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Finding the Attractor of Anger: Bridging the Gap Between Dynamic Concepts and Empirical Data

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Although it accounts for the prototypical course of emotions, the attractor concept has hardly ever been used empirically. Authors applied Empirical Differential Equations (EDE) to frequent (hourly) anger ratings to find the attractor of anger. The attractor concept, its neurological basis, and EDE are explained. The attractor of anger follows an underdamped oscillator, and is affected by the capacity to inhibit prepotent responses. Anger accelerates less fast when inhibitory control increases. Results stress the internal dynamics of emotions, and help to bridge the gap between concepts from dynamic systems theory and empirical data.

Keywords: attractors, anger, emotional system, differential equations, modeling

Emotional theorizing is changing fundamentally. Although the theoretical focus was first on emotions as states or things (Frijda, 2000), nowadays it changes toward emotions as dynamic phenomena (Barrett, Ochsner, & Gross, 2006; Frijda & Zeelenberg, 2001; Lewis, 1996, 2005; Lewis & Granic, 2000a; Scherer, 2001). 'Attractor,' 'state space,' 'positive feedback,' 'negative feedback,' 'state transition,' 'chaos', 'catastrophes,' and other concepts from dynamic systems theory are increasingly used to explain emotional phenomenon (Lewis & Granic, 2000b). Mascolo, Harkins, and Harakal (2000), for instance, used the attractor concept to explain individual differences in interpersonal anger. Similarly, Scherer (2000) used concepts from Thom's catastrophe theory (Thom, 1975) to explain a possible nonlinear relationship between frustration and anger.

These new concepts are theoretically very appealing, because they offer conceptual and technical means to understand the dynamics of emotions. They provide tools to describe, analyze, and understand why emotions change, come and go, rise and drop, as they seem to do. There is, however, still a considerable discrepancy between the theoretical use of dynamic systems concepts and their empirical application. Scherer (2000) even wondered whether the new dynamic systems approach offers only a new 'Sprachspiel,' or would lead to a real paradigm shift. In the end, the view of the emotional system as a dynamic system will only be fruitful when it leads to *empirical* applications that recognize the dynamic nature of emotional phenomena involved (cf. Bogartz, 1994; Granic & Hollenstein, 2003; Keating & Miller, 2000; Lewis, 2005).

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The lack of empirical applications of dynamic systems concepts is hardly surprising given the ubiquity of ANOVA-like models and corresponding lack of data analytic tools that may capture nonlinear change empirically (Granic & Hollenstein, 2003). An additional problem accounting for the lack of empirical applications is the scarcity of time-series data that are needed to analyze nonlinear change; however, this situation is changing. Boker and colleagues (Boker, 2001; Boker & Chisletta, 2001; Boker & Nesselroade, 2002) introduced an innovative statistical method, designated Empirical Differential Equations (EDE), to model dynamic phenomena. Boker (2001) argued from a theoretical point of view that EDE would be well suited to study the *attractors* of dynamic systems, including the emotional system. Matching this statistical development so-called Experience Sampling (Bolger, Davis, & Rafaeli, 2003; Brandstätter, 1977; Csikszentmihalyi, Larson, & Prescott, 1977; Hoeksma et al., 2000), a sampling method resulting in time series of emotional and behavioral phenomena, is used more and more (cf. Barrett et al., 2007).

The goal of our work is to help bridging the gap between theoretically important concepts from the dynamic systems approach (Lewis & Granic, 2000a; Thelen & Smith, 1994) and their application to empirical data (cf. Lewis, 2005). Specifically, the present study explored the empirical application of the attractor concept to describe the dynamics of anger. As will be explained below, an attractor can be seen as an attribute of the emotional system. It explains how the momentary states of the emotional system change in a regular consistent way, and accounts for the prototypical patterns of emotions or emotional episodes observed in daily life (cf. Barrett, Ochsner, & Gross, 2006; Russell, 2003).

To explore the attractor concept empirically we performed a secondary analysis, using EDE, on recently published time series data of Hoeksma, Oosterlaan, and Schipper (2004). The data consisted of frequent (hourly) ratings of anger collected during three to four consecutive days by means of the Electronic Mood Device (Hoeksma et al., 2000), supplemented with individual measurements of inhibitory control (i.e., the capacity to inhibit a prepotent response), obtained by means of a Stop Signal Reaction Task (Logan, 1994; Logan & Cowan, 1984).

The primary analysis of Hoeksma et al. (2004, p. 358) revealed a negative relationship between inhibitory control and the within-person variability of anger ($r = .41$, $p < .05$, one sided, $n = 27$). That is, when the capacity to inhibit a prepotent response decreased the variability of a person's anger increased. This suggests that individuals with better inhibitory control experience slower rising and less peaked anger responses, whereas individuals with less inhibitory control experience faster rising and higher peaked anger responses. As to be explained, the attractor concept may capture such differences in affective chronometry (Davidson, 1998) not only theoretically, but also empirically.

We will try to close the gap between the theoretical and empirical use of the attractor concept from both the psychological and the data analytical side. First, we will note that the emotional system contains sets of positive and negative feedback loops (LeDoux, 2002; Lewis, 2005; Panksepp, 1998; Sander, Grandjean, & Scherer, 2005; Siegel et al., 1999) that are considered necessary building blocks of dynamic systems (Box, Jenkins, & Reinsel, 1994; Thelen & Smith, 1994). Positive and negative feedback loops account for the time course of anger and how this course is affected by inhibitory control. Next, we will discuss the mathematical and psychological meaning of the attractor concept. Because the present approach is still relatively new and unfamiliar, the attractor concept will be discussed rather extensively. Four qualitatively different attractors, based on the so-called linear oscillator model (Boker, 2001), will be explained. They account for four qualitatively different sets of nonlinear temporal changes. Subsequently, we will discuss how behavioral inhibition affects the attractor of anger through negative feedback. Finally, after discussing the place of feelings in the emotional system (cf. Damasio, 2003), the attractor of anger and the role of inhibition in controlling anger will be investigated empirically.

