al., 2007, p. 255). This is an interesting idea (related to our modulation parameters, see below), yet it has not been implemented yet.

Another approach to emotions, similar to the one we postulate in PSI theory and similar to Wundt's dimensions (1896), regards emotions as a result of certain parameters/systems. Cochran, Lee, and Chown (2006, p. 1133) define emotions as a "fast, automatic assessment system" consisting of three systems: arousal system indicating importance of an event, pleasure–pain system indicating valence, and clarity–confusion system indicating competence. To test their theory, the authors simulated in a first step arousal using ACT-R and compared simulation results with empirical performance data in a memory task. In future research the authors intend to include pleasure–pain, and clarity–confusion.

Problems With Definitions

The first question we would like to discuss is, why do we need to implement emotions in our theory? Isn't it enough to have motivations that indicate needs and world knowledge on how to satisfy those needs? As we will see, motivations determine *what* must be done, emotions determine *how* it is to be done.

Emotions are often seen as the opposite to cognition, but for many people they are the core of being human. They make people marry others and sometimes kill others. A system without emotions is, in a certain sense, like a robot. An architecture or a robot can follow logical rules and without emotions it is simply a robot, but if it could have emotions, then it would resemble the human psyche.

First, we need to define emotions. This is not easy, as Kleinginna and Kleinginna (1981) showed by putting together 92 different definitions of emotion. In introductory textbooks of psychology we find the following: "Psychologists usually define it

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[emotions] in terms of a combination of cognitions, physiology, feelings, and actions.. . . For the way most people use the term emotion, the key component is the feeling" (Kalat, 2008, p. 437, see also Plutchik, 1962). So emotion is defined primarily as feeling, which is close to a tautological definition and does not explain much.

Other attempts to clarify the concept emotion are attempts to find basic emotions. Ekman (1992), one of the leading researchers on emotions, tried to reduce all emotions to six basic emotions, that is, happiness, anger, sadness, disgust, fear, and surprise, based on their universal facial expression patterns and on their unique physiological characteristics. Later, he expanded his list and came up with 15 basic emotions and 11 characteristics differentiating those from each other (Ekman, 1999). Other emotions such as romantic love or hate or grief are described as "emotional plots" (Ekman, 1999) and are more enduring than the basic emotions, thus are not part of the list (for a critique see Sabini & Silver, 2005). Ekman even concluded (1992, p. 19) "By now it should be clear that I do not allow for nonbasic emotions."

It does not seem satisfactory to reduce emotions to basic emotions and therefore explain emotions through emotions; as Scherer (1994, p. 27) stated, "I have not yet seen a convincing a priori argument, let alone evidence, that establishes the existence of basic or fundamental emotions as independent and integral biological or psychological categories or mechanisms." To put it boldly, replacing emotions with feelings and dividing them into basic emotions does not help us in understanding what emotions really are.

Wundt's Dimensions of Emotions

We consider Wilhelm Wundt's (1896) approach more fruitful. He characterized emotions as having a certain quality, intensity, and duration and defined three dimensions characterizing emotions: "Lust–Unlust," "Spannung–Lösung," and "Erregung–Beruhigung." Wundt's student Titchener (1908) translated them as pleasure–displeasure, tension–relaxation, and excitement–inhibition/tranquilization. Anger, for example, can be characterized by high displeasure, high tension, and high excitement. Sadness can be characterized by displeasure, relaxation, and tranquilization. These dimensions can be found also in newer theories of emotions which sometimes use slightly different terms or only one or two of the three dimensions (e.g., Block, 1957; Russell, 1980; Schlosberg, 1954). In contrast to Ekman, who explains emotions by dividing them into basic emotions, Wundt explains emotions as a result of a specific constellation of three dimensions.

We can elaborate on Wundt's dimensions and relate them to PSI theory and the competence tank. Pleasure[14] and displeasure, as we have discussed previously, are related to inflow and outflow in the competence tank and, specifically, to efficiency and inefficiency signals. Every time a need arises, displeasure is experienced. Every time a need is satisfied, the pleasure system is activated and relates the just reached goal situation, which allowed the consummatory response, with the need indicators.

The second dimension, tension–relaxation, is related to the level of the competence tank. A high level indicates self-confidence, that is, a high trust in one's ability to solve problems. This is the relaxation side of the dimension. A low level in the competence tank indicates a low readiness for action, leading to tension.

The third dimension, excitement–inhibition/tranquilization, is represented in the modulation parameter activation, which results from the set-point deviations in the competence tank and all other tanks. High activation does not necessarily mean high readiness for action or excitement. High activation, for example, could be related to a low level in the competence tank, in which case not much will be done. For example, anxiety is characterized by low competence, high activation, and often by immobilization.

