The emergence of personality: Dynamic foundations of individual variation ☆

Andrzej Nowak [a,b,*], Robin R. Vallacher [b], Michal Zochowski [c]

[a] *University of Warsaw, Warsaw School for Social Psychology, Poland*
[b] *Florida Atlantic University, Boca Raton, FL 33431, USA*
[c] *University of Michigan, USA*

Abstract

We conceptualize personality and individual variation from the perspective of dynamical systems. People's thoughts, feelings, and predispositions for action are inherently dynamic, displaying constant change due to internal mechanisms and external forces, but over time the flow of thought and action converges on a narrow range of states—a fixed-point attractor—that provides cognitive, affective, and behavioral stability. An attractor for personal dynamics develops through two mechanisms: the synchronization of individuals' internal states in social interaction, and the self-organization of thoughts and feelings with respect to a higher-order property (e.g., goal, self-concept). We present formal models of both processes and instantiate each in computer simulations. Discussion centers on the implications of interpersonal synchronization and self-organization dynamics for issues in personality psychology, including shared vs. non-shared environmental influences on personality development, the expression of personality in social interaction, personal stability vs. change, personal vs. situational causation, and the emergence of self-concept.

Keywords: Attractor; Cellular automata; Control parameter; Dynamical system; Emergence; Self-concept; Self-organization; Social interaction; Synchronization; Feedback loop

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* Corresponding author.

E-mail addresses: anowak@ux2.math.us.edu.pl, an@spik.swps.edu.pl (A. Nowak), vallacher@fau.edu (R.R. Vallacher).

Two people with highly different childhood experiences may nonetheless develop very similar patterns of thought, feeling, and behavior. It's also the case that two people with highly similar experiences in childhood may become very different in the way they think, feel, and act. In some quarters, these observations are taken as evidence against the experiential foundations of personality and provide a rationale for focusing instead on biological propensities, most notably genetic and hormonal influences. The role of biological factors in shaping personality cannot be denied, but experience is simply too important to human psychology to be relegated to second-class status. Humans are undeniably social animals, and any theory that purports to explain the origins of human personality must accord social experience a prominent role. Our basic aim in this paper is to reframe this role in terms of recent adaptations of dynamical systems theory to human psychology. In this account, the specific content of one's experience is less important than they way such experiences are organized and represented by the person. We develop this perspective in the context of two formal models we have employed in past research, one emphasizing the implicit or automatic foundations of personality (Nowak, Vallacher, & Zochowski, 2002), the other highlighting the explicit or self-conscious construction of personality (Nowak, Vallacher, Tesser, & Borkowski, 2000b).

At first glance, the dynamical perspective would seem to be wholly irrelevant to psychological processes, let alone to the social foundations of human idiosyncrasies and proclivities comprising an individual's personality. Dynamical systems, after all, were initially developed to model the behavior of physical phenomena in the natural world. Due in large part to the innovative work of scientists such as Esther Thelen (cf. Thelen & Smith, 1994), however, the relevance of dynamical systems to psychological phenomena has become increasingly recognized in recent years. The dynamical perspective has in fact emerged as an influential paradigm in virtually all areas of contemporary psychology, including motor control (cf. Kelso, 1995), human development (e.g., Fischer & Bidell, 1997; Newell & Molenaar, 1998; Smith & Thelen, 1993; van Geert, 1991), perception (e.g., Gilden, 1991; Petitot, 1995; Turvey & Carello, 1995), language (e.g., Cullicover & Nowak, 2003; Elman, 1995), action (e.g., Newtson, 1994), emotion (cf. Lewis, 2000), subjective well-being (Fredrickson & Losada, 2005), cognition (cf. Port & van Gelder, 1995), organizational behavior (e.g., Axelrod & Cohen, 1999; Guastello, 1995; Losada, 1999), political behavior (e.g., Hegselman, Troitzch, & Muller, 1996), and various topics in personality (e.g., Lewis, 2005; Magai & McFadden, 1995; Read & Miller, 2002; Shoda, LeeTierman, & Mischel, 2002) and social psychology (cf. Arrow, McGrath, & Berdahl, 2000; Nowak & Vallacher, 1998; Vallacher, Read, & Nowak, 2002b). The common denominator in these approaches is the recognition that a psychological process—be it self-concept, social judgment, or societal change—can be viewed as a set of elements whose mutual influences promote the emergence of higher-order properties and behavior. Thus, specific movements become coordinated to achieve a higher-order action, thoughts and feelings become organized to promote judgments and evaluations, and social interaction among individuals promotes the emergence of group-level norms and beliefs.

The task of the dynamical perspective on personality development is to show how fundamental features of individuality can emerge from interactions among elements comprising psychological systems and features of the environment. Central to this account is the notion of *attractor* (cf. Schuster, 1984). Attractors capture the interplay between structure and dynamics in a complex system and thus are useful for framing the tension between stability and change in psychological processes. After developing the relevance of attractors for personality generally, we provide an overview of contemporary theory and research exploring the emergence and expression of individual differences in attractors for thought, emotion, and action. We first discuss the reciprocal feedback between cognition and emotion that gives rise to stable attractors, and we then describe two formal models that capture the emergence of higher-order structure in people's behavioral and mental systems. These models are complementary in that one focuses on the progressive development of behavioral tendencies that occur in a relatively automatic fashion, while the other focuses on the emergence of a self-concept that occurs by means of internal integration processes that may be subject to conscious attention and control. In a concluding section, we discuss the relevance of the dynamical perspective for perennial issues concerning the origin and expression of individual variation that have proven difficult to resolve within conventional treatments of personality.

Attractor dynamics and personality

Human experience is inherently dynamic. Even in the absence of external influence, an individual's mental state and predisposition for action can take on a variety of different forms as he or she reflects on past experiences or imagines those yet to take place. Indeed, the potential for internally generated or ''intrinsic'' dynamics was accorded a prominent role in early treatments of personal and interpersonal processes. James (1890) theorized about the dynamic nature of human thought and action, with emphasis on the continuous and ever-changing stream of thought. Cooley (1902) emphasized people's constant press for action, even in the absence of incentives and other external forces. Mead (1934) discussed people's capacity for symbolic representation and the enormous range of interpretation to which this capacity gives rise. Asch (1946) suggested that social judgment reflects the interplay of thoughts and feelings, with this interplay promoting the emergence of a unique Gestalt that is not reducible to simple aggregation of the individual cognitive elements. Lewin (1936) theorized that stability and variability in overt behavior reflect a persistent struggle to resolve conflicting motivational forces, including those within the person as well as those arising from outside influences. Psychodynamic theories (e.g., Fred, 1937) shared this emphasis on conflict-induced dynamism, stressing the importance of motives and fears that are opaque to consciousness. Contemporary models of personality also incorporate the potential for intrinsic dynamics into their conceptualizations and research strategies (e.g., Carver & Scheier, 1999; Cervone, 2004; Mischel & Shoda, 1995; Lewis & Granic, 2000; Read & Miller, 2002). These models differ in important respects, of course, but they share an appreciation for the role of internal mechanisms in giving meaning to, and modulating the effects of environmental cues and demands.

Attractor dynamics

The proclivity for intrinsic dynamics cannot be denied, but neither can the tendency for psychological systems to demonstrate stability and resistance to change. People experience an enormous amount of diverse information relevant to self-understanding, social judgment, and interpersonal relations on a daily basis, yet they manage to maintain relatively stable platforms for thought and action in each of these domains. The flow of thoughts, feelings, and behavior is not random, then, but rather converges on specific states or patterns of change between states. A person may experience sadness and perhaps even depression in reaction to negative life experiences, for example, but over time his or her self-regulatory mechanisms are likely to reinstate positive moods and a sense of personal control (e.g., Johnson & Nowak, 2002). In like manner, someone with high self-esteem may experience negative self-relevant thoughts, but these are likely to be unstable, giving way over time to a flow of self-evaluative thinking that converges on a positive state (e.g., Vallacher, Nowak, Froehlich, & Rockloff, 2002a).

The constraints on psychological process can be understood in terms of *attractor dynamics*. An attractor is a state or a reliable pattern of changes (e.g., oscillation between two states) toward which a dynamical system evolves over time, and to which the system returns after it has been perturbed. In a system governed by attractor dynamics, a relatively wide range of starting points (initial states) will eventually converge on a much smaller set of states or on a pattern of change between states. An attractor in effect ‘‘attracts’’ the system’s dynamics, so that despite differences at the outset in one’s thoughts, feelings, or behaviors, the process unfolds in the direction of the attractor. Attempting to move the system out of its attractor, moreover, promotes forces that reinstate the system at its attractor.

Conceptualizing personality in terms of attractor dynamics thus captures both the human proclivity for continual change and the tendency to forge and maintain personal stability in one’s interaction with the environment. A person’s thoughts, emotions, and behaviors may initially be generated in response to situational demands, but over time they come increasingly under the control of stable internal states (cf. Lewis, 2000). With the development of attractors, moreover, there is a restriction in intra-individual variation and the emergence of inter-individual differences. Research by De Veerth and van Geert (2002) provides an illustration of these tendencies. They compared the basal cortisol level of infants and their mothers. For infants, who presumably have yet to establish strong attractors, there was substantial variation between measurements but little evidence of individual differences. But for mothers, who presumably have had ample opportunity to establish strong attractors, there was substantial individual variation in cortisol levels but relatively little variation between measurements.

Fixed-point attractors

Research across different areas of science has identified three types of attractors (cf. Eckmann & Ruelle, 1985; Nowak & Lewenstein, 1994; Schuster, 1984): fixed-point attractors, periodic (including multiperiodic) attractors, and deterministic chaos (dynamics characterized by very irregular, seemingly random temporal evolution). Although periodicity and chaos may well have relevance for certain aspects of personality functioning, fixed-point attractors have the most direct relevance for the emergence of stable internal states and accordingly have received the lion’s share of attention within the dynamical perspective (e.g., Lewis, 2000; Smith & Thelen, 1993; Nowak et al., 2002).

A fixed-point attractor describes the case in which the state of the system converges to a stable value. In psychological systems, this tendency is similar to the notion of equilibrium or homeostasis (cf. Cannon, 1932; Miller, 1944). An attractor may correspond to a desired end-state or goal (Vallacher & Nowak, 1997) that functions as a standard of self-regulation (Carver & Scheier, 1999). When faced with obstacles, a person’s thought and behavior are configured (and reconfigured if necessary) in order to overcome the obstacles and ensure achievement of the goal or maintenance of the regulatory standard. Thus, people are described as motivated to bring about and maintain various psychological states, whether cognitive (e.g., a belief), affective (e.g., a judgment or an attitude), or behavioral (e.g., an action tendency or desire) in nature.