Anger

Anger may be triggered by goal blockage, a demeaning offense of me or mine (Lazarus, 1966), a "challenge of what ought to happen" (Frijda, 1986, p.199), or possibly an aversive state of affairs (Berkowitz & Harmon-Jones, 2004). Depending on how anger is regulated (Thompson, 1994; Gross, 1999), it will follow a particular time course. Anger is a dynamic phenomenon that feels as a fast rising urge to attack someone or push a blocking object out of the way. However strong the impulse it is often inhibited (Lazarus & Lazarus, 1994).

At a neurological level the dynamics of anger, its specific temporal pattern, apparently result from two apposing processes, excitatory and inhibitory processes, or positive and negative feedback processes (Frijda, 1986; LeDoux, 2002; Lewis, 2005). Somewhat older research, largely based on animal research, suggests a unitary but not exclusive system dedicated to anger (Panksepp, 1998; Siegel et al., 1999). This so-called *rage system (*Panksepp, 1998) is thought to consist of a number of interrelated neurological structures, including the medial amygdala, the medial hypothalamus, and parts of the Periaqueductal Gray (PAG; Panksepp, 1998; Siegel et al., 1999). These structures project reciprocally to each other, forming a set of feedback loops (Gregg & Siegel, 2001; Panksepp, 2000; Price, 2003) that may account for the temporal course of anger.

The unitary view involving circuits dedicated to specific emotions has been challenged on biological and psychological grounds by Barrett, Ochsner, and Gross (2006); Morgane, Galler, and Mokler (2005), and others. These and other authors (e.g., Lewis, 2005; Sander et al., 2005) endorse a dynamic systems perspective and argue that emotions emerge from complexes of interacting brain systems. Emotions cannot be localized or represented as a locus, but rather are emergent properties of the *activity* of coherent distributed functional systems (Morgane et al., 2005). The literature offers various theoretical proposals of what makes up these complexes of brain systems producing emotional activity (cf. Barret et al., 2007; Lewis, 2005; Sander et al., 2005; Wagar & Thagard, 2004). These proposals differ in several ways, but agree that the systems consist of a smaller or larger number of neurological structures that directly or indirectly project to each other, allowing for positive and negative feedback processes, which on their turn may account for the temporal course of emotions, including anger.

Thus, both the unitary approach and the dynamic systems approaches agree that anger results from positive and negative feedback loops that allow for increasing and decreasing neurochemical activity (cf. LeDoux, 2002), accounting for the temporal course of anger.

Attractors

Together the positive and negative feedback loops of the emotional system make up a dynamic system, allowing for continuous state changes. Theoretically, the system can take on an infinite number of potential states. However, in daily life the states go through a limited number of temporal patterns. Anger, like other emotions, follows a prototypical pattern (Russell, 2003). According to the principles of dynamic systems theory such stable temporal patterns emerge from the positive and negative feedback loops the system is made of (Granic & Hollenstein, 2003; Thelen & Smith, 1994). In other words, the feedback loops constrain the number of potential patterns. Thus, the typical temporal course of anger is closely linked to the feedback structure of the emotional system.

From a dynamic systems perspective, the temporal course of a variable of interest, in our case anger, is thought to be governed by an attractor (cf. Thelen & Smith, 1994). Mathematically the attractor points to a state or set of states the dynamic system approaches when time goes to infinity (Devaney, 1989). This limit may be a single point (a point-attractor) or a set of points that follow a regular consecutive pattern (e.g., a limit cycle) or an irregular chaotic pattern (a chaotic attractor). The attractor corresponds to a single state or set of states in the end that account for the temporal course of the dynamic variable involved.

A single attractor accounts for an infinitely large number of quantitatively different but qualitatively similar temporal patterns (Abraham & Shaw, 1992; Boker, 2001). To illustrate, if an attractor accounts for emotional patterns with a single peak, the actual patterns may differ with respect to initial rise times, height of peak levels reached, and other quantitative characteristics. That is, the same attractor may account for emotions ranging from annoyance to rage.

The first row of Figure 1 shows the phase diagrams (to be explained shortly) of three qualitatively different attractors, based

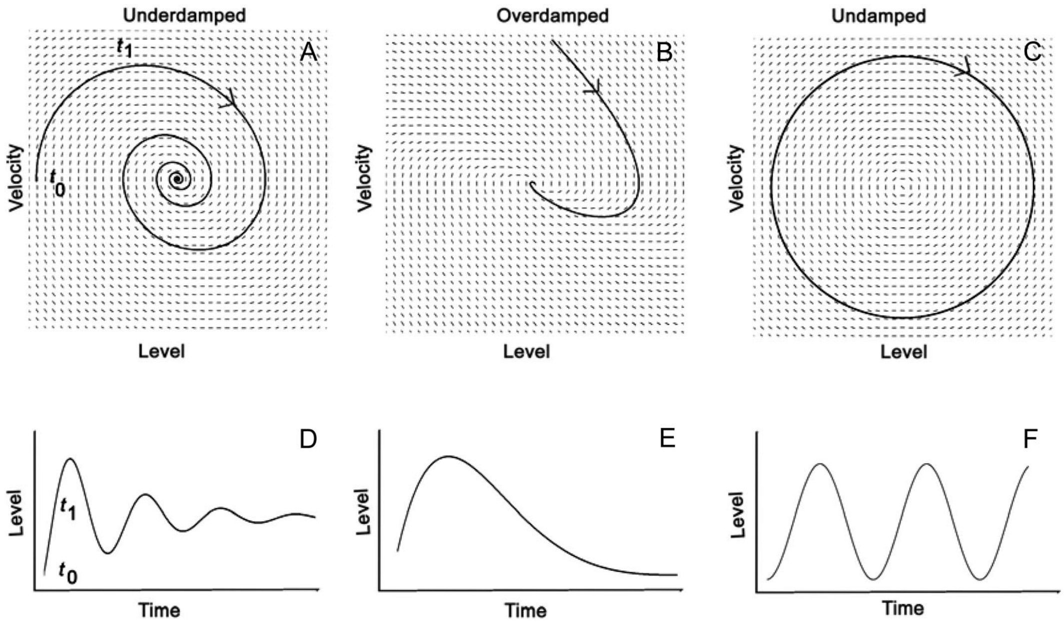

Figure 1. Phase diagrams and trajectories of an underdamped (A), overdamped (B), and undamped (C) oscillator.