Further Definitions and an Example

Aristotle indicated that a definition should have a "genus proximum" and a "differentia specifica." The genus proximum is the class to which the object to be defined belongs; for example, an ostrich is a bird. The differentia specifica is the way this bird differs from other birds, usually by indicating specific parts of the object to be defined or specific characteristics and how they are related. For example the ostrich is a ratite, flightless (differentia specifica) bird.

Returning to the topic of emotions, if we follow Aristotle, we could define anger as a reaction to frustration resulting from difficulty caused by an obstacle impeding attainment of a goal, which is characterized by high activation, low resolution of cognitive processes, and tendencies for aggression. This definition only refers to the differentia specifica and might not be very detailed, but it indicates basic processes of anger, how they are triggered, and what their consequences are. And importantly, these basic components are not other emotions.

Following this analogy, then, what is the genus proximum, the class, to which emotions belong? Psychological processes could serve as a very general class for emotions. To clarify, consider the following example: A person who is very angry happens to be drinking coffee. Reaching for the mug, the person might grab the handle strongly and quickly, very likely spilling some coffee. If, instead, the person was very anxious, he might take hold of the handle very cautiously, which could result in the cup dropping to the floor. Thus, the coffee drinking behavior is modified by emotions: The *how* of the behavior is determined by the emotions. Thus, the genus proximum of emotions is modulations of internal processes and behavior. The function of emotions is to adjust behavior to the demands of the current situation.

We have just defined anger referring to the two modulations activation and resolution level, and to a specific behavior tendency, or, more specifically, an increase in activation, a decrease in resolution level (chunky behavior, coarse cognitive processes), and a tendency toward aggressive behavior. The following section describes the three modulation parameters implemented in the PSI theory in more detail.

Emotions in PSI

Modulation parameters. Three modulation parameters have been used in PSI theory: activation, resolution level, and selection threshold (Dörner, Gerdes, Mayer, & Misra, 2006). High activation, which resembles the ascending reticular activation system

[14] Neural evidence for a "pleasure-centre" in the brain comes from studies with rats that literally press endlessly a lever that stimulates regions in their hypothalamus (Olds & Milner, 1954).

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(ARAS) in humans, prepares the entity to react. The sympathetic autonomous nervous system is activated. Muscle tension, heart rate, and breathing rate increase; the sense organs are prepared to take in sensory information.

The resolution level dials in or refines the cognitive processes. The resolution level is high when the inhibition of the cortex is low. A high resolution level results in a broad memory search for associations to the specific stimulus. When planning, a high resolution level means consideration of many side and long-term effects of possible actions. A high resolution level leads to detailed perception of all objects in the visual field (see HyPercept process in Dörner et al., 2002).

Cognitive processes under a high resolution level need a lot of time to deliver results. If time is short, quick actions are necessary; then the resolution level should be very low. At the neural level, the resolution level changes according to increases or decreases of cortex inhibition. Thus, when the resolution level is high, neural inhibition is low, and, as a consequence, memory association fields are very large and perception very detailed. The selection threshold determines how easily PSI switches between intentions. It will be described in more detail below.

Behavior tendencies. The three modulation parameters relate to internal processes. The specific behavior tendencies affect the way the person reacts to the outside world. Specific behavior tendencies are used to solve problems in specific ways (for an evolutionary view on behavior tendencies, see Gross, 1998). For example, an aggressive behavior tendency occurring during a conversation could lead to either yelling at the dialog partner or using sarcastic argumentation. An explorative behavior tendency would result in listening attentively during a conversation and gathering information from other dialog partners by asking questions. (The other behavior tendencies are discussed below.)

The purpose of all these modulations is ultimately the retention or increase of competence. Figure 5 shows how the modulations are triggered. It shows how variables change depending on values of other variables. On the left side are three tanks representing certainty, competence, and affiliation. Their levels indicate the extent of certainty, competence, and affiliation experienced by the organism.

The need indicators (NI) of the three tanks represent the needs that are dependent on the extent of the respective tanks' set point deviations. NIs are connected with variables that are shown in the two clouds. The upper cloud includes behavior tendencies focused on the outside world (tendencies for safeguarding, aggression, flight, exploration, affiliation, confirmatory perception, and self-reflection, probably represented in the cortex); the lower cloud includes parameters for the flow of internal processes (extent of analysis of conditions, side and long-term effects of actions, fanning out of memory search, and selection threshold, probably related to the executive functions of the prefrontal cortex). The plus sign indicates a positive relationship (i.e., the higher the need for competence, the higher the tendency for flight). The minus sign indicates a negative relationship (i.e., the higher the need for competence, the less the aggression tendency). These are just broad descriptions of functional relationships that are specified mathematically as shown in Figure 6.

In detail, a low level in the certainty tank means high activity for the NI. This NI generates a high tendency for safeguarding, especially when the competence need is also high. Safeguarding is background monitoring and means interrupting one's behavior frequently—when competence and certainty are low—to scan the environment and update the situation image. This is important, allowing an agent to react to the current demands of the environment. In the extreme, high safeguarding makes it hard to focus on the execution of goal-oriented actions, because it destroys the behavior flow. High safeguarding is often part of anxiety.