Attractors, however, do not necessarily refer to intentions or desired states. A person may display patterns of behavior that repetitively converge on hostility across his or her social relations, for example, even when he or she attempts to avoid behaving in this manner. In like manner, a person with low self-esteem may initially embrace flattering feedback from someone, but over time he or she is likely to discount such feedback, displaying a pattern of self-reflective thought that converges on a negative state (Swann, Hixon, Stein-Seroussi, & Gilbert, 1990). A system governed by fixed-point attractor dynamics, in other words, will consistently evolve to a particular state, whether or not this state is hedonically pleasant, and will return to this state even when perturbed by outside influences that might promote a more pleasant state.

A system may have multiple stable states, each corresponding to an attractor for the system's behavior. The particular attractor that is reached depends on the initial states or starting values of the system's evolution. The set of initial states leading to each attractor represents the *basin of attraction* for that attractor. In a system with multiple fixed-point attractors, then, the system can display correspondingly different equilibrium tendencies, each associated with a distinct basin of attraction. Within a given basin, even quite different initial states will promote a trajectory that eventually converges on the same stable value. But by the same token, even a slight deviation in initial conditions has the potential to promote a dramatic change in the system's trajectory if the deviation represents a state that falls just outside the original basin of attraction and within a basin for a different attractor. In a high threat situation, for example, there are two dominant responses, corresponding to fight versus flight. Minimal differences in the circumstances associated with the threat will thus lead to dramatically different behaviors, with virtually no option for a response that integrates the two tendencies.

The potential for multiple fixed-point attractors captures the idea that people may have different and even conflicting goals, self-views, and behavior patterns. A person may have more than one self-regulatory standard, for example, each providing for behavioral direction and self-control under different conditions. His or her actions may be in service of an achievement standard under a range of conditions that promote this tendency, but in service of affiliation standards under a different set of conditions. In similar fashion, a person may have multiple self-views (e.g., Markus & Nurius, 1986), each representing a stable way of thinking about him or herself that comes to the fore when a specific set of self-relevant information is primed, made salient by virtue of context or role expectations, or otherwise brought to consciousness. Apparent inconsistency or conflict in personality, too, can be viewed as the existence of multiple attractors associated with different basins of attraction for thought and action (cf. Nowak et al., 2002). One set of conditions and initial states might promote a trajectory that evolves toward dominance and competition, but another might promote instead warmth and compassion.

The relevance of fixed-point attractors for personality functioning is illustrated in a recent study exploring the temporal trajectories of affective states on the part of bipolar depressive individuals (Johnson & Nowak, 2002). Time-series analysis of mood and other symptoms revealed that patients whose temporal dynamics were not characterized by fixed-point attractor tendencies were at highest risk for suicide and were hospitalized more often for their depression. Interestingly, these risks were equally low for individuals whose moods oscillated around a single attractor, even one corresponding to a depressed state, and those whose moods switched between two distinct attractors representing a normal state and a depressed state. These results can be interpreted in light of the connection between attractor dynamics and self-regulatory tendencies. Self-regulation implies approach and stabilization regarding some states and avoidance and de-stabilization of other states. The stable states are manifest as fixed-point attractors for a person's dynamics. From this perspective, the absence of fixed-point attractors for one's affective state signals a breakdown in the capacity for self-regulation.

Energy landscapes for personality

As noted above, a person may have multiple fixed-point attractors, each reflecting a characteristic mode of thought, affect, and behavior. These attractors may vary in strength, so that certain attractors are more likely than others to capture and maintain the dynamics of a person's functioning. An attractor's strength is dictated by three properties—its *basin of attraction*, its *depth*, and its *shape*. The basin of attraction represents the range of values surrounding an attractor that eventually converge on the attractor. An attractor with a wide basin will "attract" a relatively large range of nearby values. A highly optimistic person, for example, might react to neutral or even moderately bad news with strong evidence of his or her tendency to view the world positively. If the width of the basin covers the whole range of values that can be adopted, the system will converge on this state regardless of the system's starting value. The highly optimistic person, for example, may reframe seemingly devastating news (e.g., the loss of his or her job) in positive terms (e.g., an opportunity to learn new skills or get to know one's kids). In contrast, an attractor with a narrower basin will attract a smaller range of nearby values. Thus, a person with an equally strong tendency to stabilize on high optimism may display this tendency only in reaction to very positive events. When the person is in a pessimistic or even a neutral mood, then, his or her optimism may not be evident.

The depth of an attractor corresponds to the force required to move the system out of the attractor. A deep attractor is one that can resist relatively strong forces in the direction of values outside the basin of attraction. If a person has a deep attractor for optimism, for example, once the person is within the basin of attraction, very strong inducements from outside this range are required to change his or her mental state. A shallow attractor is more readily destabilized by such forces. Thus, if a person's optimism is not especially well entrenched, even a brief encounter with a skeptical person might be sufficiently to undermine the person's rosy view of the world. Finally, shape represents how the system reacts to various deviations from its attractor, and how strongly each deviating state will be pulled back to the attractor. An attractor may react very weakly to small deviations, but react in a disproportionately stronger fashion for larger deviations. Such an attractor would allow an optimistic person, for example, to move freely through a range of positive moods, but strongly restrict him or her from moving into a range of negative moods. In contrast, one can envision an attractor in which the forces returning the system to its equilibrium are very strong in the immediate vicinity of the attractor, but become progressively weaker with increasing distance from the attractor. Thus, an optimistic person may strongly stabilize on a positive view of the world, but if he or she is induced to adopt a moderately optimistic view, he or she may subsequently display little resistance to an outright negative worldview.

These criteria of attractor strength can be depicted with an energy landscape metaphor. In this metaphor, it is assumed that system dynamics are governed by the rule of energy minimization. Imagine a ball rolling on a hilly landscape. The ball will roll down the hill and eventually will come to rest in a valley. The system, like a ball rolling downhill, moves to a state with lower energy, eventually coming to rest in a valley corresponding to an attractor. In effect, dynamics consist of the descent of the system from any state to the closest attractor. Equilibrium driven behavior, in other words, represents a search for a local minimum in the energy landscape.

Different attractors in an energy landscape are portrayed in Fig. 1. The *x*-axis in each case corresponds to states of the psychological system and the *y*-axis corresponds to the energy associated with these states. Each valley represents a local minimum of the energy function (i.e., an attractor), with the depth of each valley representing the strength of the attracting equilibrium. Different factors can move the system away from its current attractor, but if the force is not too strong, the system will eventually return to this attractor (i.e., the ball will roll back down the slope). The strength of the force necessary to move the system out of its attractor must equal (or exceed) the difference of the energy associated with the top and bottom of the valley.

Attractors **A**–**D** in Fig. 1A differ with respect to depth, basin of attraction, and shape. **A** portrays a weak attractor that is shallow and has a narrow basin of attraction, **B** portrays an attractor with an equally narrow but deeper equilibrium, **C** portrays a shallow attractor with a wide basin of attraction, and **D** portrays an attractor that is deep and has a wide basin of attraction. The shape of the basin of attraction for each attractor is represented by the slope of its hills and valleys, with steeper slopes corresponding to stronger equilibrium forces. **E**, **F**, and **G** in Fig. 1B illustrate this feature of attractors. **E** depicts an attractor with a weak stabilizing tendency near the equilibrium, which gets progressively stronger with distance from the equilibrium. **F** depicts an attractor with the opposite ten-

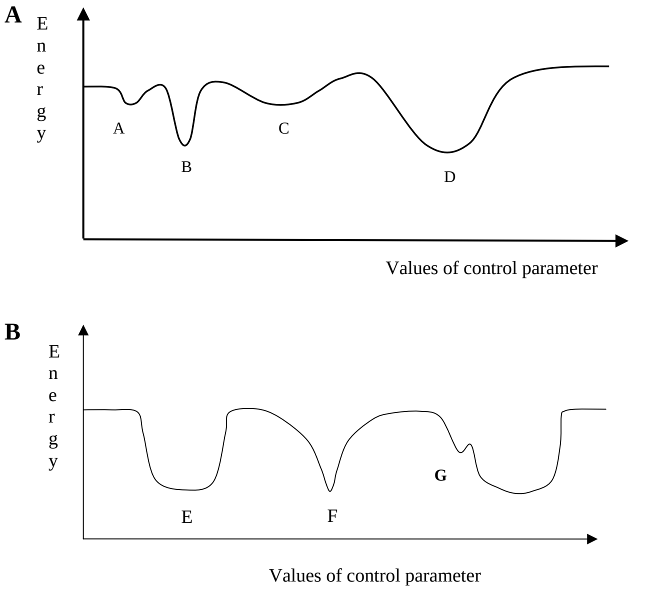

Fig. 1. (A) Energy landscapes for personality. (B) Shapes of basins of attraction for equilibria. (Source: Nowak et al. (2002). Copyright © 2002 by Guilford Publications. Reprinted by permission.)

dencies—a strong stabilizing tendency near the equilibrium, which becomes progressively weaker with distance from the equilibrium. The configuration in **G** represents a small local equilibrium existing within the general basin of attraction of a wider and stronger attractor. Yet other configurations of depth, basin, and shape can be envisioned, each capturing a potential type of attractor dynamics.

Models of attractor dynamics

Framing personality development in terms of attractor dynamics provides the point of departure for theory and research. The most basic question concerns the origins of attractors. It is usually assumed in psychological models (e.g., Lewis, 2000) that attractors are created by the repeated experience of a particular state so that, metaphorically, the state becomes ''engraved'' in the person's relevant psychological system. In a process somewhat reminiscent of learning, frequent repetition of a particular state paves the way for the system to develop a tendency to converge on this state in the future and to stabilize when in the state. This general scenario raises a set of specific questions. How do people develop particular attractors for thought, emotion, and action? How do such attractors emerge in the course of social experience? Are some social relations more consequential in this regard than others? What role does self-awareness play in the development of personality attractors? Once attractors are developed, how are they reflected in people's self-concept? How, and to what extent, are different attractors manifest in different social contexts? How is an emphasis on attractor dynamics relevant to perennial issues in personality, such as personal consistency, personal versus situational causation, and the accuracy of insight into one's personality?