on the *linear oscillator model*. This model dates back to Newton (1643–1727) and is generally used to describe wave-like patterns in physical systems. Boker (2001) argued that the model is also well suited to study self-regulative or feedback systems, such as the homeostatic system, the system governing postural control, and the emotional system.

The phase diagrams in Figure 1 picture how the relations between the level of anger, velocity of change (speed), and acceleration of the anger response (change in speed) evolve in time. The level of anger is designated by the horizontal axis and the velocity is designated by the vertical axis. The acceleration is given implicitly, and has to be inferred. To illustrate this, the points t_0 and t_1 have been added to the phase diagram in Figure 1A. Point t_0 could correspond to the moment when a person, let us say Harry, is on the verge of becoming angry. At that moment his level of anger is low (horizontal axis); the velocity is still near zero (vertical axis), but the acceleration is strong. The latter can be inferred from the fact that the velocity (vertical axis) increases fast between points t_0 and t_1. After some time (point t_1), Harry's level of anger is approximately halfway (horizontal axis) and rises with maximum velocity (vertical axis). Thereafter the velocity goes down, which results from a deceleration (negative acceleration) of his anger response.

Figure 1A portrays the attractor of a so-called underdamped linear oscillator (Kreyszig, 1999). The attractor results in recurrent, but decreasing patterns of increasing and decreasing levels. If the underdamped linear oscillator governs the dynamics of anger, this would account for a general temporal pattern of anger consisting of increases and decreases with recurrence at lower intensity as shown in Figure 1D. (Note that the curve in Figure 1D corresponds to the so-called projection on the time axis of the curve in Figure 1A.)

The linear oscillator model entails four different attractors. The three other attractors are the overdamped linear oscillator, the undamped linear oscillator and the critically damped oscillator (Kreyszig, 1999). Emotions after an overdamped linear oscillator (Figure 1B) increase fast and decrease slowly, without recurrence. If anger is governed by an overdamped oscillator, this would account for a general pattern consisting of a fast rise and slow decrease of anger as illustrated in Figure 1E. Figure 1C portrays the undamped linear oscillator. If anger follows an undamped linear oscillator this would account for a recurrent pattern of increases and decreases of anger as shown in Figure 1F. Finally, the critically damped oscillator is a unique borderline case between the overdamped and underdamped linear oscillator. Its pattern looks like the overdamped oscillator in Figure 1B and is therefore not portrayed separately.

The phase diagrams in Figure 1 capture *global* patterns of change and constitute just one of several ways to describe attractors. Another equivalent way, more suitable for empirical research, is by means of differential equations. These equations mathematically describe the *momentary* relations between acceleration, velocity, and level of a dynamic variable (cf. Doucet & Sloep, 1992; Acheson, 1997), and can be applied to real data to identify the attractor governing the internal dynamics of the system (Boker, 2001; Boker & Chisletta, 2001; Boker & Nesselroade, 2002). When applied empirically the name "Empirical Differential Equations" (EDE) is used.

EDE offer a flexible tool to find attractors. Moreover, they can be used to investigate variables that possibly affect the internal dynamics and thus the attractor of a system (Boker, 2001). EDE look like regression models and can easily be extended with predictors that are hypothesized to affect the attractor. What EDE look like, how they can be used to explore the dynamics anger empirically, and how EDE and phase diagrams of attractors are related to each other, will be explained in the method section. First, we turn to a variable that likely affects the attractor of anger.

Behavioral Inhibition

Behavioral inhibition is the capacity to inhibit a prepotent response. It is a central executive function affecting a large range of responses, such as speech, eye movements, hand movements, and squeezes (Logan, 1994; Logan & Cowen, 1984). Barkley (1997), in the context of the study of attention-deficit hyperactivity disorder, maintained that behavioral inhibition is an important prerequisite for emotion regulation. More recently Davidson et al. (2003) argued, on the basis of the results of fMRI studies by Garavan, Ross, and Stein (1999), and Konishi et al. (1999) that behavioral inhibition is a fundamental mechanism of emotion regulation.

As far as we know, there is no clear empirical evidence that behavioral inhibition affects anger. However, there are at least two reasons to hypothesize that anger is affected by the general capacity to inhibit a prepotent response. First, behavioral inhibition is closely associated with the right prefrontal cortex (Aron, Robbins, & Poldrack, 2004), which is reciprocally connected to the hypothalamus and the PAG (An et al., 1998; Öngür et al., 1998; Panksepp, 1998; Rempel-Clower & Barbas, 1998), which at their turn are thought to play a role in generating anger (Panksepp, 1998; Siegel et al., 1999). Second, a positron emission tomography (PET) study by Dougherty et al. (2004) using anger induction showed that activity in the prefrontal cortex and the amygdala are negatively correlated in normal individuals, whereas this relationship is absent in people who are prone to anger attacks. Thus, the observed anatomical and functional relationships suggest inhibitory or negative feedback loops. By means of this negative feedback loop, high levels of behavioral inhibition may result in enhanced control over anger responses, whereas low levels of inhibition may result in decreased control (cf. Davidson, Putman, & Larson, 2000).