Additionally, low certainty means a high aggressive tendency, but also a high tendency for flight. This seems contradictory, but it makes sense. If someone does not understand the current situation, how it might develop, or how an object might behave, then either destroying an object or fleeing can be appropriate behaviors. Choosing the option to destroy or flee depends on the competence and the strength of the opponent. With low need for competence, aggression tendencies decrease and flight tendencies increase. A low level in the competence tank paired with a low level in the certainty tank result in strong flight tendencies. Low competence is a consequence of failures, which are interpreted as inefficiency signals. To increase competence, PSI will try to get efficiency signals, which can be as simple as washing dishes or cleaning. Additionally, low need for competence sets high tendencies for exploration and affiliation. Both knowledge about the environment and group involvement with many friends can increase competence, because (a) both reduce certainty and affiliation needs and fill up the competence tank as well, and (b) both ultimately facilitate problem solving.

Additionally, a high need for competence results in affirming the existing perception of the environment: Information that does not confirm the entity's world knowledge and hypotheses is not regarded. In this way, the competence is protected from "inappropriate" events or events that do not fit the entity's perception. Finally, a high need for competence leads to a decrease in self-reflection. Self-reflection increases the likelihood of awareness of the limitations of one's own actions, which would further decrease the competence level.

How can a high certainty need and a high competence need lead simultaneously to safeguarding, flight, and affirming perception of stimuli? First, it is possible that all three behavior tendencies could happen at the same time. Second, these behavior tendencies can also be combined and happen sequentially, for example, first safeguarding followed by flight. Third, the selection of one or more of those behavior tendencies is primarily dependent on the learning history, that is, the epistemic competence, which was defined previously as the specific acquired knowledge on how to deal with problem situations and reach goals. Epistemic competence would therefore lead to individually unique response patterns. Fourth, situational characteristics can trigger specific behavior tendencies.

Internal modulations. Regarding internal modulation parameters, low certainty and low competence increase activation. High activation, in turn, increases the readiness to act, so that successful actions as efficiency signals can refill the competence tank. High activation, however, also leads to a decrease in resolution level because high activation increases inhibition in the cognitive system.

The degree of inhibition determines resolution level, but also selection threshold and breadth of memory search processes. With high inhibition, the memory search is relatively narrow. Only the strong connections, which are mostly old, are activated. High activation, therefore, leads to more conservative behavior. We fall

