ANXIETY, EMOTIONAL REACTIVITY, AND ATTACHMENT AS PREDICTORS OF EMBEDDING DIMENSIONALITY OF AFFECT

by

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ABSTRACT

In this study we investigated individual differences in emotionality and affect dynamics in couples over 21 days using a modified version of the False Nearest Neighbors method to estimate the embedding dimensionality of positive and negative affect. We estimated the number of dynamic degrees of freedom contributing to changes observed in time series' of affect. Patterns in daily affect may reflect an additive impact of stimuli (attending to many unique influences, high dimensionality) or a coordinative process that recruits stimuli (hyper-focus, low dimensionality). We examined the relationship between the embedding dimensionality of affect and macroscopic descriptors of emotionality that bear on affect regulation and appraisal processes. Associations were found for negative affect only. Higher levels of trait anxiety, emotional reactivity, and attachment anxiety were associated with lower dimensionality, regardless of the occurrence of daily negative events. The findings were consistent with the hyper-focus hypothesis. Individuals low in negative emotionality had high dimensionality except when they reported greater frequency of daily negative events. The pattern of results is discussed with respect to flexibility in affect regulation.

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INTRODUCTION

Affective experience is central to daily life and functioning in close relationships. Changes in affect and mood alert us to relevant threats or opportunities in our environment and allow us to respond in adaptive ways. Integrating processes of attention, appraisal, and affect regulation (Clore & Ortony, 2008) with external stimuli is a dynamic relationship between the individual and their surroundings (Russell, 2003). Affect is a functional system of interrelated cognitive and behavioral elements that guide adaptive behavior (Cacioppo & Berntson, 1999), and as such should be examined temporally across multiple levels of analysis (Cacioppo, Berntson, Sheridan, & McClintock, 2000; Lewis, 2005). This study considers how the temporal dynamics of positive and negative affect are associated with molar descriptions of emotionality known to influence how individuals perceive and respond to affectively salient stimuli in their daily lives. The affective landscape is intrinsically temporal and dynamical systems theory and methods are uniquely equipped to address questions about its characteristics.

A dynamical systems approach offers novel conceptual and methodological tools for thinking about how affect can stabilize, change, or shift coordination structure over time. Calculating the *embedding dimension* of a time series is one method for recapturing multidimensional properties from a low dimensional measurement series. Embedding dimensionality describes the active dynamics of a time series; it is an estimate of the number of unique equations needed to depict the trajectory of a time series, and thus the number of unique axes needed to represent the time series multidimensionally (it is the active degrees of freedom of a system). In cognitive and motor development (Thelen, 1989), as well as motor behavior and learning (Mitra, Amazeen, & Turvey, 1998), changes in embedding dimensionality are associated with specific functional constraints that arise in the context of a particular task. This is consistent with soft-assembly descriptions of cognition and action (Thelen, 1989; Van Orden & Kloos, 2009), and can be applied to the study of affect over time.

I will briefly review research on the measurement of affect followed by a description of the neural substrates and functional nature of the affect system. Building on this foundation I will argue that trait level descriptions of emotion regulation and emotionality, specifically trait anxiety, emotional reactivity, and measures of attachment style, should correspond to the dynamical patterning of affect in time. Using a version of the False Nearest Neighbors method (Kennel, Brown, & Abarbanel, 1992) modified for multilevel modeling (Butner & Story, Manuscript under review), I estimated the embedding dimension of affect for individuals using multiple weeks of daily reported affect. Variability in dimensionality should correspond to trait level descriptions of emotionality, thus differentiating patterns of affect coordination across individuals.

Affect

The structure and measurement of affect has been a central focus of psychological research for many decades (Bradburn, 1969; Cacioppo & Gardner, 1999; Diener, 1999; Green & Salovey, 1999; Gross, 2002; Watson & Tellegen, 1985. Some researchers have focused on whether self-reported positive and negative affect are polar ends of a single continuum (negatively associated) (Green, & Salovey, 1999; Green, Salovey, & Truax, 1999) or rather two orthogonal dimensions (Tellegen, Watson, & Clark, 1999; Watson, Clark, & Tellegen, 1988; Watson & Tellegen, 1985). Others describe affect in terms of behavioral activation and inhibition neural subsystems (Gray et al., 2005; Carver, 2006; Watson, Wiese, Vaidya, & Tellegen, 1999) where positive affect is associated with successful approach or avoidance behavior, and negative affect is associated with failure to reach or avoid an outcome. These literatures imply a phenomenological distinction between positive and negative affect, but also situates them in a larger affect system that attends and responds to numerous contexts and sensory inputs as required across time and contexts (Cacioppo, Larsen, Smith, & Berntson, 2004).