If the capacity to inhibit a prepotent response amounts to negative feedback it will affect the time course of anger. Individual differences in level of inhibition thus become apparent from differences in the shape of the attractor. Because behavioral inhibition likely involves negative feedback between the prefrontal cortex and hypothalamus and the PAG (An et al., 1998; Öngür et al., 1998; Panksepp, 1998; Rempel-Clower & Barbas, 1998), it is to be expected that the attractor of anger will be more constrained when inhibitory control increases. The corresponding typical course of the anger response is expected to be less peaked and die out more rapidly.

Inhibition was measured using a stop signal task (Logan, 1994; Logan & Cowen, 1984) resulting in an estimate of the individual's Stop Signal Reaction Time (SSRT), which is an estimate of the latency of the inhibitory process. A person able to inhibit his or her ongoing response will have a short SSRT. Thus, we expected the attractor of anger to be more constrained for short SSRTs.

Feelings of Anger

A key task in studying dynamic systems is to identify the so-called collective variable (Granic & Hollenstein, 2003). A collective variable refers to an observable phenomenon capturing the coordinated changes in the system. It reflects the ongoing activity in the dynamic system and should be useful to make inferences about the system's dynamic nature. When applied to anger the collective variable should reflect state changes because of positive and negative feedback processes in the emotional circuits dedicated to anger, and it should be useful to make inferences about the attractor.

The present study uses feelings of anger as collective variable. As often explicated by Damasio feelings and emotions are not the same (Damasio, 2000b, 2003). Feelings can be conceived of as mental representations of neuro-chemical and physiological changes that occur during emotions (Damasio, 1994, 2000b). Feelings are output from the emotional system (Ledoux, 1994), reflecting all components of the emotional process (Greenfield, 2000), including appraisal, physiological responses, expression, and actions tendencies (Scherer, 2001b).

Thus changing feelings of anger reflect the ongoing activity in the emotional system. When sampled frequently, by means of experience sampling (Bolger et al., 2003; Brandstätter, 1977; Csikszentmihalyi et al., 1977) during several days, feelings offer a road to study the dynamics of anger (Hoeksma et al., 2000).

Finding the Attractor

The use of the attractor concept has been mainly limited to theorizing (Scherer, 2000; Keating & Miller, 2000), because commonly used statistical models such as ANOVA and regression analysis are not very useful to describe the internal dynamics of the emotional system empirically (cf. Bogartz, 1994; Granic & Hollenstein, 2003). As noted previously, Boker (2001), proposed to use the linear oscillator model to describe the internal dynamics of the emotional system. He showed how Differential Equations describing the linear oscillator model can be applied *empirically* to find the attractor of a dynamic system (Boker, 2001; Boker & Nesselroade, 2002).

EDE are new, but have already been applied successfully in emotion research. Chow et al. (2005) applied EDE to the notion of emotion as a self-regulatory system and used them to study individual differences in emotion regulation and emotional stability. Bisconti, Bergeman, and Boker (2004) used EDE to describe the temporal course of well-being in recently bereaved widows. In the present study EDE were used to explore the attractor of anger and how it is affected by behavioral inhibition. Because the method is still new it will be explained rather extensively in the method section below.

Method

Participants

To apply the attractor concept empirically, we reanalyzed data on anger and behavioral inhibition reported by Hoeksma et al. (2004). Participants were 30 preadolescent (15 boys, 15 girls) lower to upper class children, aged 10 to 13 years (mean age 11.44 years, $SD = .61$) equally divided over three elementary schools, each with a fifth and sixth grade class. Two cases were deleted because of technical problems with the EMD. A third case was deleted because of extreme values, for the acceleration and velocity (see data transformations). One outlier for the SSRT was reduced to the nearest highest value. Full data records were available for 27 participants. The total number of anger ratings was 1,043; corresponding to an average number of 38.6 observations per participant ($SD = 8.7$).

Instruments

Anger. Using the Electronic Mood Device (EMD; Hoeksma et al., 2000), participants rated the intensity of 10 feelings, including anger, every hour (plus or minus a random interval of 5 minutes), during 3 to 4 days. The EMD provides a portable electronic version of a mood adjective scale with nine points (1–9). Feelings were presented in random order. Similar to Hoeksma et al. (2004), the present study only used the participant's anger ratings.

Inhibitory control. The Stop Signal Paradigm (SSP; Logan, 1994; Logan & Cowan, 1984) was used to study the inhibitory process. The paradigm, based on the well-established theory of inhibitory control known as the race model (see for reviews, Logan, 1994; Logan & Cowan, 1984), measures the *latency* of the inhibitory process, that is the time needed to stop the inappropriate response measured in milliseconds (ms), designated as SSRT.

To measure SSRT, children were seated in front of a dark computer screen with a push button located on each side. Children wore headphones. First, 64 go trials were presented each consisting of the presentation of a small-stylized plane either pointing to the right or left corner of the screen. Children were instructed to react as fast as possible to the appearance of the plane by pushing either the right or left button, appropriate to the direction of the plane. Next four blocks were presented, consisting of 48 go trials and 16 stop trials in random order. Stop trials were identical to go trials but in addition, an audible stop signal was presented. Children were instructed *not* to press either of the two buttons, that is, to inhibit their response, when the stop signal was presented. The interval between the onset of the go stimulus and onset of the stop signal was varied dynamically contingent upon the child's responses, using a tracking algorithm proposed by Osman, Kornblum, and Meyer (1986). The dynamic tracking algorithm has been shown to result in an efficient and reliable estimate of SSRT (Logan, 1994; Logan, Schachar, and Tannock, 1997).