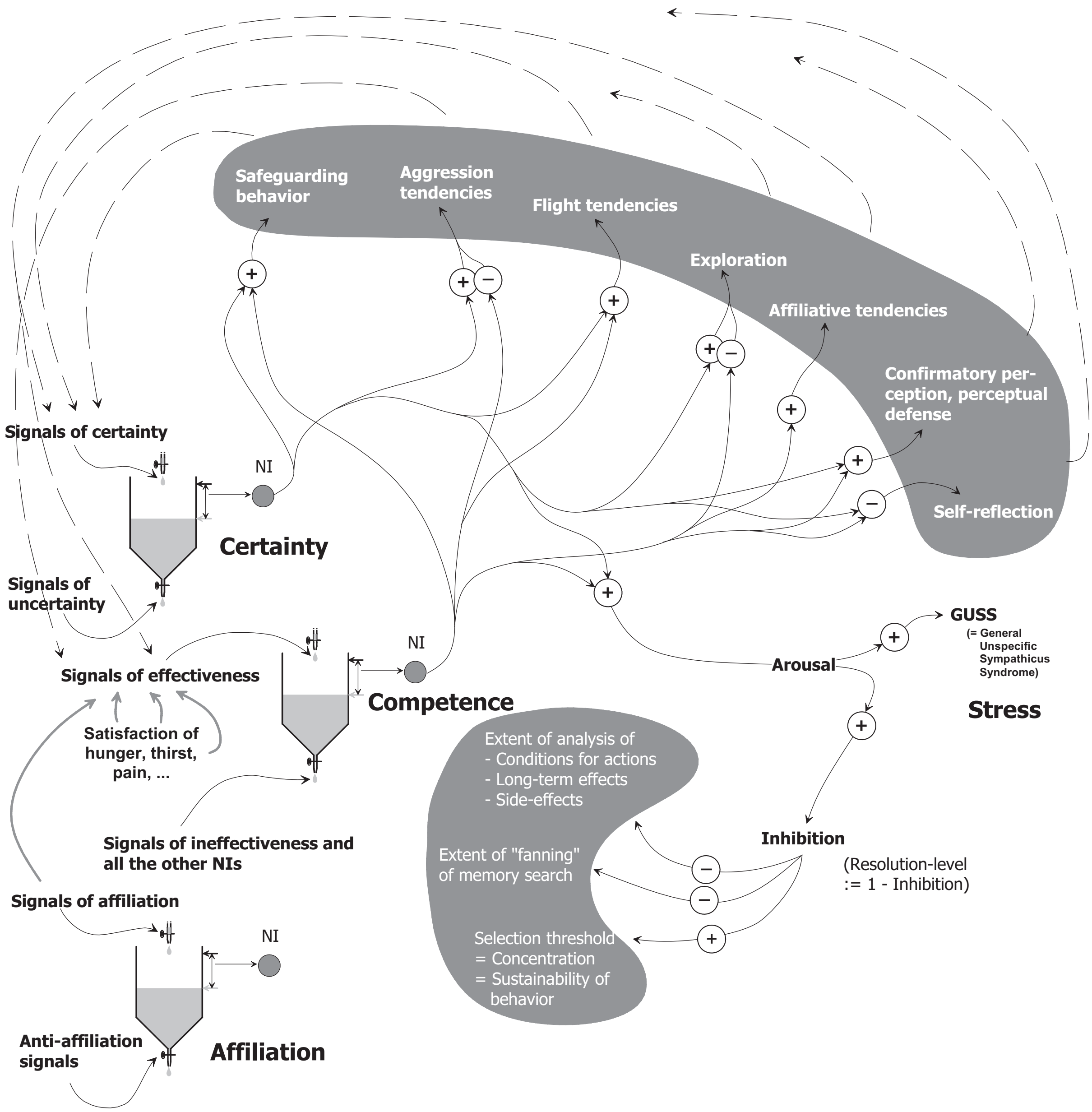

Figure 5. Emotions as modulation parameters and behavior tendencies. *Note*: For better clarity, the figure does not include all feedback loops, for example, those from the behavior tendencies back to the certainty and competence tanks. Certainly, successful exploration, for instance, is connected to a refilling of the certainty tank.

back on well-known and reliable thoughts and behaviors. Search processes in memory are related to the quad structure described before. An associative network is searched in a specific direction, for example, the sub-elements referring to whole-part or has-part relations and the sur-elements to part-whole or is-part-of relations are searched until possibly an end node is found. If the elements of the associative field are inhibited, however, it is less likely that the search will be successful. Thus, if inhibition increases, the number of associations decreases. On the one hand, high inhibition speeds up the search process; on the other hand, only a few strong associations are activated.

The resolution level affects planning. When planning happens under high inhibition, then side and long-term effects of actions are not considered. Planning becomes superficial and risky because it refers only to the immediate consequence of an action. Inhibition leads to an increase in transition weights between associations, prohibiting the planner from remembering side effects and making it harder to remember long-term effects.

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(1) $LEVEL_{COMP} := MAX(0, MIN(1, LEVEL_{COMP} + SIGNAL_{EFF} \times W_{EFF} - SIGNAL_{INEFF} \times W_{INEFF}))$;

(2) $LEVEL_{CERT} := MAX(0, MIN(1, LEVEL_{CERT} + SIGNAL_{CERT} \times W_{CERT} - SIGNAL_{UNCERT} \times W_{UNCERT}))$;

(3) $NEED_{COMP} := 1 - LEVEL_{COMP}$;

(4) $NEED_{CERT} := 1 - LEVEL_{CERT}$;

(5) $BEHTEN_{SAFEGUARD} := NEED_{CERT} \times NEED_{COMP}$;

(6) $BEHTEN_{AGG} := NEED_{CERT} \times (1 - NEED_{COMP})$;

(7) $BEHTEN_{FLIGHT} := NEED_{CERT} \times NEED_{COMP}$;

(8) $BEHTEN_{EXPLOR} := NEED_{CERT} \times (1 - NEED_{COMP})$;

(9) $AROUSAL := \ln (1 + NEED_{COMP} \times WEIGHT_{AR})$;

(10) $RESLEV := (1 - AROUSAL^2 \times WEIGHT_{RESLEV})$;

(11) $SELECTTHR := AROUSAL^2 \times WEIGHT_{SELECTTHR}$;

Figure 6. Formalized relationships of some of the variables of the emotional process.

The selection threshold determines the degree to which a change in motivations is possible, that is, when one motive replaces another. When following a goal, it is important to be aware of the opportunities and dangers present in the current situation. On a neural level, the selection of a motive can happen by successive inhibition until only one element remains. This is shown in Figure 7. To avoid motive oscillations, we can postulate that the current intention inhibits all other possible intentions. It is difficult for the nonactive motives to oust the current motive and to take over the leading role. This inhibition process stabilizes the system. The stronger the inhibition of the current motive, the more tenacious or enduring the whole system becomes. As a consequence, the system becomes less sensitive to possible opportunities and dangers. The advantage of being focused and concentrated on one activity comes with the disadvantage that opportunities and dangers are overlooked.