The following sections address these concerns. First, we describe a perspective on personality developed by Lewis (2000, 2005) that emphasizes the reciprocal feedback between cognitive and affective processes and the role of this feedback loop in promoting the emergence of stable attractors. We then describe two formal models we have developed to capture basic mechanisms for the emergence and expression of attractors. The first model focuses on the interpersonal origins of personality that occur without the need for substantial conscious mediation. The second model takes into account people's capacity for self-reflection and thus emphasizes the intrapersonal bases of personality development. With these perspectives in hand, we develop the implications of the dynamical perspective for issues in personality psychology. Because the models we describe are relatively new, the implications to a large extent can be viewed as establishing agendas for theory and research in the years to come.

Emotion–cognition linkages and the emergence of attractors

Events in the environment elicit both cognitive and emotional reactions. The question of which type of reaction plays the primary and which plays the secondary role has attracted considerable attention in psychology. One view (Lazarus, 1982) holds that emotions result from cognitive appraisals. This emphasis on cognitive primacy assumes that stimuli have to be recognized before they can elicit specific emotions. An alternative view (Zajonc, 1980, 1984) argues for the primacy of affect, citing experimental evidence that emotional reactions arise before the eliciting stimuli are consciously recognized, and can occur even in the absence of recognition. In addressing this issue from a dynamical perspective, Lewis

(2000, 2005) argues that emotional and cognitive reactions to an event form a bi-directional causal loop, such that emotions facilitate cognitive appraisals that are congruent with them, while cognitions, in turn, elicit emotions that correspond to the content of the cognitive appraisals. This process may be called emotional interpretation. Lewis (2005) offers ‘‘road rage’’ as an example of such a loop. Imagine a person driving a car who experiences interference by another driver (e.g., cutting off the person while changing lanes). This event evokes frustration and thus elicits anger in the person. This emotional state promotes an interpretation of the other driver’s behavior as intentional and challenging. This interpretation, in turn, intensifies the person’s anger, which then sets the stage for interpreting subsequent behavior of the other driver as hostile.

The dynamics of emotional interpretation, according to Lewis (2005), can be divided into three phases: trigger, amplification, and stabilization. The initial phase of the reaction has trigger like properties. An event, which may take the form of environmental input, cognition, or change in emotion, perturbs the system, decreasing the order of ongoing processes. This increases the sensitivity to the environment and sets the stage for mutual interaction between the emotional and cognitive elements. Positive feedback loops between cognitions and emotions have the effect of a self-amplifying reaction. Cognitive elements recruit congruent emotional reactions and vice versa, and the reaction grows stronger over time as perceptual, emotional, and attentional processes enhance each other. In this self-organizing process, meaningful emotional interpretations emerge. In addition to positive feedback loops, there are also negative feedback loops that serve to stabilize the system. After the self-enhancing process reaches a certain level, the effect of the negative feedback loops equals the effect of the positive feedback and the system reaches an asymptotic, relatively stable state. The resulting psychological system’s states of emotional-cognitive amalgamations, as Lewis (2000, 2005) points out, are attractors of the cognitive-emotional system. In fact, the main role of the initial triggering event is choosing among the existing attractors toward which the system will stabilize.

The causal loops in this process not only span different levels of emotional-cognitive linkage, but also span different time-scales. At the lowest level are emotional reactions, which last seconds or minutes. On the intermediate level are moods. On the highest level are personalities, which are relatively stable. In the top down process, personalities influence the organization of affective emotional states and the structure of attractors for emotional-cognitive processes. These in turn can influence the moods to be internally coherent. At this moment, emotional and cognitive discrepancies with other psychological systems can be reduced and the system can achieve coherence with other psychological systems. Influences from other systems can further enhance stability and the system may achieve higher levels of complexity as cognitive appraisals become more elaborated. The resultant appraisals may take the form of schemata or scripts. The state of the system may be further stabilized by influences from the action system. The emotional interpretation may serve as a basis for the formation of action plans, goals, and so forth. System stability, in turn, may influence momentary reactions to incoming stimuli.

In the bottom up process, personality emerges from reoccurring episodes of emotional-cognitive reactions. Each episode, in the process of learning, enhances the chance that the next episode will take a similar form. Personality, then, is a relatively orderly and stable organization, produced by learning based on reoccurring emotional interpretation, and by means of self-organization of different lower-level components of relevant psychological systems. It arises from episodes of emotional interpretation and sets constraints for later emotional interpretations.

Lewis (2000, 2005) develops a parallel interpretation of the development of personality at the level of the nervous system. He stresses that in the neural system, emotional-cognitive loops are abundant, and that they play a prominent role in both learning and recognition. The typical pattern of functioning of the brain involves reentrant feedback loops between different neural structures. In such organization, different neural structures mutually activate and inhibit each other in an incremental fashion. Current research concerning the brain uses dynamical systems terminology and focuses on such processes as synchronization, self-organization, press for coherence and complexity, and phase transitions. Lewis (2005) stresses that at the brain level, all the functions are performed by the ensembles of structures located in all levels of the brain, from the brain stem to the neo-cortex, including hypothalamic and other systems responsible for affective reactions. Each emotional interpretation thus may be portrayed as a tree with its roots in the brain stem providing lower and phylogenetically earlier components, and its branches in the cortex providing cognitive interpretations that refine the emotional reactions. Different timescales of neural events involve, respectively, temporary activation of specific neurons, temporary strengthening of synaptic efficiency in the form of LTP, and, at the level of personality, structural changes in the pattern of connections between neurons.

Interpersonal synchronization and the emergence of attractors

The social foundations of personality have been the primary focus of theory and research on personality development since the inception of this line of scientific inquiry. Despite the sustained emphasis on interpersonal processes, however, it is still not entirely clear what features of social relations shape an individual's personal proclivities for thought, feeling, and action. To be sure, social reinforcement, social learning, and vicarious arousal have been shown to be important, but there is also abundant evidence that these factors fall short of providing a complete depiction of personality development. One would think, for example, that children's personality would be disproportionately influenced by their parents because of the opportunities available in the parent–child context for learning through reinforcement, modeling, and empathy. The evidence, however, suggests that parental influence plays a relatively modest role in shaping personality (cf. Harris, 1995; Scarr, 1992). It appears, in fact, that children may be more influenced by peers and other non-shared social factors than they are by their parents.

Synchronization dynamics

We suggest that the influence of social experience can be understood by framing social interaction in terms of *synchronization*, a phenomenon that characterizes coupled dynamical systems (Kaneko, 1993; Shinbrot, 1994). The central idea is that individuals in an interaction or a relationship are not static or passive entities, but instead represent separate systems capable of displaying rich dynamics, and that the synchronization of their respective dynamics produces a higher order system with its own dynamic properties. To achieve synchronization, each individual adjusts his or her internal state or overt behavior in response to the state or behavior of the other individual. Thus, the individuals modify their respective thoughts, feelings, or action tendencies to promote coordination over time in these features of experience.

The most basic and ubiquitous form of synchronization is positive correlation, such that the overt behaviors, attitudes, or emotions of one person induce similar behaviors or states in the other person. Imitation and empathy provide clear instances of this form of synchronization. Clearly other forms of synchronization are possible, however, and may be manifest in social interaction. As noted by Newtson (1994), for example, turn-taking in conversation is a clear instance of negative correlation (anti-phase relation) between individuals in their respective talking and listening (i.e., when one person speaks, the other is silent). Negative correlation can also epitomize antagonistic relationships, with the sadness of one person inducing satisfaction in the other and vice versa. Synchronization can also be manifest in more complex forms that reflect nonlinear relationships and higher-order interactions between the partners' respective behaviors and internal states (cf. Nowak & Vallacher, 1998; Nowak, Vallacher, & Borkowski, 2000a). Gottman, Swanson, and Swanson (2002), for instance, have identified complex forms of emotional coordination among marital partners. They have shown that different forms of coordination are specific to different types of marriages, and that empirical measurement of this dependency can be used to assess the quality of the marriage. Yet other types of relationships may be defined in term of specific forms of coordination in behavior and internal states. Nonetheless, positive correlation represents the most fundamental and arguably the most common form of coordination of internal states and behavior. For this reason, we focus on this form in our model of interpersonal dynamics. It remains for subsequent research to model other forms of coordination and their implications for social relationships.

As a result of synchronization attempts, social interaction revises the individuals' settings for their respective internal states, or engraves entirely new settings, which then provide the foundation for subsequent social interactions. With repeated episodes of the synchronization process, each individual's setting of internal parameters becomes increasingly engraved in his or her system in the form of attractors, thus creating a particular propensity for social interaction. In principle, this reciprocal relation between settings of internal parameters and social interaction can iterate continuously throughout a person's life. In reality, however, the engravings of some tendencies are likely to become particularly stable and thus resistant to modification in subsequent social encounters. The attractors for these settings constitute a latent structure of personality that fosters uniqueness and stability in the surface structure of interpersonal behavior.

A formal model of synchronization

A dynamical system is composed of a set of *dynamical variables* (x) that change in time, and one or more *control parameters* (r) that play a decisive role in influencing the dynamical variables. The logistic map is the simplest dynamical system capable of complex (e.g., chaotic) behavior (Feigenbaum, 1978; Schuster, 1984). Like all dynamical systems, the logistic map involves repeated iteration. This simply means that the output value of the dynamical variable (x) at one step (n) is used as the input value at the next step ($n+1$). The current value of the dynamical variable (which varies between 0 and 1), in other words, depends on the variable's previous value—that is, $x_{n+1} = f(x_n)$.

The logistic map represents this dependency in two opposing ways. First, the higher the previous value, the higher the current value—specifically, x_{n+1} equals x_n multiplied by the value of r. Second, the higher the previous value, the lower the current value—specifically, x_{n+1} equals $(1 - x_n)$ multiplied by the value of r. The combined effect of these two forces is represented in the logistic map, and is expressed as $x_{n+1} = rx_n(1 - x_n)$, where x_{n+1} is the value of a dynamical variable at one time, x_n is the value of the same variable at the preceding time, and r is the control parameter (the crucial variable influencing temporal changes of x). For different values of r, the logistic equation may display qualitatively different patterns of behavior (i.e., patterns of changes in x), including convergence on a single value, oscillatory (periodic) changes between two or more values, and very complex patterns of evolution resembling randomness (i.e., deterministic chaos). These patterns have been shown to be invariant in a wide variety of systems that transcend traditional topical boundaries in science.