Data Analysis

EDE. EDE were used to find the attractor of anger and the possible role of inhibitory control. As noted earlier, phase diagrams (as depicted in Figure 1) describe the global relations between level, velocity, and acceleration, that is, the general pattern across time. EDE, in contrast, describe momentary relations, that is, the relations between level, velocity, and acceleration at moment *t*. EDE can be conceived as regression models (Boker & Nesselroade, 2002), with the Acceleration of the anger response as the response variable and the Velocity and Level of Anger as predictors. The model does not contain an intercept. The equation is:

$$\text{Acceleration }(t) = a * \text{Velocity }(t) + b * \text{Level of Anger }(t).$$

The Acceleration, Velocity, and Level of Anger are empirical variables. To start with the latter, Level of Anger refers to the time series of anger ratings obtained by means of the EMD. Velocity refers to the changes between ratings adjacent in time. Acceleration refers to changes in velocity. Velocity and Acceleration were computed from the time series of Anger ratings (Level of Anger) using the formulas given in Boker (2001) and Boker and Nesselroade (2002). Specifics of the computations will be given in the Data Transformations section.

The weights a and b in the equation above are so-called *control parameters* and are to be estimated from the data. Parameters a and b are designated the *damping* and *frequency* parameter, respectively, and are interpreted as feedback coefficients. To illustrate this; if anger is rising fast (i.e., Velocity (t) is positive), whereas the damping parameter a is negative, the fast rise will, according to the model, be "fed back" to the Acceleration and result in a deceleration (i.e., negative Acceleration (t)). The same will happen when the Level of Anger is highly positive and control parameter b is negative.

The numerical values of the control parameters a and b determine both the quantitative and qualitative characteristics of the attractor. Damping parameter a determines how fast the anger response comes down to equilibrium. When a becomes more negative, anger will be damped more strongly. Frequency parameter b determines the frequency by which anger goes up and down. When b becomes more negative the frequency increases.

Qualitative differences between the attractors are dependent upon the value of the damping parameter a relative to the value of the frequency parameter b (cf. Kreyszig, 1999). The attractor of an underdamped oscillator (depicted in Figure 1A) is found when the damping parameter is relatively small, specifically when the inequality $a^2 < -4b$ holds. The overdamped oscillator (Figure 1B) is found when the damping parameter is relatively large, that is, when $a^2 > -4b$. A limit cycle, as depicted in Figure 1C is found when $a = 0$ and $b < 0$, that is when damping is absent. The critically damped oscillator is found when $a^2 = -4b$. Finally, it should be noted that the values of the parameters a and b must be zero or negative; if not anger would grow infinitely.

We hypothesized that inhibition affects anger by means of negative feedback. To test the effect of inhibition on the attractor, we extended the model with the SSRT as a predictor variable (cf. Boker, 2001). Low values of the SSRT correspond to high levels of inhibitory control, whereas high values of the SSRT correspond to lack of inhibitory control. The extended model is

$$\text{Acceleration }(t) = a * \text{Velocity }(t) + b * \text{Level of Anger }(t) + c * \text{SSRT}.$$

The parameter c indicates how the time needed to stop a prepotent response affects the acceleration of the anger response. It is expected to be positive, because increasing values of the SSRT (less inhibitory control) should result in stronger acceleration. Finally, we extended the model with the interactions between the SSRT and the two other predictors in the model, the Velocity and the Level of Anger. The interaction "SSRT × Velocity" reflects how the SSRT affects the damping, whereas the interaction 'SSRT × Level of Anger' reflects how the SSRT affects the frequency. The first parameter is expected to be positive, whereas the second is expected to be negative, because the damping is expected to decrease, whereas the frequency is expected to increase when the SSRT increases.

Data transformations. To estimate the parameters a, b, and c and possible interactions, the response variable Acceleration and the predictor variable Velocity were computed first. Formulas, and their rationales grounded in calculus, can be found in Boker (2001) and Boker and Nesselroade (2002). To explain the computations, let a person's time series of anger ratings at a specific point in time be indexed by *t*. His or her current rating of anger is designated by Level(t); the previous rating is designated by Level(t-1); and the subsequent rating by Level($t+1$). The time passed between ratings is designated by Δt. The change per time unit between the current and previous rating corresponds to the difference (Level(t)-Level(t-1))/Δt, and the change per time unit between the next rating and the current rating corresponds to the difference (Level($t+1$)-Level(t))/Δt. Velocity(t) is found by averaging the changes between current rating and previous rating and between the subsequent rating and current rating: Velocity(t) = [(Level(t)-Level(t-1))/Δt + (Level($t+1$)-Level(t))/Δt)]/2 = (Level($t+1$) -Level(t-1))/2Δt. The acceleration corresponds to difference in change per time unit and is computed by Acceleration(t) = ((Level(t)-Level(t-1))/Δt - (Level($t+1$)-Level(t))/Δt)/Δt = (Level($t+1$)-2Level(t)+ Level(t-1))/Δt^2.

Because the Velocity(t) and Acceleration(t) cannot be computed for the first and last ratings in a day-series of observations, the original number of observations was reduced from 1,043 to 843; corresponding to an average of 31.2 observations (SD = 8.0) per participant.

Parameter estimation. To find the attractor of anger and the effect of the SSRT, the parameters a, b, and c and possible interactions were estimated by means of Multilevel Modeling (Goldstein, 2003), which is also called Hierarchical Linear Modeling (Bryk & Raudenbush, 1992). Although the EDE can be conceived of as regression models, ordinary regression analysis could not be used, because the anger ratings are nested within days; and days are nested within persons. As a result the observations within persons are correlated (i.e., not independent). Multilevel Modeling takes this dependence into account and adjusts the parameter estimates and test-statistics accordingly. MLwiN (Goldstein et al., 1998) was used for this purpose. The multilevel structure was as follows: 843 anger ratings (level 1) were nested in 100 days (level 2), which were nested in 27 persons (level 3). The model is an extension to three levels of the two level model used by Boker and Chisletta (2001). Our main interest is in the parameters of the so-called fixed part of the model, containing the parameters a, b, c, and interactions. Parameters were tested for significance by comparing their corresponding test-statistics to the normal distribution.