Evidence for the dynamic nature of affect is presented by Cacioppo and colleagues (Cacioppo & Berntson, 1994; Cacioppo et al., 1997, 1999, 2000) in their evaluative space model of affect and related attitudes. Within their model multiple patterns of affective activation can occur: 1) reciprocal activation; where an increase in one (positive or negative affect) decreases the other; 2) uncoupled activation where positive or negative activation occurs independently of the other;

or 3) nonreciprocal activation where an increase (or decrease) in positive or negative affect occurs in conjunction with the other. Affect allows for behavioral flexibility by being able to operate in various coupled and uncoupled configurations given context and task specificity. From this perspective affect can be seen as a holistic, multivariate, interactive system which brings together individual differences in emotionality, cognitive appraisal processes, and behavioral responses.

Positive and negative affect can be independently or simultaneously experienced (Cacioppo, & Berntson, 1994: Larsen, McGraw, & Cacioppo, 2001; Reich, Zautra, & Davis, 2003), as well as demonstrate cyclical (Larsen, 1987), coupled (Butner, Diamond & Hicks, 2007), or other patterns of interrelation (Bisconti, Bergeman, & Boker, 2004). Neurological, cognitive, and social psychological research suggests a more complicated picture that reflects their functional interrelationship and phylogenetic histories (Cacioppo, Larsen, Smith, & Berntson, 2004). Social interaction and affect regulation inherently involve the interplay between positive and negative valence and level of arousal. The ability to appropriately engage and regulate positive and negative affective experience and flexibly move around the affective landscape is implicated in many aspects of social functioning, e. g., maintaining close relationships (Gottman et al., 2002) or adjusting to the loss of a relationship (Bonanno, Goorin, & Coifman, 2008). Thus, maintaining a flexible and responsive coordination dynamic between positive and negative affective processes over time may be indicative of a healthy affective system.

Dynamic systems and affect

Dynamical systems theory (Kantz & Schreiber, 2004; Lewis, 2000, 2004, 2005; Vallacher & Nowak, 1994; van Bertalanffy, 1951; 1972) allows questions about the composition of a system and its stability and change to be examined in ways unique to psychological science (Thelen & Smith, 1994). A systems approach is based on the notion that system elements interact over iterations of time and that self-organized, complex or coordinated behavior, emerges as a function of elements' interactions. Systems are not static but rather dynamic, interactive, and in constant flux.

Examining a phenomenon over many measures allows for questions to be asked about trajectories, patterns of change, and system dynamics. Lewis (2000, 2004, & 2005) has described the importance of understanding nested timescales in emotional development and attempts to link small-scale neurobiological processes to affect/mood, emotion, and trait level constructs using dynamical systems theory. How is it that microscopic and regional activation in the brain over seconds and minutes give way to patterns of mood or affective valance over hours and days, or emotional habits or trait level affect over months and years? These are not questions easily answered or conceptualized from perspectives that attempt to distill affect into constituent parts or emphasize static properties or relationships between affect and various outcomes. In the same way that contemporary approaches to studying interpersonal processes emphasize patterns of coordination and interrelation over time (Gottman et al,. 1994), a dynamic systems approach to affect focuses on the ways that system variables self-organize over time, yielding novel qualitative patterns across multiple timescales.

Butner, Diamond, and Hicks (2007) examined couples' affect coregulation (covariation and coupling) finding that partners' positive and negative affect covaried within-day and increasingly more so as they spent more time together in a day; positive affect was coupled across partners. Covariation and coupling in affect also varied as a function of attachment style, suggesting that patterns in affect coregulation in time may relate to broader constructs implicated in affect regulation in interpersonal contexts. When examining positive and negative affect we should not only be addressing mean levels (and variability) but larger coordinated patterns that may be captured in the trajectory or system-level characteristics of affect. Together, the literature presented argues for the importance of understanding the temporal qualities of affect, particularly patterns of coordination in affect as a function of context and larger scale descriptors of affect regulation.