In modeling human dynamics, the dynamical variable (x) can be interpreted as behavior. Changes in x thus correspond to variation in the intensity of behavior. The control parameter, r, corresponds to internal states (e.g., personality traits, moods, values, etc.) that dictate the person's pattern of behavior (i.e., changes in x over time). The logistic equation is generic in form and is intended to reflect basic processes involving the conjunction of conflicting forces, and does not depend on specific identities of x and r. Thus, x can refer to behavior at any level of identification, from simple movements to broad action categories, each of which may be associated with a correspondingly different time scale (e.g., seconds vs. days). The identity of r is similarly flexible, and can refer to a wide variety of internal states, from temporary moods and momentary concerns to enduring features of temperament and personality. The central point is that a person described by this simple equation can display a pattern of changes in behavior in the absence of external influences. External factors do not induce activity in an otherwise passive person, in other words, but rather exert their influence by modifying the person's intrinsic dynamics—his or her internally generated patterns of behavior.

Coupled logistic maps can be used to model the synchronization of people in social interaction (Nowak & Vallacher, 1998; Nowak et al., 2000a). The dynamics of each interaction partner are represented by a logistic equation. To capture interpersonal synchronization, the behavior of each person not only depends on his or her preceding state but also on the preceding state of the other person. This influence is introduced by assuming that the behavior of each partner at a given moment depends to a certain degree on the behavior of the other partner at the preceding moment. The coupling is achieved according to the following equation:

$$x_1(t+1) = \frac{r_1 x_1(t)(1 - x_1(t)) + \alpha r_2 x_2(t)(1 - x_2(t))}{1 + \alpha},$$

$$x_2(t+1) = \frac{r_2 x_2(t)(1 - x_2(t)) + \alpha r_1 x_1(t)(1 - x_1(t))}{1 + \alpha}.$$

To the value of the dynamical variable representing one person's behavior (x_1), one adds a fraction, denoted by α, of the value of the dynamical variable representing the behavior of the other person (x_2). The size of this fraction (α) represents the strength of coupling and can be viewed as reflecting the mutual interdependency of the relationship. When the fraction is 0, there is no coupling on the behavior level. When the fraction is 1, each person's behavior is determined equally by his or her preceding behavior and the preceding behavior of the other person. Intermediate values of this fraction correspond to intermediate values of coupling.[1]

Modeling the synchronization of behavior

In social interaction, individuals' respective control parameters are rarely, if ever, identical, nor are all interactions and relationships characterized by the same degree of influence and interdependence. In computer simulations (Nowak & Vallacher, 1998), therefore, we systematically varied the similarity of partners' control parameters (r), representing their internal states, and their degree of coupling (α), representing their mutual influence (e.g., intensity of communication). For each simulation, we started from a random value of x for each person, drawn from a uniform distribution that varied from 0 to 1. We let the simulations run for 300 steps, so that each system had a chance to come close to its pattern of intrinsic dynamics and both systems had a chance to synchronize. For the subsequent 500 simulation steps, we recorded the values of x for each system and measured the degree of synchronization.

The results revealed that the degree of synchronization between partners' behaviors increased both with α and similarity in r. This implies that similarity in internal states and interdependence can compensate for one another in achieving or maintaining a particular level of synchronization. For two people to achieve a high degree of synchronization, then, relatively little coupling is necessary if they have similar control parameters. Conversely, if the partners have different internal states, high mutual influence (mutual reinforcement, constant monitoring, communication, etc.) is necessary to maintain the same level of synchronization. Results also revealed that for very low values of coupling, the two systems evolved independently, but that for relatively weak coupling, complex forms of synchronization were achieved. Interestingly, for moderate values of coupling, the systems tended to stabilize one another's behavior, such that each system behaved in a considerably more regular manner than it would have without the coupling (cf. Ott, Grebogi, & York, 1990).

Modeling the synchronization of internal states

To model the synchronization of control parameters, one need only assume that on each simulation step, the value of each person's control parameter drifts somewhat in the direction of the value of the other person's control parameter. The rate of this drift and the size of the initial discrepancy between the values of the respective control parameters determine how quickly the control parameters begin to match. This mechanism assumes that people in social interaction can directly estimate the settings of one another's control parameters. In many types of relationships, considerable effort may be focused on communicating or inferring these settings (cf. Jones & Davis, 1965; Kunda, 1999; Nisbett

[1] In certain conditions, one might assume multiplicative dependence, where the behavior of each person amplifies the state of the other person. For the sake of simplicity in our subsequent simulations, we have limited dependence to additivity. The assumption of additivity reflects the intuition that the resultant behavior is a weighted average of the states of both partners.

& Ross, 1980; Wegner & Vallacher, 1977). Even with such effort, however, the exact values of the relevant control parameters may be difficult or impossible to determine.

In such instances, control parameters may achieve synchronization through behavioral coordination. The facial feedback hypothesis, for instance, holds that when people are induced to mechanically adopt a specific facial configuration linked to a particular mood (e.g., disgust), they tend also to adopt the corresponding affective state (e.g., Strack, Martin, & Stepper, 1988). The matching of internal states to overt behavior is evident as well—and may be enhanced—when the behavior is interpersonal in nature. Even role-playing, in which a person simply follows a behavioral script in social interaction, has been shown to produce pronounced changes in attitudes and values on the part of the role-player (e.g., Zimbardo, 1970).

Behavioral coordination occurs when each person modifies the value of his or her own control parameter in an attempt to match the other person's pattern of behavior. The exact value of the partner's control parameter may be invisible to the person, but he or she remembers the partner's most recent set of behaviors (i.e., the most recent values of x) as well as his or her own most recent behaviors. The person compares his or her own behavior with that of the other person, and adjusts his or her control parameter until there is a match in the partners' respective behavior patterns (cf. Zochowski & Liebovitch, 1997, 1999). If the pattern of the partner's behavior is more complex than his or her own pattern of behavior, for example, the person slightly increases the value of his or her own control parameter. If the partner's behavior is less complex than one's own behavior, on the other hand, the person slightly decreases the value of his or her own control parameter. In effect, each person can discover the partner's internal state by monitoring the evolution of one another's behavior. (The Appendix A provides a formal description of this scenario.)

Fig. 2 shows the time course of synchronization as two maps progressively match each other's control parameters in the manner described above (Nowak & Vallacher, 1998). This simulation was run for relatively weak coupling ($\alpha = .25$). The x-axis corresponds to time in simulation steps, and the y-axis portrays the value of the difference between the two maps. The solid line corresponds to the difference in x (behavior), whereas the dashed line corresponds to the difference in r (internal state). Over time, the difference in the respective control parameters of the two maps decreases, with the maps becoming perfectly synchronized in their behavior. This suggests that attempting behavioral synchronization with weak levels of influence (e.g., control over one another's behavior) will facilitate matching of one another's internal states.

Fig. 3 shows the results when the simulation was run with a stronger value of coupling ($\alpha = .7$). Note that although coordination in behavior develops almost immediately, the control parameters fail to converge, even after 1000 simulation steps. Strong coupling causes full synchronization of behavior, even for systems with very different control parameters. Once the behavior is in full synchrony, the two systems do not have a clue that their control parameters are different. Hence, if the coupling were to be removed, the dynamics of the two respective systems would immediately diverge. This suggests that using very strong influence to obtain coordination of behavior may hinder synchronization at a deeper level. In more general terms, there is optimal level of influence and control over behavior in relationships (cf. Vallacher, Nowak, & Miller, 2003). When influence is too weak, synchronization may fail to develop. Very strong influence, on the other hand, can prevent the development of a relationship based on mutual understanding and empa-

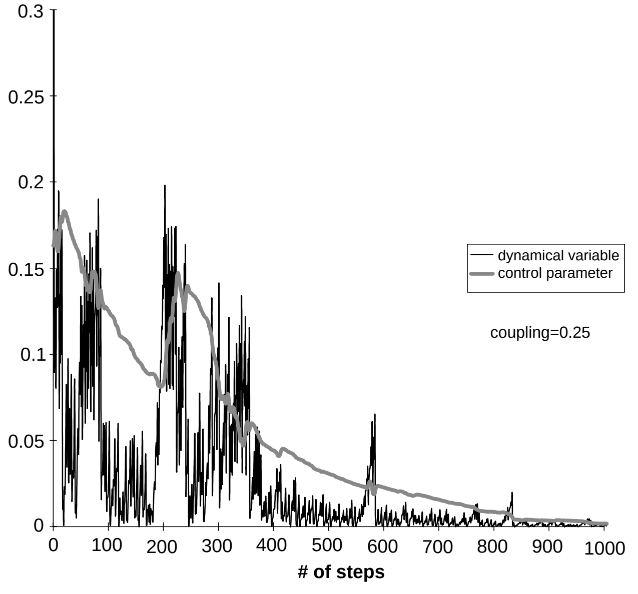

Fig. 2. Development of synchronization under weak coupling. (Source: Nowak et al. (2002). New York: Guilford Press. Copyright © 2002 by Guilford Publications. Reprinted by permission.)

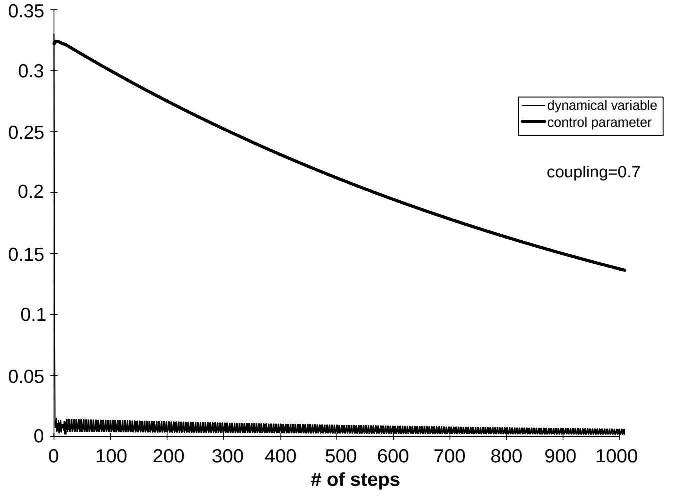

Fig. 3. Development of synchronization under strong coupling. (Source: Nowak et al. (2002). Copyright © 2002 by Guilford Publications. Reprinted by permission.)

thy. Highly controlled partners may fully synchronize their behavior, but they are correspondingly less likely to internalize the values of control parameters necessary to maintain such behavior in the absence of interpersonal influence. For such internalization to occur, intermediate levels of mutual influence would seem to be most effective. Overall, then, the most advantageous degree of coupling is the minimal amount necessary to achieve synchronization.