Retrieving the phase diagram. The phase diagrams (see Figure 1) and EDE both describes the relations between Level, Velocity, and Acceleration. The phase diagrams are clearly *nonlinear,* whereas the EDE are estimated using a linear model. There is, however, a well known, but not easily explained relationship between the given Differential Equation and the phase diagrams depicted in Figure 1 (see Acheson, 1997; Doucet & Sloep, 1992). After the control parameters (a, b, c, and possible interactions) have been estimated by means of MLwiN, the phase diagram and specific trajectories could have been retrieved by mathematically integrating the EDE. The resulting functions, which can be found in Kreyszig (1999), are clearly nonlinear and differ depending on the values of the estimated control parameters. Moreover, they are hard to read. A more easy way to derive the phase diagram and trajectories from the EDE is by means of so-called numerical integration (Doucet & Sloep, 1992). Dedicated software can be used for that purpose. In the present study we used the freeware program Dynamic Solver (Aguirregabiria, 2000). After entering the estimated parameters of the EDE and initial values for Level and Velocity, the program produces both the trajectory and the phase diagram. Dynamic Solver uses the so-called Runge Kutta algorithm to calculate the trajectory originating from the initial values for Level and Velocity. After entering the initial values the algorithm uses a set of five equations (cf. Acheson, 1997, p. 51) to compute the level of the variable of interest (in our case anger), for the next moment close to the starting point. This outcome is plotted and subsequently used as a starting point to calculate the next value close in time. The steps are repeated until the trajectory reveals itself and the user stops the calculations. The phase diagram is similarly found by repeatedly computing the first steps of algorithm for an array of starting values, that is, for a range of levels and velocities.

Results

Anger ratings were first transformed to the rate of change (Velocity) and the acceleration. The mean Level of Anger was M = 1.97 (SD = 2.07). The mean rate of change and mean acceleration were near zero: $M = -0.10$, (SD = 2.07) and M = 0.02 (SD = 4.13), respectively. The mean Stop Signal Reaction Time was M = 93.7 ms (SD = 29.67). The estimated mean SSRT appeared to be relatively short, but agrees with earlier findings of Scheres et al. (2004).

Table 1 displays the results of the multilevel analysis that was performed to find the Differential Equation describing the attractor of anger. Both the damping parameter ($a = -1.26$, SE = .23) and the frequency parameter ($b = -0.80$, SE = .24) appeared to be significantly smaller than zero, suggesting a point attractor. The parameters agree to the inequality $a^2 < -4b$ ($-1.26^2 < -4 * -.80$) corresponding to the attractor of an *underdamped* oscillator.

The parameter reflecting the effect of inhibition (c = 0.028, SE = 0.007) appeared to be significantly larger than zero. This suggests that increasing SSRT result in increasing acceleration (decreasing deceleration) of anger responses. In line with our expectations, anger responses accelerate more strongly and decelerate more slowly when inhibitory control decreases.

Subsequently, we extended the model with the interactions between SSRT and Velocity, and between SSRT and Level of Anger. None of the interaction terms appeared to deviate significantly from zero, indicating that the effect of Behavioral Inhibition on the Acceleration of anger does not depend on the speed of

Table 1
Parameter Estimates of Fixed and Random Part of the Empirical Differential Equation Describing Anger

Parameter	Estimate	SE	t-value	p-value
Fixed				
a (velocity)	−1.27	.23	5.52	<.001
b (level of anger)	−.80	.24	3.37	<.001
c (SSRT)	.028	.007	4.00	<.001
Level III				
σ_a^2	.21	.12		
σ_b^2	.59	.20		
$\sigma_{,ab}$	−.41	.15		
Level II				
σ_a^2	.51	.14		
σ_b^2	.37	.09		
$\sigma_{,ab}$	−.36	.10		
Level I				
σ_e^2	5.29	.28		

change (Velocity) or the Level of Anger. The correlation between the observed and predicted values was $r = .85$ corresponding to 72% explained variance.

The estimated parameters describing the Differential Equation of the attractor of anger were subsequently entered in the computer program Dynamic Solver (Aguirregabiria, 2000) to depict the attractor. Figure 2A depicts the attractor of anger for the mean SSRT = 97 ms. The attractor follows an underdamped oscillator. Figure 2A reveals a fast increase and slow decrease to baseline level. The recurrence, characterizing the undamped oscillator (cf. Figure 1A) is small, and hardly noticeable. The temporal patterns governed by the attractor found show fast increases and slow decreases, with a far less intense recurrence.

Figure 2B depicts the attractor of anger for three different values of the SSRT (the mean level ± one standard deviation). It illustrates the affect of inhibition on the attractor. Starting from the same point (*p*), the attractors appear to end in different points (*c3* to *c1*), suggesting that anger rises faster and reaches higher intensities when inhibitory control decreases (i.e., when SSRT increases). Figure 2C confirms this. It shows three corresponding trajectories. Anger appears to accelerate relatively fast and to higher peak intensities and returns to higher equilibrium levels when inhibitory control is low (*c1*). In contrast, anger increases less fast, to less high peak intensities and returns to a lower equilibrium level when inhibitory control increases (*c3*).

The effect of inhibition on fastness and peak intensity is in line with the observed correlation between inhibitory control and the within-person variability of anger ($r = .41$, $p < .05$, one sided, $n = 27$; Hoeksma et al., 2004, p. 358). Moreover, current findings suggest a relationship between inhibitory control and the equilibrium level of anger. Indeed there appears to be a small positive correlation ($r = .28$, $p < .10$, one sided, $n = 27$) between SSRT and the individual mean level anger (that approximates the equilibrium level).

The observation interval used (1 hour ± 5 minute random interval) is clearly arbitrary and may have affected the findings. To explore this issue we artificially increased the observation interval from 1 ($\Delta t = 1$) to 2 hours ($\Delta t = 2$), by deleting every evenly numbered observation within days. Next the Velocity and Acceleration were computed anew using the formulas of Boker (2001) and Boker and Nesselroade (2002) with $\Delta t = 2$ (see data transformations). The reduced sample contained 322 observations.