Quantifying the coordination dynamics of affect; dimensionality

Bernstein (1967) examined degrees of freedom in the biomechanics and physiology of motor learning and posed a question that remains apropos today. How do individuals coordinate variables in motor and cognitive development in a fashion that generates structure, predictability, *and* flexibility? Contemporary researchers continue to grapple with questions about change in degrees of freedom as a function of learning, as well as increases and decreases in degrees of freedom specific to particular tasks (Kugler, Kelso, & Turvey, 1980, 1982; Newell & Vaillancourt, 2001; Vaillancourt & Newell, 2002). This idea is particularly relevant to a systems model of affect as the affect system embodies the same form of unidirectional change in coordinative processes posited by Bernstein (1967) (as in development) and bidirectional change due to task constraints (Newell & Vaillancourt, 2001; Vaillancourt & Newell, 2002) . Kay (1988) offered a form of dimensionality analysis called the embedding dimension as a method for examining the active degrees of freedom of a temporal trajectory.

Degrees of freedom represent the number of unique elements making up a system. In motor development many degrees of freedom (possible combinations of joints, muscles, tendons generating motor movement) are reduced through coordination (development, learning) to produce functional behavioral outcomes such as reaching and grasping, or learning to ski. The state of the coordinated or dynamical system at a particular moment can be described with active degrees of freedom or the *embedding dimension* (dynamic systems theory recognizes several forms of dimensionality) (Kay, 1988). Thus, the change in time of many coordinated system elements can be represented by a smaller number of equations of change or active degrees of freedom. In this way dimensionality represents the number of independent variables required to describe the current motion or trajectory of a system. If each new variable corresponds to a dimensional axis, the embedding dimension can be thought of both, as a representation of unique variables influencing the time series trajectory, and the dimensional volume required to fully depict the dynamics.

Calculating the embedding dimension of affect allows for variability in affect dynamics to be examined as a function of individual difference variables associated with affect regulation. Specifically anxiety, emotional reactivity, and attachment style should function as control parameters (Haken, 1983) that impact the dimensionality of affect, and correspond to various patterns of affect coordination. A brief literature review of anxiety and attachment as they relate to affect follows.

Higher order affect constructs: Anxiety, emotional reactivity, and attachment

Anxiety

Individuals high in trait anxiety have an enduring attentional bias toward threatening stimuli compared to low-trait individuals who tend to redirect attention away from threatening stimuli. Mogg and Bradley (1998) argue from a cognitive-motivational perspective that anxiety is related to a ‘hyper-vigilant mode’, which is a pattern of attention characterized by scanning the environment for threat. This heightened attentional state tends to prioritize some cognitive processes over others; i.e., initial encoding of threat but impairment in elaboration processes that would impact later recollection of detail. Anxious individuals interpret ambiguous stimuli as negative and favor negative stimuli perceptually. When a threat is detected, attentional focus becomes constrained at the expense of other information in the environment. Thus highly anxious individuals, on average, are both being influenced by a greater number of perceived negative events, and are more constrained in their affect dynamics.

Emotional reactivity

Emotional reactivity describes the tendency for individuals to be emotionally labile, hypersensitive, and prone to experience emotional flooding (Skowron & Friedlander, 1998). Emotional reactivity is associated with poor affect regulation, decreased relationship satisfaction, and poor psychosocial health (Skowron, Stanley, & Shapiro, 2009). Emotionally reactive individuals lose behavioral and affective flexibility by becoming consumed with their emotional experience, and thus are more likely to manifest maladaptive outcomes. Affective experiences are psychologically sticky for reactive individuals; once they become affectively aroused they have difficulty down-regulating. Similarly to anxiety, emotional reactivity is characterized by a greater likelihood of being overly aroused by a wide variety of affectively valanced stimuli, yet simultaneously showing affective rigidity in response (inertia). The impact of reactivity should be apparent in the temporal dynamics of affect, particularly negative.