Modeling personality development

We assume that the values of the control parameter that allow for synchronization of behavior become engraved as attractors that define the person's psychological tendencies. These attractors facilitate further synchronization in social interaction, and shape the person's behavior even in the absence of the interaction partner. To the extent that attractors are engraved during childhood, the synchronization scenario captures essential features of personality development.

In computer simulations of this scenario (Nowak et al., 2002), we investigated the course of synchronization of two interacting systems as a function of initial differences in the value and strength of attractors for the control parameters of the two systems. Specifically, we varied the existence, value, and strength of the attractor for one system (B), and observed how these attractor properties influenced the course of synchronization with another system (A) whose control parameter was kept a constant value of 3.65. In all cases, the control parameters of the two systems initially differed by the same amount. We examined whether, and how quickly, the control parameter of system B would converge on the value of the control parameter for system A. Fig. 4 shows the time course for the convergence of system B's control parameter to system A's control parameter under different scenarios.

In the first scenario, system B had no attractor for its control parameter. In this case, the control parameter of system B matched the value of system A's control parameter over

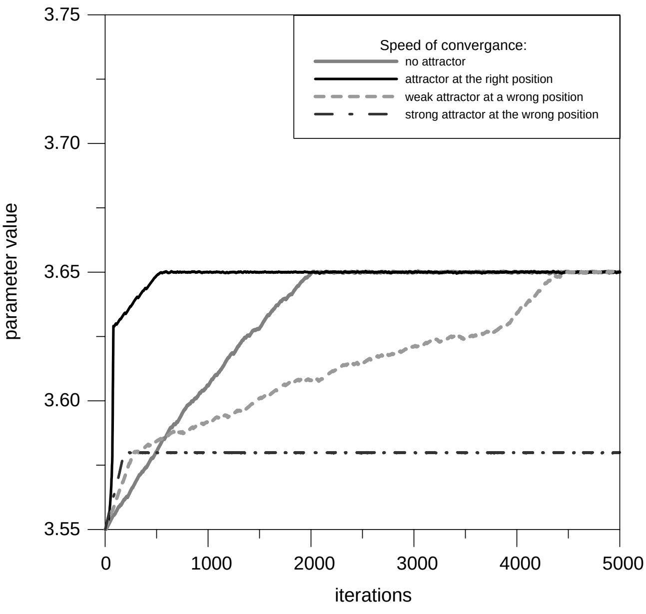

Fig. 4. Development of synchronization as a function of differences in the value and strength of attractors for internal states. (Source: Nowak et al. (2002). New York: Guilford Press. Copyright © 2002 by Guilford Publications. Reprinted by permission.)

a moderate amount of time. In the second scenario, system B had an attractor whose position matched the value of system A's control parameter (i.e., an attractor at the correct position). Such a configuration could be produced, for example, by prior frequent synchronizations between the two systems. In this case, matching of control parameters was achieved on a very short time-scale. This is because there are two mechanisms working in concert: the tendency of system B to match system A's control parameter and the tendency of system B to converge on its own attractor. This scenario represents a situation in which synchronization with another person is fully compatible with one's personal tendencies.

In the third scenario, system B had a weak attractor at a value that did not match the value of the control parameter for system A (i.e., a weak attractor at the wrong position). In this case, system B could eventually match its control parameter to that of system A, but it took a relatively long time to do so because it had to overcome the pull of its own attractor. Matching was eventually achieved because the tendency to synchronize was stronger than the pull of its own relatively weak attractor. Such a scenario corresponds to moderately frequent interactions with others who have a different control parameter than that characterizing one's current interaction partner. In the fourth scenario, system B had a strong attractor at a value that did not match system A's control parameter (i.e., a strong attractor at the wrong position). Under this condition, system B was unable to match the value of system A's control parameter. Instead, system B's control parameter stabilized near its own a priori value. This corresponds to a case in which very strong habits cannot be overcome despite the tendency to synchronize with others.

The second scenario is perhaps the most interesting from our perspective because it shows the functional significance of engraving the values of a control parameter as an attractor. Attractors formed through interaction with a specific type of person enable one to achieve synchronization quickly in subsequent interactions. More generally, the configuration of attractors for personality may reflect an individual's history of synchronization with others. Such attractors in turn may decide with whom the individual will be able to synchronize and thus form personal relationships. This model, in sum, illustrates how personality may be formed in the process of social interactions. Success in the synchronization of behavior, especially under conditions of relatively weak control, may be more important than direct behavior instructions and explicit attempts of transmitting values and norms.

These findings shed light on the finding noted earlier concerning the relative impact of parents and peers on children's personality development (e.g., Harris, 1995; Scarr, 1992). Despite the disproportionate amount of time that children spend with their parents as opposed to any single peer—particularly when they are very young and thus most impressionable—there is reason to think that children develop personality traits that are more similar to those of their peers than to those of their parents. This conclusion is controversial, but it is not particularly surprising in light of the simulation results. Because of the strong coupling characterizing parent–child relationships, children have little need to internalize the values of their parents' control parameters to develop and maintain behavioral coordination with them. In monitoring a child's behavior, praising it when it is deemed appropriate and attempting to suppress or redirect it when it is less so, parents exert fairly constant and strong influence over what the child does. Because parents' behavior control is obvious to the child, he or she learns to act in accordance with the underlying reinforcement contingencies, rules, and expectations.

Children internalize certain lessons from these experiences, of course, and thus may develop certain control parameters that resemble their parents'. The need for adopting parents' internal states, though, pales in comparison to the strategic value of matching the internal states of their peers. Unlike parents, peers are not in a position to monitor a child's behavior, let alone control it on a daily basis. Peers are also less faithful interaction partners than are parents, and the surface structure of their behavior is more erratic as well. These features of peer relations—the relatively weak coupling, the uncertain stability of the relationship, and the potential for unpredictable action—all suggest the practical value of learning the bases for peers' behavior. It's true, too, that it is simply easier to resonate with the interests, moods, and thoughts of someone who is similar to oneself in age, life experiences, competencies, and power. Children certainly love and appreciate their parents, but they probably do not empathize and identify with them as readily as they do with their peers. Synchronization with peers, in short, has the critical ingredients for convergence on common control parameters, and thus may be more influential in engraving the values of such parameters in children's cognitive-affective system.

Our model of synchronization dynamics is consistent with the scenario of attractor development described by Lewis (2000, 2005). In both cases, attractors for internal states are said to develop when these internal states are repeatedly experienced. The more often these states are experienced, the more strongly they become engraved in the person's mental system and pave the way for subsequent experiences of these states. In short, control parameters for internal states become attractors for mental and behavioral processes.

Our results, however, suggest that whether frequently experienced states become engraved in the mental system depends on the degree to which these states are internally generated. Under weak coupling, the mental system of one person needs to tweak its control parameters to match the dynamics of the other person. Such internally generated effort leaves a trace and becomes engraved in the person's system. However, if the person's behavior is directly controlled by the other person (i.e., under strong coupling), engraving is less likely to occur, since behavioral coordination is possible despite differences between interactants' respective internal states. The person, in other words, is unlikely to learn the internal states that maximize behavior synchronization. It is also the case that behavior attributed to external causes is much less likely to promote psychological change than is behavior attributed to internal causes. In research traditions as distinct as cognitive dissonance (cf. Festinger, 1957), self-perception (cf. Bem, 1967; Lepper & Greene, 1978), and psychological reactance (Brehm & Brehm, 1981), people have been shown to resist changing their attitudes and other internal states if they believe that their behavior was in response to direct orders, rewards, threats, and other external influences. Salient external influences, in fact, may induce mechanisms to counter the influences and thus, ironically, create an internal state that counters the influence rather than accommodates it.

Self-organization and the emergence of self-concept

Humans are social animals, but they are also noteworthy for being self-aware. Indeed, the capacity for self-reflection, and especially for self-concept formation, distinguishes humans from virtually every other species (cf. Gallup & Suarez, 1986). Research on this unique feature of human psychology has demonstrated that the self is more than an epiphenomenon, but rather functions as an important platform for the regulation of thought, emotion, action, and interpersonal relations (cf. Baumeister & Twenge, 2003). To the extent that people differ in their respective self-concepts, then, a complete account of personality development must incorporate the dynamics of self-concept formation.

One might consider self-concept formation to be fundamentally different from the formation of attractors through synchronization. Synchronization is inherently an interpersonal process and can occur without conscious representation. The self-concept, in contrast, is symbolic in nature and thus often the target of conscious attention, a process which presumably can contribute to its formation. On examination, however, these two sources of personality share important features. Both classic and contemporary theories on self-concept, first of all, emphasize the social foundations of self-awareness and the sense of self that arises through this process (Baumeister & Twenge, 2003). Goffman (1959), for example, emphasized that the self is a composite of multiple roles, each representing the real or imagined perspectives of a particular social audience. Self-development in this view consists of an ever-widening set of possible selves reflecting the multiplicity of interpersonal concerns. Role theorists share this emphasis on interpersonal experience, and discuss how social relationships becomes internally represented in the person's sense of self and personal identity (cf. Biddle & Thomas, 1966; Sarbin & Allen, 1968). The internalization of societal perspectives is central as well in the approach of symbolic interactionism (cf. Mead, 1934). By seeing oneself through the eyes of other individuals in society, the person develops a structure for understanding and evaluating oneself as an object. In this view, the content of self-concept represents the person's internalized representations of his or her relations with other people, with special weight given to the person's "significant others."

We suggest that self-concept formation is similar to the synchronization scenario not only because it has foundations in social experience, but also because it reflects attractor dynamics. Central to this idea is the ongoing integration of self-relevant information encountered during development and on a daily basis thereafter. In this process, separate elements of information are compared, adjusted, and assembled into higher-order units, each representing a region of the overall self-structure. These integrated units function as attractors for self-relevant thought in that they resist external influence and rebound after disruption from such influences. Individual thoughts about the self may be feeble, in other words, but integrated self-views such as traits, identities, and roles are resistant to change, thereby providing stability in self-understanding and promoting stability in thought, emotion, and action.

The Society of Self model

We recently developed a formal model of self-organization tendencies in the self-system (Nowak et al., 2000b). This model depicts the emergence of global self-concept properties (e.g., self-esteem, differentiation, and self-certainty) as a result of internal integration processes. The self-structure is conceptualized as a complex system composed of cognitive elements representing self-relevant information, with mechanisms of self-organization promoting coherence and stability in self-understanding in much the same way that such mechanisms promote social consensus among autonomous agents in a society. The S*ociety of* S*elf* model details the emergence of coherence in self-structure and illustrates how the self can maintain its coherence in response to incoming information.