To summarize, and referring back to Figure 5, an emotion is not its own distinct entity in PSI (compared with other theories that take emotions as distinct entities; e.g., O'Rorke & Ortony, 1994), but a modulation of a cognitive-motivational process furnished with specific behavior tendencies. Emotions as modulations are adjustments of thinking, perceiving, and other cognitive and motivational processes relating an organism to the current demands of its environment. Emotional regulations are based on the needs for certainty, affiliation, and competence. In other words, an emotion is a specific organizational form of psychological processes. Emotions emerge through the specific constellation of the described parameters and these parameters are not emotions themselves. Thus, organizational form can be regarded as the genus proximum for emotion.[15]

An Example: Anxiety

Perhaps the best way to explain modulations is through the use of a specific example, such as anxiety. Anxiety is characterized by a low level of competence, and certainty is also very low. Anxiety makes it nearly impossible to make predictions about the future or explain important events. Additionally, anxiety may cause the anticipation of adverse events. Activation is high and therefore the resolution level of cognitive processes is very low. Thinking is superficial. Activities are interrupted frequently by safeguarding; however, though the situation image is often updated, it is not thoroughly updated. Behavior switches from one motive to another because the selection threshold is very low. Actions are cautious because of flight tendencies. Many things are started but nothing is completed, which further lowers competence. There is a tendency to explore, but this is followed only hesitantly because it is not possible to know the results. Information in concordance with the

[15] We are not alone with our view of emotions—although we might have it specified more formally and in more detail than others. It is similar to Scherer's view (1994, p. 27) of emotion "as a sequence of interrelated, synchronized changes in the states of all organismic subsystems (information processing/cognition, support/ANS, execution/motivation, action/SNS, monitoring/subjective feeling) in response to the evaluation of an external or internal stimulus event that is relevant to central concerns of the organism." It is also similar to Keltner and Shiota (2003, p. 313), who defined an emotion as "a universal, functional reaction to an external stimulus event, temporarily integrating physiological, cognitive, phenomenological, and behavioural channels to facilitate a fitness-enhancing, environment-shaping response to the current situation."

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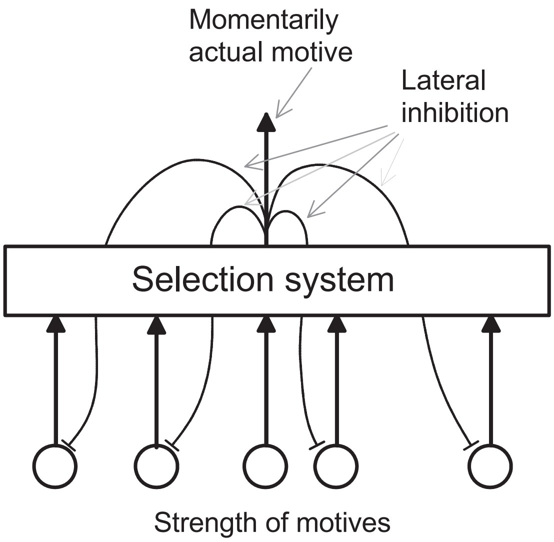

Figure 7. Motive selection.

existing worldview is readily absorbed because it engenders feelings of security and reduces uncertainty.

As can be seen in this example, anxiety is not one state, but the flow of cognitive and motivational processes in a specific direction. It is not a separate module that influences thinking, but a specific organizational form, a specific modulation of motivation, thinking, perceiving, and acting. Anxiety emerges from these modulations (on the general importance of emergent properties in systems, see McClelland, 2010). If the previously mentioned tendencies are removed, anxiety does not exist. In fact, nothing remains.

Testing PSI

How can such a complex theory of motivation, cognition, and emotion be tested? A first form of validation would be to investigate whether PSI Theory predicts known reactions of humans to certain conditions. We studied for instance how PSI reacts to the availability of alcohol (Hagg & Dörner, 2009) or to crowding-conditions. We applied this method by constructing artificial "mice." The "mice" are minimodels of PSI with reduced cognitive processes (to enable a normal computer to simulate rather large populations). The mice can reproduce and they teach their offspring, providing them a lot of knowledge about their respective environment. The mice live on a virtual "island" which provides food, medical plants that can be used to heal wounds, and certain dangers, too. The mice must explore their environment to identify sources of food ('F' in Figure 8), waterholes ('W'), medical plants ('M'), and dangerous regions ('D,' such as falling rocks or fights with enemies).

As the reproduction rate is (normally) larger than the mortality rate, the mouse-population grows over time; the island slowly becomes overcrowded. We know the effects of crowding on humans. In crowding situations men live under continuous stress; they experience anger, anxiety, and become to that effect aggressive and prepared for flight (Stokols, 1972). They experience hostility in their social environment and therefore strive for friendships and close relations to others. And what are the consequences of stress for the mice? Nearly the same, as Figure 9 shows. The *x* axis in the figures below show the time in 100 simulated cycles reflecting approximately five real-time hours. In brief, the population increases steadily until cycle 110,000 where it reaches 140.