Attachment

Bowlby (1969) posited attachment theory to explain how experiences with caregivers in infancy influence later relationships through the development of affect regulation strategies and internal working models (cognitive-affective representations) of interpersonal relationships. Attachment theory was extended to adult romantic relationships and provides a meta-theoretical framework for the formation, maintenance, and dissolution of close relationships in adulthood (Hazan & Shaver, 1987, 1994) and across the life-course (Diamond and Aspinwall, 2003). Mikulincer and Shaver (2003) review evidence indicating that anxiously attached people tend to have overarching threat sensitivity, negative self-views, and negative beliefs about both social and nonsocial contexts. Avoidant individuals tend to suppress or deny negative emotions and project negative views of self onto others. Attachment working models should be evident in the embedding dimensionality of affect.

Study aims

The aim of this study is to establish that embedding dimensionality of positive and negative affect map on to trait level descriptions of emotionality. To examine the relationship between the embedding dimension of affect and individual differences in emotionality I'll first establish that embedding dimensions vary across individuals. Because the estimation of dimensionality can be thought of as the number of unique variables required to describe the system's change in time *and* a description of the system's current coordination dynamics, there are implicitly two competing expectations; additivity versus coordination. Emotion and affect research suggests that individuals experience heightened cognitive arousal and sensory vigilance after the experience of negative affect (Ito, Larsen, Smith, & Cacioppo, 1998; Smith, Cacioppo, Larsen, & Chartrand, 2003). This process could be thought of as attending to more information in the environment in an absolute sense. Given that anxiety lends itself to the interpretation of ambiguous stimuli as negative, the affective dynamics of anxiety also appear to coordinate information in a particular fashion. Thus, one can imagine anxiety and information processing as either high or low dimensional.

If affect is functioning additively the dimensionality of negative affect should increase as traits related to emotional arousal and vigilance increase. Trait level anxiety has been shown to increase the experience of negative affect (Watson, Clark, & Carey, 1988) and as a result increase vigilance and perceptions of threat (Broadbent & Broadbent, 1988). The embedding dimension of negative affect will be higher for individuals who score high on anxiety if dimensionality is responding to the number of unique pieces of information that anxious individuals attend to. Alternatively, if the way anxious individuals attend to and are affected by their environment reflects a restricted or more rigid pattern of attention and processing of information, dimensionality should be lower when anxiety is high. The latter pattern of findings would be more congruent with the motor coordination literature which argues that dimensionality can increase or decrease in response to functional or task specific constraints (Newell &

Vailancourt, 2001; Newell, Broderick, Deutsch, Slifkin, 2003). The dimensionality of positive affect should not change because of anxiety.

Emotional reactivity should also be associated with the embedding dimension of affect, and in a similar direction as anxiety. If reactive individuals are responding uniquely to each event they should show higher dimensionality for both positive and negative affect. Alternatively if individuals are incorporating stimuli into an existing, more rigid pattern of appraisal, it will be evidenced in lower dimensionality or more constrained temporal dynamics.

The proposed study

In order to address the patterns of affect I have described I will be examining the ratings of positive and negative affect of heterosexual romantic couple members over a three week period. Participants in the proposed study completed three weeks of daily affect ratings, as well as measures of anxiety, emotional reactivity, and attachment. By relating trait level descriptions of affect regulation with the temporal dynamics of affect coordination we can take steps towards understanding the affect system in much the same way that Altman and Rogoff (1987) suggested in their description of transactionalism, and in a fashion consistent with contemporary dynamical systems theorizing.

I estimated the embedding dimension of positive and negative affect for 48 couples (90 individual estimates) using 21 days of self-reported mood. First, I wanted to examine whether positive and negative affect dynamics could be differentiated using this measure of dimensionality. Second, I examined whether there was variability in dimensionality across individuals, and third, whether that variance could be predicted by molar descriptions of affect regulation. To gain power in estimation and to account for the within person dependency created in the process of estimating the embedding dimension, I used a multilevel modeling approach in the analyses.

METHOD

To address the empirical and theoretical questions outlined above I conducted a secondary data analysis on a subset of a larger sample that was involved in a daily diary study on couples, conducted by Lisa Diamond and colleagues that examined physical separation, and day-to-day proximity in relationships.   In this sample, all couples were together for the entire study period.