The attainment of coherence is possible because the elements of self-structure, though diverse by many criteria, can be scaled with respect to the common parameter of evaluation. Self-relevant information runs the gamut of possible self-evaluation, from memories of misdeeds and perceived character flaws to memorable accomplishments and firmly held values. The elements of self-structure are not static in valence but rather influence each other. An element incongruent with neighboring (thematically related) elements may change its valence or change the valence of its neighbors, so as to establish evaluative coherence with the related elements. "Distractable," for example, may take on positive valence in the context of other self-perceived qualities that together convey an image of oneself as a creative scientist.

We assume that a stable and coherent self-structure can emerge because the separate elements of self-relevant information influence each other via multiple feedback loops. In this process, congruent elements provide cross-validation for each other, whereas incongruent elements set in motion mechanisms designed to eliminate the incoherence or isolate the incongruent elements (e.g., Clary & Tesser, 1983; Hastie & Kumar, 1979). In this way, the salience of low-level elements provides for the emergence of higher-level structures (cf. Vallacher & Wegner, 1987). To build an image of oneself as a good friend, for example, one needs to integrate a wide set of relevant facts and evaluations. This press for integration generates subsets of self-relevant information that are coherent with respect to a shared evaluation. The self-structure thus becomes differentiated, with different sets of elements stabilizing on different values of self-evaluation. A person may have a coherent and positive view of him or herself as a parent, for example, and an equally coherent but negative view of him or herself as an athlete. From this perspective, self-esteem can be viewed as the weighted average of all the self-relevant information in the self-system.

Implementation of the Society of Self model

Models of cellular automata provide a formal platform for investigating properties of systems consisting of mutually interacting elements. Cellular automata are discrete dynamical systems composed of many simple elements. Each element may display two or more states. Time is also discrete, consisting of innumerable successive moments, $t_1, t_2, \ldots, t_n$. The elements are arranged in a specific spatial configuration, usually a two-dimensional lattice. The state of a given element at time $t + 1$ depends on the states of its neighboring elements at time t. In a two-dimensional lattice, for instance, each element may have four neighbors (one on each side) or eight neighbors (the original four plus an additional four in the diagonals). The specific form of this dependence is expressed in updating rules. The updating rules are local in that they specify how the state of a given element in the next moment in time depends on the state of its neighboring elements. A theoretical model is translated into a cellular automata model by appropriate formulation of updating rules.

Cellular automata are well suited for investigating how global properties of a complex system emerge from locally defined rules of influence between lower-level elements. Such models allow one to observe regularities at the system level, such as spatial or temporal patterns, that were not directly programmed into individual elements (cf. Wolfram, 2002). The connections between local rules and collective properties have been identified with respect to such group- and societal-level phenomena as the nature of social influence (e.g., Nowak, Szamrej, & Latané, 1990), the emergence of cooperation (e.g., Messick & Liebrand, 1995), and key features of political and economic transitions in society (e.g., Nowak, Lewenstein, & Szamrej, 1993; Nowak, Urbaniak, & Zienkowski, 1994; Nowak & Vallacher, 2001).

The *Society of Self* model resembles in key respects the model of social influence proposed by Nowak et al. (1990). In this model, the self-system is represented by a square grid of 20 by 20 cells. Each cell corresponds to a specific item of information relevant to the self. The proximity of cells represents their degree of relatedness and thus their potential for mutual influence. The crucial aspect of each item in the simulations is its evaluation. For sake of simplicity, it is assumed that evaluation of an element is either positive, denoted by light gray, or negative, denoted by dark gray (see Fig. 5). Because the elements can be in one of only two states (i.e., either positive or negative), when they change they do so in an all-or-none rather than in an incremental manner.

The elements also differ in their respective importance, which is represented by a number between 2 and 10, with higher numbers denoting greater importance. An element's importance is displayed as its height in Fig. 5. Importance determines the strength of an element's influence on other elements and does not change during the course of simulation. We also assume that, to some degree, importance characterizes regions of self-structure, so that neighboring elements have similar strength. To represent this assumption, we randomly positioned three maximally important elements (i.e., elements with an importance value of 10) in the grid and surrounded them with rings of elements with gradually decreasing importance. Islands of relatively important elements correspond to personally meaningful and central domains of the self.

To study how the self can achieve organization, we assumed that items of self-relevant information initially are not integrated. The simulations therefore began with a system that is totally disordered with respect to evaluation. We assumed that the governing principle for integrating self-relevant information is a press for evaluative coherence (e.g., Festinger, 1957; Heider, 1958; Osgood, Suci, & Tannenbaum, 1957). Local rules of influence between elements provide the mechanisms by which the system achieves coherence. This can happen if the evaluation of each element is changed to match the prevailing evaluation among its neighbors. We assume that each element has eight neighbors, four adjacent cells and 4 four on the connecting diagonals.

In the course of simulation, each element tries to determine the dominant evaluation in its local region so it can change its own evaluation, if necessary, to match the prevailing evaluation of the region. This involves weighting the valence of each neighbor by the neighbor's importance, which is equivalent to computing the weighted sum of evaluations of the neighboring elements, reflecting a process similar to information integration

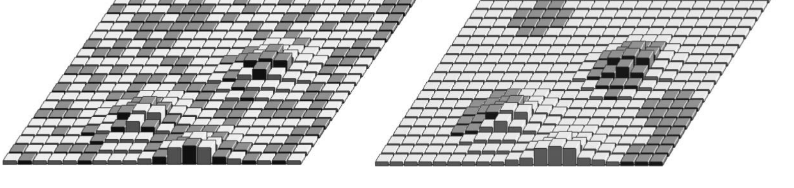

Fig. 5. Self-organization and the emergence of self-concept. (Source: Nowak et al. (2000b). Copyright © 2000 by the American Psychological Association.)

(Anderson, 1981).[2] If the sign of the element agrees with the overall evaluation suggested by its neighboring elements, no change in the element's evaluation takes place; in effect, its evaluation is confirmed by the comparison process. If the sign of the element differs from the overall evaluation suggested by its neighboring elements, the element changes evaluation, but only if the combined weight of evaluation from other elements is higher than the element's own weighted evaluation. In other words, relatively unimportant self characteristics can be changed easily, but important elements require a strong disconfirming influence from neighboring elements to change. After the element's state is adjusted, another element is randomly chosen in a Monte Carlo fashion and the process is repeated. This process continues until the system reaches an asymptote, reflecting either no further change in the states of elements or a stable pattern of changes in the system.

The results of computer simulations run by Nowak et al. (2000b) illustrate how self-relevant information may become differentiated into coherent substructures (Fig. 5), each corresponding to a distinct aspect of self-perception (e.g., social roles, traits, and areas of competence). The first grid represents a self-system with a random configuration of positive and negative elements. The second grid represents the same self-system after being subjected to the integration process. Note that the self-system has become differentiated into coherent regions (i.e., clusters of negative elements surrounded by areas of positively valenced elements) and that the initial positivity bias has been enhanced (i.e., the number of positive elements has increased) (cf. Nowak et al., 2000b). A very simple locally defined integration rule (i.e., match one's neighbors) has thus resulted in global organization of the self-system.

Coherence and attractor dynamics

Subsequent computer simulations revealed that the degree of integration attained by the self-system depends on how strongly each element is influenced by its neighboring elements. When this "press for integration" is strong, self-relevant information tends to achieve integration into locally coherent clusters. When the press for integration is weak, however, self-relevant information may remain unintegrated, with each region representing a mix of positive and negative elements. Variation in press for integration has counterparts in psychological theory (Nowak & Vallacher, 1998). A weak press for integration corresponds to distraction, cognitive busyness, and lack of self-awareness, whereas a strong press for integration corresponds to executive processes, availability of cognitive resources, and self-focused attention.

The results of computer simulations also revealed that a differentiated (locally coherent) self-system is relatively resistant to external influences, especially under a strong press for integration. This is because each element in a coherent region that is challenged by external influence is supported by influence from its neighboring elements. To be effective in changing an element, the external influence must be stronger than the element plus the combined influence of other relevant elements (its neighbors). If a person has evaluatively coherent sense of him or herself as a competent writer, for example, even a stinging critique of an essay can be countered by a wide variety of other relevant information (e.g., others' comments, awards, etc.). Results also revealed that even when a coherent region

[2] Since the number of elements entering into each computation is constant (i.e., 8), the weighted sum of elements is directly proportional to the weighted average of elements.

yields to external influence, it tends to rebound in a fairly short period of time. This result reflects the ongoing operation of the integration process, which is likely to realign the challenged element with its neighbors. On the macro level, both self-evaluation and self-differentiation are likely to be maintained and restored after challenges from the outside (e.g., disconfirming social feedback).

The simulation results suggest that the coherence of self-structure determines the fate of internally and externally generated self-relevant thoughts. Because the elements in a coherent region support and validate each other, thoughts that correspond to the valence of these elements receive support and become stable, whereas thoughts that conflict with the region's evaluative tone are overpowered by the combined influence of the region's elements and destabilized, changed in valence, or rejected. In dynamical terms, a coherent region functions as an attractor for self-relevant thought. In an incoherent region, in contrast, elements receive conflicting influences from other relevant elements and thus are vulnerable to external influence. This is because some of the neighboring elements counter the influence, while others support the influence, so that the combined influence of the neighboring elements is incoherent, with one element canceling the influence of another element. The dynamics of an incoherent region, in other words, are less likely to conform to attractor dynamics.

The tendency for the stream of thought to converge on the evaluative state associated with a coherent region promotes a sense of self-certainty, a property of self-concept that has received considerable attention in recent years (e.g., Campbell, 1990; Kernis, 1993; Pelham, 1991; Vallacher, 1980). In an incoherent region, by contrast, both positive and negative thoughts are supported by some elements and rejected by others. This conflicting influence renders self-relevant thought prone to external influence, volatility, and change. Incoherent regions thus promote a lower sense of self-certainty. Individuals who think about their behavior in narrowly defined terms as opposed to broad categories, for example, are uncertain about themselves with respect to trait dimensions and are susceptible to social influence (Vallacher et al., 2003; Vallacher & Wegner, 1989).