Figure 9 shows the effects of growing density on the mouse-population. Arousal is growing as well as the average number of enemies and friends. The number of aggressions and the frequency of affiliative activities increase. Accordingly, the number of fear reactions increases. Yet, the resolution level decreases, resulting for example in superficial perception and narrow planning. Generally, anxiety of the mice increases as all the above mentioned effects of crowding are symptoms of anxiety. In summary, the simulation of crowding in the mouse-population shows similar processes and effects that have been identified in the literature on human crowding.[16] And this is all the more noteworthy, because the PSI theory was not originally developed to simulate crowding effects.

A second possibility to test the validity of PSI would be to put PSI in different environments and demonstrate that it can solve environment-specific problems and that it can adapt its behavior to the specific demands of the environments. Detje (1999) followed this approach when he put PSI on a virtual island and described how it adapted. Another example is the work of Hille (1997), who put PSIs in a virtual city world and could show that PSIs with emotions performed better than PSIs without emotions, that is, PSIs with a working modulation system as described before in the section on emotion performed better than PSIs with random parameter combinations or PSIs with states of fixed values.

A third possibility to test the validity of PSI is to conduct experimental research comparing the behavior of PSI with the behavior of humans as a whole considering not a few single variables, but their interaction in the stream of behavior (e.g., Bartl & Dörner, 1998). Detje (1999) and Dörner et al. (2002), for example, analyzed the strategies of 30 participants and compared their behavior with 30 different PSIs. The goal for human participants and PSIs was mainly to explore a simulated island and to survive on this island. The authors compared when planning occurred and to what extent, the number of locations on the island visited by participants at the beginning and at the end of the simulation, what emotions were shown, when those emotions changed and how often. Thus, it was possible to compare human and PSI participants' behavior regarding the goals they reached, but also regarding their behaviors during the simulation. According to Dörner et al. (2002), it was crucial to observe PSI extensively in order to compare PSI behavior with human behavior and analyzing what behaviors in PSIs were unlike human behavior, which led to substantial modifications of PSI.

A fourth possibility to test the validity of PSI is to apply the theory to explain complex historical events. We have done exactly this by trying to explain Adolf Hitler's decision making during World War II (Dörner & Güss, 2011), referring to his decision-making failures and their potential causes.

Bach (2009, p. 144) summarized this approach the following way: "By designing an architecture that can be directly compared

[16] A copy of the mice-simulation is available and can be downloaded (Dörner, 2010).

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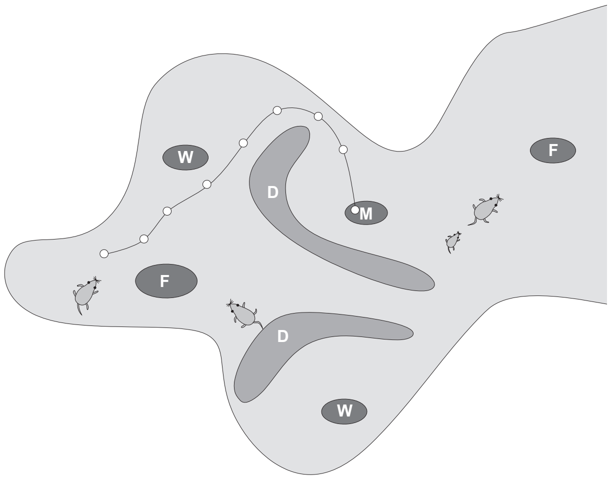

Figure 8. The mice in their world.

to human performance in the Island simulation and that can even be fitted to the problem-solving strategies of different personality types in human subjects, (Dörner et al., 2002; Detje, 2000; Dörner, 2003) Dörner has become one of the first researchers to create an experimentally validated computer model of human emotion during complex problem solving."

In the future, PSI could be compared with other theories, for example with ACT-R (Anderson & Lebiere, 2003) or CLARION (Sun, 2009). Such a comparison would highlight strengths and weaknesses of the respective theories and could help in further advancing the theories.

The relevance of studying cognitive, motivational, and emotional processes in their interaction was recently shown in a study in five countries with more than 500 participants (Güss, Tuason, & Gerhard, 2010). All participants worked on the two dynamic computer simulations (see below for more details on this methodology), WINFIRE and COLDSTORE. In the first simulation, participants took the role of a fire fighting commander who tried to protect forests from approaching fires. In the second simulation, participants took the role of a supermarket manager who tried to control a broken temperature wheel to preserve dairy products until cooling trucks could arrive. Thinking-aloud protocols of all participants were tape-recorded, transcribed, and analyzed. Participants from all cultures expressed statements regarding the problem-solving process, referring to, for example, gathering of information, elaboration of goals, predictions, planning, and decision making. At the same time, for all participants, an average of about 15% of their statements included references to their positive and more so negative emotions and evaluations of themselves and their feelings of competence (e.g., "I will never be a good fire fighting commander. . . oh no").