Participants

Participants were 48 cohabitating or married heterosexual couples who had been together for at least 1 year. Participants were recruited through newspaper advertisements and electronic messages sent to departments at local colleges and universities.   Additional couples were recruited as part of a broader study examining travel-related physical separation, and day-to-day proximity; their data have been reported elsewhere (Diamond, Hicks, & Otter-Henderson, 2006). All participants were remunerated with US$100. Participants ranged in age from 20 to 52 (*M*=27, *SD*=7, for both males and females). Couples were together for an average of 5 years (*SD* = 4) and 73% were married. The sample was predominantly Caucasian (85%) and highly educated (with 74% having completed a college degree). Mean household income was US$30,000 (*SD* =

$30,000, median = $25,000). Participants were screened for relationship satisfaction to ensure that couples had comparable levels of satisfaction. Relationship satisfaction was determined with Hendrick's (1988) Relationship Satisfaction measure, rating items on a 1-5 Likert scale (*M* = 4.5, *SD* = 0.48, male and females combined).

Participants completed baseline measures at an appointment prior to commencing a three-week survey during which daily measures were collected.

Baseline measures

The Experiences in Close Relationships questionnaire was used (Brennan, Clark, & Shaver, 1998) to measure attachment style. The measure consists of 36 items rated on a 7-point Likert scale, and yields two subscales: attachment anxiety and attachment avoidance (anxiety, α =.86, avoidance, α =.87)

Individual differences in emotional arousal were measured using the Emotional Reactivity Scale (Melamed, 1994). The scale consists of 6-items that measure individuals' tendency toward heightened arousal to both positive and negative emotionally valanced stimuli (e.g. ‘‘Whenever I think about an unpleasant event that once happened to me, I get upset about it all over again’’) (α = .60).

Trait anxiety was measured using a revised 10-item scale (Spielberger, 1983; State-Trait Anxiety Inventory) and will help to disentangle the hypothesized attachment effects from other trait dimensions (stable characteristics of individuals related to emotionality) as well as provide convergent support for the relationship between the dimensionality of affect and constructs known to impact arousal and interpersonal perception (α = .88).

Daily measures over 3-week period

Daily positive and negative affect was assessed using the Positive and Negative Affect Schedule (PANAS) (Watson, Clark, & Tellegen, 1988). The PANAS is a 20-item scale that yields two 10-item scales, one for positive affect (α = .90) and one for negative affect (α = .89). The PANAS has been widely used and found to predictive of a number of psychosocial outcomes.

Participants also reported the number of positive and negative events experienced each day using a daily event checklist adapted from Gable, Reis, & Elliot (2000) that has been shown to relate to daily affect. This measure allows me to parcel out variability in affect dimensionality that resulted from having good or bad days. Positive items include ”Had enough time to do what I wanted” and ”Did something special for someone that was appreciated.“ Negative items include “Something happened that made me feel awkward or embarrassed” and ”Experienced a setback at work”. There were 12 positive and 15 negative items.

A measure capturing the valance of daily interactions with one’s partner (Reis, Sheldon, Gable, Roscoe, & Ryan, 2000) was used to assess associations between everyday interpersonal experiences and dimensionality. Positive and negative interaction quality was indexed by ratings on a 5-point Likert. Positive interaction items capture the extent to which the interaction elicited feelings of closeness one’s partner, involved meaningful conversation, and elicited feelings of being understood and appreciated. Negative interaction items capture the extent to which the interaction was characterized by arguments or conflict and made the individual feel self-conscious or judged by others.

Participants also reported the estimated number of waking hours they spent in together throughout the day, the number of contacts and the length of the longest phone conversation. These items will help to understand the ways in which contact in person or through other means influences the relationship between affect dimensionality and attachment scales.

Analytic strategy

I used a method of embedding dimension estimation posited by Takens (1981) that is often used in phase space reconstruction in the study of dynamic systems. Takens (1981) demonstrated that a multidimensional space can be reconstructed from a single variable or scalar sequence in time, in this case positive and negative affect, and depict the larger multivariate system dynamics. One can imagine a multi-dimensional pattern expressed in the form of three equations (X, Y, Z) of motion. Takens showed that a multidimensional pattern, isomorphically similar to the original, can be created using a single variable and lags of the same variable (e.g., X(t), X(t-tau), X(t-2tau), where tau is a lag of some integer value).