Because integrated regions of self-structure establish clear standards for self-relevant thought, they have strong potential for self-regulation (cf. Vallacher & Nowak, in press). This potential may be manifest, for example, in people's response to social feedback about their personal qualities. Someone lacking coherence may embrace feedback regardless of its valence, but for someone with high coherence the likelihood of incorporating inconsistent feedback into the self-structure is low. Research conducted within different paradigms provides evidence for the connection between self-concept coherence and vulnerability to socially provided self-relevant information (e.g., Kernis, 1993; Swann, 1990; Vallacher & Wegner, 1989).

The attracting tendency of coherent regions also has implications for action. When presented with an incentive to act in a selfish manner, for example, a person with a coherent self-view as a moral agent may resist the temptation to do so, because the mutual support of elements in that region of self-structure overpowers the incoming information. Differential coherence across regions of self-structure, meanwhile, enables the person to choose among alternative courses of action reflecting these regions. Consider, for example, a person with a self-view that is more coherent with respect to morality than to achievement. When a choice between actions is encountered, he or she is more likely to see and act upon the morality aspects of the choice than on the achievement aspects. Self-regulation should be problematic for people lacking self-structure coherence. Action control with respect to goals, values, and traits is likely to be erratic and to falter when obstacles to attainment are encountered. For such a person, action tends to be governed by external influence, momentary impulse, and opportunity rather than by purpose, commitment, and other criteria of self-regulation. And when confronted with alternative courses of action reflecting different regions of self-structure, the person is likely to experience difficulty in choosing one course over the other, and to make choices that are inconsistent from one occasion to the next.

Implications for issues in personality

People are deeply invested in establishing stable and meaningful relationships with one another. The concern with interpersonal relations provides an important mechanism for the generation of individual differences with respect to a variety of internal states. Individual differences, in turn, are manifest in the choice of relationship partners and shape the course of social interactions with them. This reciprocal feedback loop between social interaction and personality is complicated by the human capacity and proclivity for self-reflection. Below we discuss the implications for personality development and expression of both dynamic processes and of the relationship between them.

Personality and social interaction

The temporal coordination of expressed thoughts, feelings, and actions between individuals represents a defining feature of social interaction. To a certain extent, the synchronization of interpersonal experience can be achieved through mechanisms of direct influence, such as communication, monitoring, and reinforcement. Successful synchronization is more efficiently attained, however, by the matching of relevant internal states that dictate the tempo and content of social interaction. By achieving concordance in internal states, interacting individuals do not need to expend as much energy monitoring and influencing each other's actions directly. Rather, they can spontaneously synchronize their verbal and behavioral output over time by virtue of their common wellspring for action.

To the extent that a person's internal states promote prolonged synchronization, they become engraved as attractors in the person's cognitive-affective system and thus provide for regularity and consistency in his or her behavior. Once specific internal states are established as attractors, moreover, they guide the choice of subsequent interaction partners. Because these choices are based on the potential for effective synchronization, people seek out others with similar attractors for internal states. Interaction with these partners, in turn, tunes and reinforces the person's attractors. This positive feedback loop between social interaction and personality may serve as an important mechanism promoting stability in personality, despite the continual turnover in relationships characterizing social life.

If this feedback loop is broken, however, the decoupling of the individual from similar others has the potential for producing a drift in the individual's attractor values. This is because of the internal forces within the person's cognitive-affective system that operate independently of incoming information or social influences. The intrinsic dynamics of thought produced by these forces can take the form of attitude polarization (cf. Tesser, 1978), sustained oscillations between evaluatively conflicting judgments (cf. Vallacher, Nowak, & Kaufman, 1994), and repeated episodes of thought deconstruction and emergent understanding (cf. Vallacher, Nowak, Markus, & Strauss, 1998). The intrinsic dynamics of thought are critically important for establishing and maintaining coherence in the cognitive-affective system as a whole (Vallacher & Nowak, 1999), but if such processes are unchecked by social reality, they may cause the control parameters that enable synchronization to drift to new values that hinder future interactions, which in turn can reinforce the person's social isolation (Vallacher et al., 1998). It's noteworthy that individuals who commit random acts of violence (e.g., shooting rampages) are often described in fairly benign terms as loners who do not bother other people. The existence of social relations is critical not only for the development of personality structure, but also for its maintenance.

Personality and consistency

People may desire to interact with similar others, but often their choices are constrained. A person can choose with whom to talk at a party or establish an intimate relationship, but he or she has little control over the identities of his or her parents, teachers, and co-workers. If these people have different attractors for control parameters, the person's interaction with them can create new attractors in his or her system. If the person has synchronized with a relatively homogenous collection of individuals and groups, then a single attractor is to be expected. But to the extent that relationships are formed with widely different individuals and groups, the person is likely to have formed multiple attractors for various internal states.

Each attractor attracts states within its basin of attraction. Thus, the same person may actively pursue highly energetic interactions in one setting but very relaxed interactions in another setting, depending on which basin of attraction captures the person's internal state in each setting. In this view, cross-situational consistency in behavior would signify a single attractor for the dimension in question. But even here, the degree of consistency would depend on the strength of the attractor. If the attractor is relatively weak and easily destabilized, the person's behavior may appear to be governed by forces in the situation. A person might be inclined to pursue relaxed social interactions, for example, but if the basin of attraction for this attractor is narrow or the attractor value is easily destabilized, he or she might be decidedly non-relaxed if the situation is tense or otherwise calls for more volatile behavior.

By the same reasoning, the meaning of temporal and situational variability on a particular dimension is not always clear. High consistency of a given behavior over time and across contexts indicates that the system is stabilized with respect to a strong and narrow attractor, but the lack of such consistency is open to three alternative interpretations. A high degree of variability, first of all, could simply mean that the person does not have an attractor for this parameter, but instead is responsive to external forces and noise in his or her behavior.[3] A second, equally plausible interpretation is that high variability represents the presence of a single, relatively flat attractor with a wide basin of attraction.

[3] Conceivably, some people may fail to achieve stable attractors with respect to any internal state relevant to social interaction. In research relevant to this possibility, Vallacher and Wegner (1989) found that people differ in the extent to which they characteristically identify their behavior in relatively low level, mechanistic terms as opposed to higher level, comprehensive terms reflecting consequences and self-evaluative implications. Compared to "high-level agents," the "low-level agents" were less certain of their standing on common trait dimensions and were more open to social feedback regarding themselves with respect to certain personality traits. Interestingly, the low-level agents were also more likely to have experienced environmental and interpersonal instability during childhood. This association is consistent with the synchronization perspective, since prolonged interaction with specific others fosters the engraving of attractors for internal states.

Variability in this case would signal flexibility in the person's control parameter for behavior rather than the absence of the corresponding internal state. The third possibility is that high variability reflects the presence of two or more attractors, with noise or a consistent external influence moving the system between their respective basins. A person characterized by such a landscape might have two or more distinct—even conflicting—settings with respect to a particular control parameter, each of which provides a stable platform for action. In this case, the person may display considerable variability in his or her social behavior, depending on the interaction partner and social context, yet act in accordance with his or her personality in each instance.

More generally, the dynamical perspective suggests that a person's standing on a dimension of individual variation does not simply represent some aggregate value or central tendency of the person's behavior (cf. Caprara & Cervone, 2000; Mischel & Shoda, 1995). First of all, not everyone can be characterized with respect to preferences on every possible dimension (cf. Bem & Allen, 1974; Markus, 1980). For some people, the ability to synchronize may require settings of some parameters (e.g., conscientiousness) but not of others (e.g., independence). Only for those parameters that develop energy landscapes can one detect internal forces attributable to personality. For those parameters without clear energy landscapes, the person's behavior is likely to reflect the impact of forces in the immediate situation. Even if a person has developed stable attractors for a given dimension, the existence of multiple attractors renders the description of average tendencies misleading, because such values may represent a setting the control parameter never adopts. Someone who has tendencies toward both aggressive and conciliatory behavior, for example, may never demonstrate the average of these two tendencies, although an approach emphasizing aggregation would make this prediction.

Personal versus situational causation

The exact value of a psychological system at a given moment is influenced by a host of biological, cognitive, environmental, and social factors. The combined effect of these forces may be represented as a random influence or "noise." Noise can be envisioned as "shaking up" the landscape, with the potential for qualitatively changing the dynamics of the system. In the presence of low noise, the value of the system will hover around its attractor rather than remain at its precise value. For stronger values of noise, weaker attractors may become unstable and lose their ability to capture the dynamics of the system. This scenario provides insight into the well-documented tendency for people to engage in dominant responses under conditions of stress and other forms of arousal (Zajonc, 1965). Thus, weak attractors, representing non-dominant responses, are destabilized under such conditions, leaving the person with only his or her strongest attractor.

Under very high values of noise, even strong attractors may become unstable and the system may be unable to achieve any coherent mode of functioning. In this case, internalized states no longer provide cues to thought, emotion, and behavior. This scenario corresponds to the loss of individuality and heightened attention to situational cues under high stress or other "noisy" circumstances that can destabilize internalized bases for action (e.g., Diener, 1980; Turner & Killian, 1957; Zimbardo, 1970). Under conditions that promote panic, for example, everyone may behave the same way (e.g., run), despite considerable variation in each person's characteristic emotional reactions, thought processes, and behavioral tendencies.

The reasoning suggests a curvilinear relationship between noise and the expression of individual differences. Under low levels of noise (e.g., minimal outside influences, low levels of stress), most people can adopt a wide variety of internal states, even those corresponding to a relatively weak attractor. Clear individual differences thus are unlikely to be observed, since most people can modify their behavior to match the norms and expectations they experience from one context to the next. Individual variation is also unlikely to be observed under conditions of high noise, because even strong personal attractors are destabilized. People are likely instead to behave in a reactive fashion to the forces acting on them. Under such conditions, in other words, personality represents a fairly weak force in generating behavior. Personality is likely to be manifest under moderate levels of noise, however, because of the tendency for such conditions to destabilize all but the strongest attractors in people's energy landscape. Thought, emotion, and behavior in this case are likely to reflect a person's most deeply engraved tendencies, with weaker tendencies being psychologically unavailable.

Personality and self-concept

Social interactions are clearly relevant to the development and maintenance of stable internal states that function as attractors for thought, affect, and behavior. Because of people's capacity for self-reflection, however, the effect of social experience is not limited to its occurrence. Long after an interaction has occurred—indeed, long after a social relationship has ended—a person can reflect on the his or her experience and evaluate it in the context of other social and non-social sources of self-relevant information. In thinking about his or her behavior over the past few years, for example, a person may note his or her penchant for approaching social interactions in a friendly manner or his or her tendency to establish social relations with energetic people. Each interaction or relationship may have been undertaken with a different identification of what he or she is doing—wanting to have a good time, seeking excitement, pleasing a mutual friend, etc.—but the press for integration in self-understanding may generate a higher-level act identity that integrates these diverse experiences. In this sense, self-reflection builds on synchronization and promotes higher-level understanding of one's behavioral tendencies.