Other Evidence: Cognitive Failures

Other evidence for the theoretical assumptions outlined in this article comes from experimental studies on complex problem solving and dynamic decision making. Over the last two decades, researchers have investigated how humans solve complex problems (e.g., Dörner, 1996; Schaub, 2001; Strohschneider, 2001). As methodology, researchers often applied microworlds, which are computer simulations of complex, uncertain, and nontransparent problems (Brehmer & Dörner, 1993; Frensch & Funke, 1995). Participants took, for example, the role of developmental aid assistants in the MORO simulation, or the role of fire chiefs in the WINFIRE simulation, or the role of top managers in MANUTEX or SCHOKOFIN. While participants were working on these simulations, every decision they made and every change in the simulation system were saved in computer files. Often, their thinking aloud was tape-recorded. Analyzing those files and analyzing audio-taped and videotaped protocols of participants revealed a multitude of participants' cognitive failures that can be explained though the emotional mechanisms outlined before. Among those were (and we refer here because of space limitations only to examples from MORO, e.g., Strohschneider & Güss, 1999; and WINFIRE, e.g., Güss et al., 2010).

Confirmatory Perception

Confirmatory perception, as discussed previously, refers to a perception of the environment and search for information that confirms one's assumptions and world knowledge. Competence and certainty are low and conflicting information is disregarded. In the MORO simulation, for example, participants took the role of developmental aid assistants who tried to improve the living conditions of the Moros, a tribe of seminomads living in the Sahel zone in Africa. Participants often hired teachers to educate the Moro children. Participants were not bothered by the fact that the teachers were not accepted by the Moros and that Moro children were not attending class because they had to help their parents in the fields or to help at home. As justification, they offered that going to school is not always fun and some disapproval is normal and has to be accepted for the better good. In WINFIRE, many parts of the forest burn and even some houses catch fire. One Brazilian participant once justified his actions and the loss of houses saying: "This is the city where mainly government officials, the mayor, and politicians live. It can burn. It does not matter, because they do not do anything for their citizens anyway."

Methodism

Methodism is a tendency to act following learned automatism. Actions that prove to be successful in the past are automatically applied in the present without realizing that the demands of the past and present situations might differ and thus other actions could be required in the current situation. Methodism is a result of high arousal and high inhibition, which lower the search for memory content by limiting the breadth of the memory fan. Participants in MORO, for example, did not want to drill deep-water wells, because they assumed that wells would lower the ground water level dramatically. And rightly so, a very low ground water level has dramatic consequences for the environment and further complicates the water situation. However, participants did not even inquire whether the ground water level indeed sunk dramatically after experimenting with a few wells. In WINFIRE, methodism was shown by some participants who always sent the same amount of trucks to each starting fire. This action might not always be successful because some fires die down by themselves and other fires spread quickly, partly because of changing wind direc-

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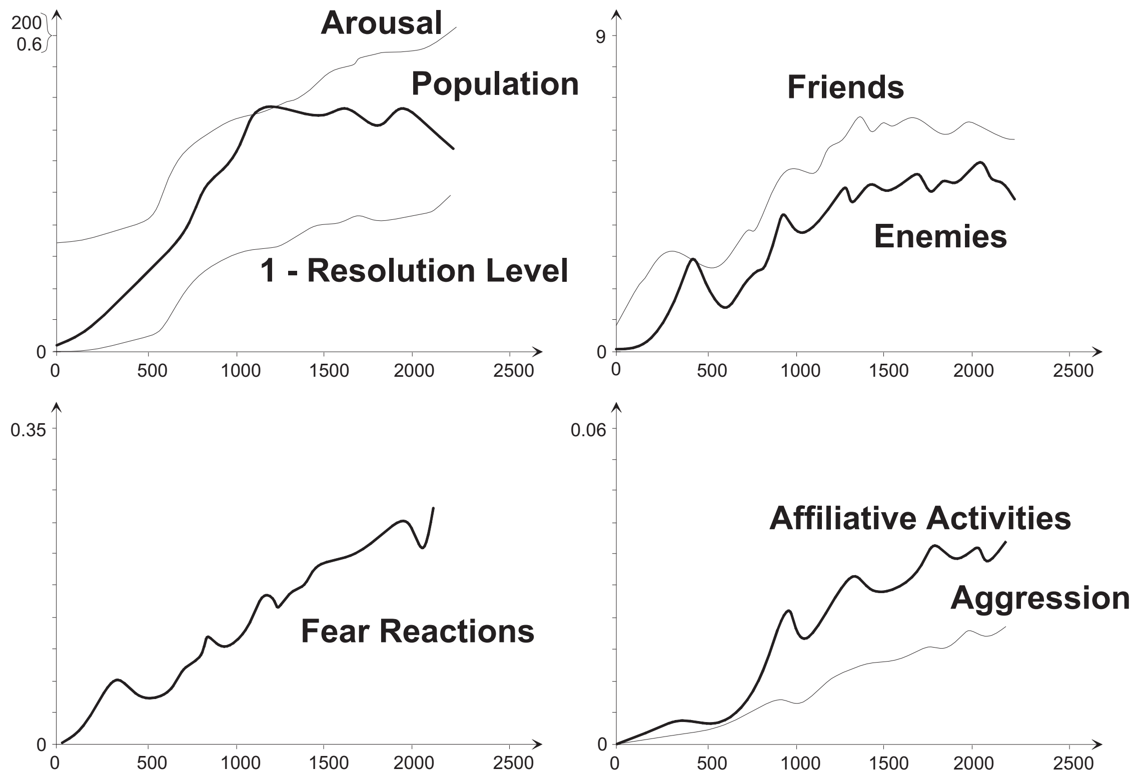