Using a modified False Nearest Neighbors method (Butner & Story, under review; Kantz & Schreiber, 1999; Kennel, Brown, & Abarbanel, 1992) the number of dimensions or lags needed to depict the system dynamics can be calculated (see Appendix). An appropriate lag (tau = 1) was determined by calculating the first minimum of the average mutual information (Fraser & Swinney, 1986). There are many methods used for calculating lags though most yield similar results. Given the short nature of the time series used, a threshold of 2 was used for determining true from false neighbors.

I estimated the embedding dimension for positive and negative affect in separate models using PASW MIXED 18 in combination with a modified version of the False Nearest Neighbors method (Kennel, Brown, & Abarbanel, 1992). Multileveling modeling aids in gaining power both across and within individuals, partially addressing the relatively short time series for any one individual. The models included three terms predicting the embedding dimension; FNN, VALID, and the interaction between FNN and VALID. FNN and VALID are calculated for embedding dimensions 1 to 8. The intercept takes on the value of the embedding dimension when both FNN and VALID are zero. FNN indicates whether the points near each other in dimensional space are true neighbors or not, and the change in dimensionality when going from true to false neighbors. VALID indicates whether a particular vector of points qualifies as a potential neighbor or not, and is a group average of those points that are potentially true neighbors and those that cannot meet criterion in terms of extremity. The interaction between the two terms should be included to meet basic regression assumptions. I excluded an embedding dimension of one from the analyses because it has a tendency to bias results given that most neighbors are false at a dimension of one. In order to interpret the dimensionality estimate, coefficients for each term in the models needed to reach statistical significance. A random effect was estimated for the intercept to examine variability in dimensionality across individuals.

RESULTS

For each individual I generated four different measures of dimensionality: positive affect, negative affect, positive affect after controlling for partner’s same time positive affect, and negative affect after controlling for partner’s same time negative affect. The controlling methodology was generated by predicting one partner’s affect from the other (negative/negative, positive/positive) in individual regression analyses, for example, and using the residual scores for the dimensionality analysis. Differences in the findings between raw positive and negative affect and their residualized equivalents were negligible. Furthermore, the intraclass correlations of the dimensionality metrics within couples on the transformed affect data were negligible (positive affect =.00003, negative affect = .00007; these were calculated on the level 1 residuals in HLM 6.08) and did not change as a function of the residualized or raw data. This indicated that assumptions of residual independence had been met. I therefore report all findings on the dimensionality of raw positive and negative affect ignoring couple (effectively doubling my sample size).

Comparison of positive and negative affect dimensionality

For positive affect, all terms reached significance at p<.05 indicating that an adequate estimate of dimensionality was reached (Table 1). The embedding dimension of positive affect was 3.67 (95% CI: 3.60<m<3.74). There was no variability observed in the dimensionality of positive affect ($\sigma_{intercept}$=.058, *p*=.153). This finding suggests that the temporal dynamics of positive affect could be depicted in a similar embedding dimension for all individuals, or that the temporal dynamics of positive affect were functionally equivalent across persons.

The average embedding dimension for negative affect was 3.86 (95% CI: 3.79<m<3.94) and greater than the dimensionality of positive affect (Table 1). To compare the estimates across the two models, I created a confidence interval of the difference in dimensionalities following the recommendations by Cohen, Cohen, West, and Aiken (2003) (using the square root of the sum of the standard errors for the two models as the standard error). On average, negative affect temporal dynamics had a significantly higher dimensional volume than positive affect (95% CI of difference between dimensionalities: .09≤.19≤.29). This can also be interpreted to mean that there are more unique variables contributing to the dynamics of negative affect on average. Unlike positive affect, negative affect showed significant variability across individuals ($\sigma_{intercept}$=.23, *p*<.001) indicating individuals varied in their patterning of negative affect but not positive. Note that the average variability for negative affect suggests that some individuals potentially could have had equal positive and negative dimensionalities (Table 1).