Given people's remarkable capacity for interpretation, however, there is no guarantee that the self-concept that emerges via self-organization processes will perfectly match, let alone accurately integrate, the attractors for social behavior that develop via synchronization. A person may develop an attractor that promotes synchronization with energetic people, for example, but self-reflection on this tendency might lead to different conclusions regarding his or her personality—not simply as energetic, but perhaps as anxious or domineering. Particularly if different attractors are brought into mental juxtaposition, there is considerable potential for a person's self-understanding to depart from what an objective perspective on his or her interaction tendencies would suggest. If a person's history of synchronization has engraved attractors for both optimistic and pessimistic interpersonal tendencies, for example, the person might think of him or herself as inconsistent on this dimension or perhaps as insincere, displaying different facets depending on their strategic value with specific interaction or relationship partners.

There are many unanswered questions regarding the link between the synchronization and self-reflection foundations of personality. What is the relation between the attractors that develop via interpersonal synchronization and those that develop due to people's capacity for self-reflection? Is there a general correspondence between synchronization and self-reflection dynamics? Are some features of personality functioning especially prone to divergence between implicit, experiential foundations and explicit, self-conscious constructions? Do some people tend to show greater divergence in this regard than others? Are there self-correcting feedback mechanisms that bring a person's self-concept into line with his or her synchronization tendencies? Conversely, can self-reflection override synchronization tendencies, creating attractors for interpersonal behavior that match the person's self-conceived attributes? These and no doubt a host of other questions constitute an agenda for theory and research in the years to come. Hopefully, such efforts will provide into insight into the interplay of social experience and self-reflection in shaping and maintaining stable internal states.

Conclusions, caveats, and future iterations

The notion of personality implies some form of stability in thought, emotion, and action. At the same time, human experience is inherently dynamic and constantly evolving in response to external circumstances and events. These conflicting human tendencies can be reconciled by conceptualizing personality as a set of attractors for the dynamics of experience. Attractors are central to regulation, in that they constrain and channel the flow of mental and behavioral phenomena. Indeed, the absence of fixed-point attractors has been implicated in the breakdown of self-regulatory functions, which may result in severe personal problems (Johnson & Nowak, 2002). Lewis (2000, 2005) points out that these attractors operate on multiple timescales and at multiple levels of functioning. The models we have presented concerning interpersonal synchronization and self-concept formation, meanwhile, provide scenarios by which attractors are formed and expressed. In personality development, then, both social processes and internal integration processes are of central importance.

Our aim in this article was not to propose a new set of dimensions for describing individual differences. The approach we have outlined is intended to provide a dynamical framework for describing and investigating how social experience and self-reflection create stable internal states for regulating interpersonal behavior and other psychological processes. Lewis' (2005) model, however, provides clues concerning the possible nature of the internal states that are engraved as control parameters and the mechanisms by which they are maintained. In particular, he proposes that cognitive-affective amalgamations are created and maintained by positive feedback loops among cognitive and affective elements. He also proposes the neurophysiological structures that are involved in the formation of attractors for these cognitive-affective states. In so doing, he charts a course for the direct testing of the proposed mechanisms and also for their investigation with neuro-imaging techniques.

It is likely that the control parameters for internal states run the gamut from highly specific thoughts and feelings to broad values, traits, and self-views. Some internal states, however, may be more critical than others for interpersonal synchronization and self-understanding and thus especially likely to become engraved in people's cognitive-affective system. The "big five," for example, have been shown to have a great deal of universality (cf. Costa & McCrae, 1995) and one can easily make the case for the role of each these traits in social relations. The same can be said for taxonomies of interpersonal orientation, such as dominance-submission and agreeableness (cf. Wiggins, 1980), temperament dimensions (cf. Buss & Plomin, 1984), and basic values such as achievement, affiliation, intimacy, and power (cf. Atkinson, 1964). It remains for future research to identify which classes of internal states are most responsive to experiences of interpersonal synchronization and which provide the most plausible and sustainable bases of self-concept.

Biologically based dispositions are interesting to consider in this regard (cf. Plomin, Owen, & McGuffin, 1994). To the extent that these characteristics represent pre-wired attractors for specific internal states, their settings may be relatively unresponsive to a person's history of social interactions and difficult to discount or reinterpret in self-reflection. If this is the case, people may experience difficulty achieving synchronization on these dimensions with dissimilar others, regardless of the stability of the interaction context (see, e.g., Dunn & Plomin, 1990; Harris, 1998), and they may have difficulty as well in denying the relevance of these dimensions to self-evaluation. Even the most genetically influenced personality characteristics, of course, are shaped to some degree by environmental influences and interpretation. Future research on this point could explore whether such influences simply modify a person's "innate" attractors for internal states, or instead engrave entirely new attractor values that vie for prepotence with the pre-existing values.

Finally, we do not claim that interpersonal synchronization and self-organization are the only means by which experience engraves attractors in people's cognitive-affective system. Theory and research in personality science have identified a host of other plausible mechanisms of personality development and maintenance, including direct reinforcement, social learning and modeling, labeling and self-fulfilling prophecies, identification, and guilt induction. Such processes can perhaps be viewed in dynamical terms, each associated with a particular balance of coupling and the progressive matching of internal states or with a specific self-organization tendency. But this is not a foregone conclusion. Hopefully, research in the years to come will establish the social mechanisms responsible for individual variation, and identify the interactions among these mechanisms that give rise to each person's uniqueness. Only through repeated iterations of the scientific method can we hope to achieve a stable attractor for our theoretical understanding of the interplay between personality and social interaction.

Appendix A.

We used a system of two coupled logistic equations to model complex interactions between individuals:

$$f(x) = px(1 - x).$$

Logistic map is a discrete system exhibiting a wide variety of dynamical behaviors. Dependent on its control parameter (p), the system can change the type of its dynamics from periodic to chaotic.

The proposed model incorporates two separate mechanisms that allow for: (1) adjustment of macroscopic properties (control parameters) of interacting systems; and (2) synchronization of the two systems. This is achieved through application of a double, fast and slow, coupling of a target system based on ***single type*** of signal emitted by a control system (Fig. 6).

In some of the simulations, the applied coupling was reciprocal (i.e., the control system was a target system at the same time, receiving input from the other coupled unit).

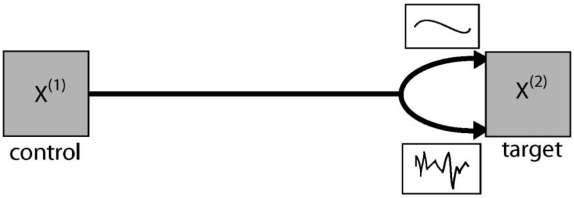

Fig. 6.

The fast coupling is applied through a direct coupling of the iterates of the control map to the target map. Thus, this coupling monitors instantaneous changes in the evolution of the control map:

$$x_{n+1}^{(1)} = f(x_n^{(1)}, p_n^{(1)}),$$

$$x_{n+1}^{(2)} = \frac{f(x_n^{(2)}, p_n^{(2)}) + \varepsilon x_n^{(1)}}{1+\varepsilon},$$

where $\epsilon = 0.25$ is a coupling strength.

The slow coupling, on the other hand, integrates signal acquired from the control system over longer time and determines macroscopic properties of the signal (i.e., is the control map in periodic or chaotic regime, what is the specific type of the dynamics, etc.). This information is then compared with the internal properties of the target system and allows the target system to adjust its dynamics (through changes of the control parameter) to better match that of a control system. This is achieved through estimation of Liapunov exponents:

$$\lambda = \lim_{N\to\infty} \frac{1}{N} \sum_{i=1}^{N} \ln \left| \frac{\mathrm{d}f}{\mathrm{d}x} \right|.$$

Here we estimate the Liapunov exponent as a running average

$$\lambda_{n+1} = \frac{\lambda_n + \alpha \ln \left|\frac{\mathrm{d}f}{\mathrm{d}x}\right|}{1+\alpha},$$

where $\alpha = 1.0$ is a weight that determines the contribution of the new value to the running average.

We then compare the resulting Liapunov exponents of the two coupled systems by defining a function

$$A(\lambda_n^{(1)}, \lambda_n^{(2)}) = \left(\left|\lambda_n^{(1)} - \lambda_n^{(2)}\right|\right)^{1/4} \mathrm{sgn}\left(\lambda_n^{(1)} - \lambda_n^{(2)}\right).$$

Additionally, we define for each system a parameter surface $\boldsymbol{L}(\boldsymbol{p})$, which consist of predefined or learned attractors. The evolution of the parameter may be seen as a ball rolling on a sloping surface. The slope of the surface is determined by function $\boldsymbol{A}$, where as the wholes, and valleys are the local attractors. Thus, the changes of the control parameter are modulated by the local shape of the attractor and the dynamics of the control parameter takes the form:

$$p_{n+1}^{(2)} = p_n^{(2)} + \gamma A(\lambda_n^{(1)}, \lambda_n^{(2)}) + \beta\left(\frac{\mathrm{d}L^{(2)}(p_n^{(2)})}{\mathrm{d}p}\right),$$

where $\gamma = 0.0004$ determines the speed of parameter adjustment and $\beta = 0.00005$ defines the contribution of the local shape of the parameter surface. The parameter surface is by itself a dynamic identity and may undergo changes like the creation of new attractors (learning) or the disappearance of old ones (forgetting):

$$L_{n+1}^{(2)}(p) = L_n^{(2)} - \phi\cos^2\left(\frac{\pi}{2\kappa}\left|p - p_n^{(2)}\right|\right) + \theta.$$

The second term on the right hand side is the learning term (κ is the width of constructed attractor), where as θ is the forgetting term. Thus, during learning the system modifies its landscape locally, but forgets indiscriminately. Additionally, we set the constraints to limit the depth of the attractors and set the baseline

$$\phi = \begin{cases} 0 & \text{if } L(p) \leqslant -1, \\ 0.00007 & \text{if } L(p) > -1, \end{cases}$$

$$\theta = \begin{cases} 0 & \text{if } L(p) \geqslant 0, \\ 0.00002 & \text{if } L(p) < 0. \end{cases}$$

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