Figure 9. The effects of crowding, anxiety. The *x* axis in the figures below show the time in 100 simulated cycles reflecting approximately five real-time hours.

tion and wind strength, thus, some fires would pose a bigger danger and therefore would demand more fire fighting units than others.

Neglecting Side and Long-Term Effects of Plans

Often, people do not take important side and long-term effects of their actions into consideration. This is because of an increase in arousal and a high inhibition, which in turn lowers the resolution level of planning and the related analysis of side and long-term effects. Fighting the tse-tse fly in MORO, for example, leads to an increase in cattle, which ultimately leads to an increase in the Moro population. These are all desired effects. If one forgets, however, to consider long-term effects of one's actions and to adequately irrigate the pasture area, soon there will not be enough food for the cattle. The grass will be gone, cattle will die, and ultimately Moros will die, too. In WINFIRE it takes time for a fire fighting unit to reach the burning forest area. Often, participants send trucks to a location that has been burning for quite some time already. Participants forget to predict the long-term effects of their action, namely that by the time the unit reaches the desired location it will have arrived too late and the forest will have completely burned. The unit will not be available for use elsewhere for some period of time.

The three cognitive failures originate, so we assume, from a specific constellation of parameters in PSI. Confirmatory perception happens when the competence level and the certainty level are very low. Then, participants desire certainty and do not have the capability to investigate contradicting or conflicting information. This would further reduce the level of competence and certainty. Methodism originates in a narrow fan of associations in memory as a result of high activation and high inhibition of memory content, resulting in an inability to consider changed conditions. The neglect of possible side and long-term effects of actions is related to the low resolution level, that is, high inhibition of memory content, which in turn is also a result of high arousal/activation. Thus, the assumptions specified in PSI theory can be used to explain participants' behaviors when they are confronted with complex, dynamic, and uncertain problem situations.

Limitations

It is hardly possible to describe all the details of PSI-theory in this article (for details see Dörner, 1999). Whenever possible we have referred to other literature which describes specific aspects of the theory. Yet, we also would like to mention that certain psychological processes such as language or self-reflection are not yet simulated in great detail in PSI.

More future research should validate PSI theory in empirical studies. These studies could focus on some detailed assumptions proposed in the theory.

Another limitation refers to the other architectures discussed briefly. Our inclusion and discussion of other architectures has been selective. It was not possible to include and focus on all the many different approaches in this growing field. Yet, referring to some of the most widely known theories allows the reader to see

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similarities and differences compared to the PSI-theory. It will be the task of another study to describe and compare one or two specific phenomena in different architectures. In this article we wanted to give an exhaustive overview of PSI theory.

Conclusion

PSI theory is an attempt to simulate cognitive, motivational, and emotional processes in their interaction. We have outlined the specific assumptions, central variables, and processes of the theory in this study.

Assessing the breadth of PSI theory we refer to the DARPA proposal for cognitive architectures (DARPA, 2005). PSI addresses 14 topics of the 22 major areas of cognitive functioning recently defined in DARPA: memory, learning, executive processes, language, sociality/emotion, consciousness, knowledge representation, logical reasoning, elementary vision, object perception, spatial perception, spatial cognition, attentional mechanisms, and motivation (Bach, 2009, p. 304). We hope Ritter is right when he says that PSI theory is the theory that covers “perhaps the largest number of phenomena to date” (2009, p. VI).

Varma (2011) discussed in his article evaluation criteria for cognitive architectures and one of those desired criteria should be ‘strangeness.’ Possible reactions to strange architectures according to Varma might be ignoring them or dismissing them. Other reactions are Hegelian reactions (Varma, 2011, p. 1339), recognizing that like a given conventional architecture (the *thesis*), the strange architecture has value (the *antithesis*), and future research will try to reconcile the two or more architectures (a *synthesis*). In this sense we hope the PSI theory is a strange theory and the reader follows a Hegelian response ultimately stimulating future research.

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