Before concluding with certainty that there was not a random effect for the dimensionality of positive affect I visually inspected a Q-Q plot of the level 2 residuals for non-normality and extreme values (generated in HLM). There was one extreme case, however, the Q-Q plot suggested the residuals were normally distributed meaning that assumptions had been met for variance components to detect random effects. Rerunning the analyses with and without the case included did not impact any of the findings. Therefore, all findings are reported with the extreme case included. These data, thus, suggest that the dimensionality of positive affect was functioning similarly for all individuals. Since variability was only found in the dimensionality of negative affect all further analyses only focus on negative affect.

Negative affect as a function of anxiety, emotional reactivity, and attachment style

The embedding dimensionality of negative affect should be conditional on individual difference measures known to relate to the experience and patterning of affect. Trait anxiety, emotional reactivity, and measures of attachment anxiety and avoidance were entered as predictors of dimensionality. If negative affect dynamics are the outcome of additive influences, increased emotionality would correspond to higher embedding dimensions. If emotionality serves to functionally coordinate the dynamics of negative affect, higher emotionality would be associated with lower dimensionality. The data were consistent with the second interpretation.

Trait anxiety predicted dimensionality such that higher trait anxiety was associated with lower dimensionality (Table 2). Emotional reactivity similarly predicted dimensionality where higher levels of emotional reactivity were associated with lower dimensionality (Table 3). When emotional reactivity and trait anxiety were both included in the model emotional reactivity failed to reach significance while trait anxiety continued to predict indicating that trait anxiety predicted dimensionality above and beyond emotional reactivity but not the other way around. The two variables are highly related (*r* = .30, p<.05) thus overlap was expected in the variance in dimensionality accounted for by the predictors. From these initials models there was evidence that the dynamics of negative affect could be differentiated across individuals based on their level of trait anxiety and emotional reactivity. The pattern of findings is consistent with increased emotionality being associated with increasingly constrained coordinated temporal dynamics.

For measures of attachment anxiety and avoidance, anxiety predicted the dimensionality of negative affect similarly to the prior anxiety/reactivity effects, where higher attachment anxiety was associated with lower dimensionality (Table 4). Attachment anxiety did not uniquely predict dimensionality above and beyond trait anxiety. There was no effect observed for avoidance or the interaction between avoidance and anxiety (Figure 1).

Given the pattern of findings, the index of embedding dimensionality is sensitive to and able to differentiate individual differences in temporal patterns of negative affect. More specifically, the multivariate volume (embedding space) required to accommodate the reconstructed temporal dynamics of negative affect is reduced for those high in emotionality. Overly constrained affect dynamics (emotionality) is maladaptive when sustained but not when experienced in shorter durations in response to appropriate cues or stimuli. Low dimensionality should be associated with the experience of daily negative events, where all individuals regardless of trait level characteristics would have lower dimensionality as a function of negative events.

Trait anxiety, average daily negative events, and their interaction were entered in the model. The interaction was significant (Table 5) indicating that the relationship between negative events and dimensionality was different for those high and low in anxiety. Figure 2 shows the prediction plot of individuals 1 standard deviation above average, at average, and 1 standard deviation below average on average daily negative events (x-axis), and 1 standard deviation above average, at average, and 1 standard deviation below average on trait anxiety. Individuals high in anxiety had low dimensionality regardless of the frequency of negative daily events. Individuals low in anxiety, however, had high dimensionality when the occurrence of negative events was low, and low dimensionality when the occurrence of negative events was high.

Similarly, emotional reactivity, average daily negative events, and their interaction were entered in a separate model. The interaction was significant (Table 6) indicating that the relationship between negative events and dimensionality was different as a function of emotional reactivity. Figure 3 shows the prediction plot of individuals 1 standard deviation above average, at average, and 1 standard deviation below average on average daily negative events (x-axis) and 1 standard deviation above average, at average, and 1 standard deviation below average on emotional reactivity. Individuals high in emotional reactivity had low dimensionality regardless of the frequency of negative daily events. Individuals low in emotional reactivity again had high dimensionality when the occurrence of negative events was low, and low dimensionality when the occurrence of negative events was high.