Replicating the model with the 2 hour interval failed at first, because the level three parameters did not converge (possibly because of the large reduction of the number observations within persons). After setting the level 3 parameters to zero, the replication succeeded. The damping parameter ($a = -.73$, $SE = 0.14$, $t = 5.27$, $p < .01$) and the frequency parameter ($b = -0.16$, $SE = 0.07$, $t = 2.48$, $p < .01$) appeared to be significantly smaller than zero and agreed to the inequality $a^2 < -4b$ $(-.73^2 < -4 * .-16)$, pointing again to the attractor of a *underdamped* oscillator. The parameter reflecting the effect of inhibition ($c = .006$, $SE = .002$, $t = 3.00$, $p < .01$) appeared to be significantly larger than zero, suggesting again that increasing SSRT result in increasing acceleration of anger responses.

The analyses based on the 1 hour and 2 hour interval lead to the same conclusion: The attractor of anger is a *underdamped* oscillator affected by the SSRT. Nevertheless, the parameter estimates are clearly different. These differences result from difference between the variables Acceleration and Velocity in the 1-hour model and 2-hour model. This can be explained as follows. When the level of anger changes by the same amount over a 2-hour interval, instead of over a 1-hour interval, the corresponding speed of change will be halved. Similarly, the acceleration is reduced to one-fourth of its original value. Thus, taking sampling error into account, the values of Velocity and Acceleration in the 2 hour model are roughly one-half (1/2) and one-fourth (1/4) of the corresponding values in the 1 hour model. To accommodate these reductions the control parameters have to chance accordingly. Indeed, the ratio of the damping parameters *a* in the 2-hour and 1-hour model was .73/-1.26, approximating 1/2. The ratio of the frequency parameters *b* was: −.16/.80, which approximates 1/4. Finally, the ratio of the parameters *c* of the SSRT of the two models was .006/.028, which approximates 1/4.

In summary, the attractor of anger follows an underdamped oscillator. Anger goes up swiftly, and goes down slowly and returns to some extent. In addition the attractor of anger is smaller or more constrained for smaller SSRT-values, that is, when inhibitory control increases. It should be stressed that the three depicted curves are just examples of all possible curves. A curve could be drawn from any point in state space. The patterns starting from each point will be qualitatively similar to the patterns shown, and each possible curve will reflect the main characteristics of the curves given. The response increases quickly and returns to baseline level slowly, and depends on inhibitory control.

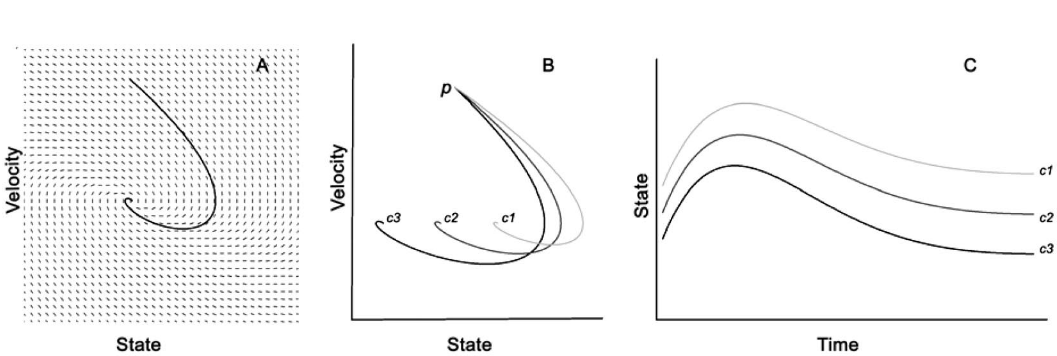

Figure 2. Attractor of anger for the mean SSRT (A), for the mean SSRT ± 1 *SD* (B), and corresponding trajectories (C).

Discussion

The goal of the present study was to apply the attractor concept empirically to the field of emotion research. To close the gap between the concept and its empirical use, we dwelled upon the psychological and mathematical side of the attractor concept and reanalyzed data of Hoeksma et al. (2004) to find the attractor of anger.

The results of the analyses, based on the work of Boker (2001), showed that the attractor of anger follows an underdamped oscillator. Accordingly, anger rises rapidly and subsequently levels off slowly and returns to some extent. It appears to oscillate, but the oscillations are small. Results further showed that behavioral inhibition affects the attractor of anger. The attractor of anger is more constrained for shorter SSRT. Accordingly, anger will rise less rapidly and level off more quickly for individuals who are better able to inhibit prepotent responses. The attractor determines the qualitative form of the anger response and describes a large range of quantitatively different responses. As noted previously, curves in state space may start from any point, resulting in qualitative similar but quantitatively different patterns, that is, patterns with different peak heights and durations.

The form of the attractor found and the observed role of behavioral inhibition apparently agree with phenomenological descriptions of anger. For example, Frijda (1986) portrays anger as a fast rising urge that needs to be controlled in some way. Lazarus and Lazarus (1994) refer to feelings of anger as ". . .have the impulse to attack—without actually attacking anyone" (p. 25). In addition, according to Panksepp (1998) "To be angry is to have a specific kind of internal pressure or force controlling one's actions and views of the world." (p. 191). The apparent agreement with descriptions from the literature adds validity to the use of EDE.

The attractor found and the observed role of inhibitory control give detail to the results of Hoeksma et al. (2004) which showed that the variability of anger rating increases when the inhibitory control decreases. The present analyses suggest that increasing within-person variances reported by Hoeksma et al. (2004) are because of differences in acceleration and deceleration, and because of increasing peak intensities.

Although this was not our primary goal, the findings underline the role of behavioral inhibition in emotion regulation. Emotion regulation refers to all conscious and nonconscious strategies to increase, maintain, or decrease components of the emotional response including feelings, behaviors and physiological responses (Gross, 1999). The attractor found confirms the assumptions of Barkley (1997) and Davidson et al. (2003) that the executive function behavioral inhibition plays an important role in emotion regulation. Given the observational nature of the present data, it is difficult, however, to make inferences about cause and effect. Obviously, there are three options: (1) behavioral inhibition could slow down anger, (2) anger could incapacitate behavioral inhibition, and finally (3) anger and behavioral inhibition could be reciprocally related to each other. In line with neurological findings of Dougherty (2003), showing a reciprocal relationship between the prefrontal cortex and the amygdala, we think the latter is most likely. Inhibition may prevent the anger response to run its full course. However, once the anger response is at full speed it likely incapacitates inhibition.

It may come as a surprise that *appraisal* hardly plays a role in the present analysis, given that the majority of emotion theories take a cognitive view (Scherer, Schorr, & Johnstone, 2001). We think the present findings complement appraisal theory and possibly help to reconcile appraisal theory with some of the doubts that were recently articulated by Berkowitz and Harmon-Jones (2004). Without going into detail, some appraisal theories (e.g., Frijda, 1986; Scherer, 2001a) assign a major causal role to *agency* in shaping and organizing the anger response (see Barrett et al., 2006; Frijda & Zeelenberg, 2001; Lewis, 2005, for alternative views). The response to a particular anger provoking stimulus is thought to depend on, among others, whether the agent is animate or inanimate, whether the agent is responsible or not, and the agent's intentions (Frijda, 1986; Scherer, 2001a). In our view, the attractor concept does not deny the role of agency. On the contrary, it adds the role of the internal dynamics to it. This can be argued as follows. Appraisal, specifically agency, cannot fully account for the fast rise and slow decrease of anger (Berkowitz & Harmon-Jones, 2004). However, as the present study shows, this temporal pattern can be accounted for by the attractor that is closely linked to the neurological feedback system. At the same time, the attractor of anger cannot fully explain why anger is triggered. Appraisal, specifically agency, may account for this trigger (Sander et al., 2005). This view is in line with Scherer's component process model of emotions (Scherer, 1987, 2001a). His dynamic emotion theory *avant la lettre* posits a layered set of oscillators and continuous stimulus evaluation checks that may lead to an organized emotional response.

Recently, Berkowitz and Harmon-Jones (2004) suggested that most analyses do not go far enough in considering what factors generate anger. They argued that other factors are involved in generating anger besides appraisal. They discuss a large amount of evidence, including studies of pain effects (e.g., Hatch et al., 1992), and studies of anger-related skeletal muscle movements (e.g., Laird, 1984), showing that angry feelings may arise without apparent appraisal. The fact that the model of the attractor is clearly nonlinear (see Figure 2), may help to account for the upheavals of anger in the absence of significant appraisals. According to the model, the effect of a specific trigger depends on the system's momentary state (cf. Acheson, 1997; Freeman, 2001; Frijda & Zeelenberg, 2001). To illustrate this, when the momentary level of anger is somewhat heightened and already slowly rising, an appraisal could result in a strong response, because it is in line with the direction the state of the system is already going. In contrast, the same appraisal will affect the system to a lesser extent when the level of anger is momentary going down, because it is not supported by the present direction of change. We suggest that pain and stress, and anger-related skeletal muscle movements influence the direction of changes in the emotional system, which is conducive of an anger response when an anger-related stimulus (possibly a thought) comes about.

The present empirical application of the attractor concept could be improved and extended in several ways. First, it should be remembered that the data pertain to a restricted age range; youngsters from 10 to 13 years of age. We can only speculate on how the attractor changes with age. Likely, the attractor becomes more constrained, because behavioral inhibition improves with age (Scheres et al., 2003; Williams et al., 1999). Second, the sampling interval of one hour is arbitrary. Artificially increasing the interval did not lead to materially different conclusions. Even so, the interval chosen may have obscured short cycles of anger responses (Gottman, 1982). Follow-up studies, both empirically and statistically (cf. Boker & Nesselroade, 2002) are needed to show to what extent the estimated attractor depends on the interval chosen.

A first option to extend this study is to include individual neuropsychological parameters of brain-activity obtained by means of brain imaging (MEG or fMRI). It could be shown for instance, that the attractor of anger varies according to activity in specific parts of the amygdala (cf. Morris, deBonis, & Dolan, 2002). A second option is to extent the EDE with measurements of individual differences with respect to the appraisal of agency. It could be shown that the attractor of anger varies according to individual differences in the appraisal of agency. A third option is to apply EDE to other emotions, such as sadness, happiness, fear, guilt, and shame, and to compare the attractors found. Still another option is to experiment with other kinds of Differential Equations (cf. Acheson, 1997) including coupled Differential Equations (Butner, Amazeen, & Mulvey, 2005) that take account of the dynamics of other emotions or cognitive processes including appraisal (cf. Lewis, 2005).

We think the major contribution of this study is that it shows how the attractor concept can be applied empirically. Attractors can be used with real data. As such the results seem to refute the critical analyses and doubts of Keating and Miller (2000); Panksepp (2000), and Scherer (2000) about the usefulness of concepts from dynamics systems theory. The attractor concept appears, when applied empirically, well suited to describe the internal dynamics of the emotional system which are closely related to its neurological layout (Davidson et al., 2003; Freeman, 2000). Attractors offer parsimonious accounts of nonlinear temporal characteristics of emotions and encompass several concepts from affective chronometry and affective style (Davidson, 1998; Thompson, 1988), including emotional stability, emotional threshold, rise time, and peak intensity.

Several researchers from different fields, including Berkowitz and Harmon-Jones (2004); Cole, Martin, and Dennis (2004), and Scherer (2001) recently urged emotion theorists and emotion researchers to widen their methodology and analysis. We suggest that the attractor concept and its link to the neurological structure of the emotional system, together with the innovative methods proposed by Boker (2001), should be considered as one of the answers to this urge.

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