This pattern of findings suggests that the temporal dynamics of negative affect are constrained (lower dimensionality) when individuals are either high on trait level variables associated with emotionality, or when there is a greater number of daily negative events. Individuals high in emotionality consistently function at lower dimensionality whereas those low on emotionality show a similar pattern of dynamic constraint only when negative events have occurred.

Table 1
Unconditional model parameter estimates for positive and negative affect

	Positive Affect Dimensionality			Negative Affect Dimensionality		
Parameter	Estimate	*SE*	*t*	Estimate	*SE*	*t*
Estimate of fixed effects						
INTERCEPT	3.67*	.03	105.91	3.86*	.04	101.94
FNN	-.75*	.04	-16.70	-.64*	.04	-15.41
VALID	-2.44*	.07	-35.99	-2.25*	.06	-37.17
FNNxVALID	1.18*	.09	13.15	.98*	.08	11.83
Estimate of covariance parameters						
Residual	1.95*	.028		1.96*	.028	
INTERCEPT (participant variance)	.005	.004		.053*	.011	

Note: * $p < .05$

Table 2
Parameter estimates for negative affect dimensionality conditional on trait anxiety

	Negative Affect Dimensionality		
Parameter	Estimate	*SE*	*t*
Estimate of fixed effects			
INTERCEPT	4.22*	.12	35.96
FNN	-.64*	.04	-15.48
VALID	-2.24*	.06	-37.13
FNNxVALID	.97*	.08	11.78
TRAIT ANXIETY	-.20*	.06	-3.24

Note: * *p* < .05, trait anxiety mean centered.

Table 3
Parameter estimates for negative affect dimensionality conditional on emotional reactivity

Parameter	Negative Affect Dimensionality Estimate	*SE*	*t*
Estimate of fixed effects			
INTERCEPT	4.12*	.12	32.34
FNN	-.64*	.04	-15.43
VALID	-2.25*	.06	-37.16
FNNxVALID	.98*	.08	11.83
EMOTIONAL REACTIVITY	-.08*	.06	-2.03

Note: * *p* < .05, emotional reactivity mean centered.

Table 4
Parameter estimates for negative affect dimensionality conditional on attachment dimensions

	Negative Affect Dimensionality		
Parameter	Estimate	*SE*	*t*
Estimate of fixed effects			
INTERCEPT	3.70*	.04	98.63
FNN	-.92*	.04	-24.82
VALID	-2.49*	.06	-44.84
FNNxVALID	.45*	.07	6.00
ATTACHMENT ANXIETY	-.07*	.03	-2.38
Estimate of fixed effects			
INTERCEPT	3.70*	.04	98.63
FNN	-.93*	.04	-24.82
VALID	-2.49*	.06	-44.84
FNNxVALID	.45*	.07	6.00
ATTACHMENT AVOIDANCE	-.04	.03	-1.20
Estimate of fixed effects			
INTERCEPT	3.70*	.04	93.02
FNN	-.93*	.04	-24.82
VALID	-2.49*	.06	-44.84
FNNxVALID	.45*	.07	6.00
ATTACHMENT ANXIETY	.07*	.04	-1.96
ATTACHMENT AVOIDANCE	-.01	.04	-.23
ANXIETYxAVOIDANCE	.01	.04	.19

Note: * $p < .05$, attachment anxiety and avoidance centered at their means.

Table 5
Parameter estimates for negative affect dimensionality conditional on trait anxiety interacting with average negative daily events

	Negative Affect Dimensionality		
Parameter	Estimate	*SE*	*t*
Estimate of fixed effects			
INTERCEPT	3.84*	.04	104.90
FNN	-.64*	.04	-15.52
VALID	-2.24*	.06	-37.15
FNNxVALID	.97*	.08	11.75
TRAIT ANXIETY	-.09*	.06	-1.39
NEGATIVE EVENTS	-.07*	.01	-4.52
ANXIETY x NEGATIVE EVTS	.08*	.03	2.70

Note: * $p < .05$, trait anxiety and average daily negative event variables centered at their means.

Table 6
Parameter estimates for negative affect dimensionality conditional on emotional reactivity interacting with average negative daily events

	Negative Affect Dimensionality		
Parameter	Estimate	*SE*	*t*
Estimate of fixed effects			
INTERCEPT	3.86*	.04	109.24
FNN	-.64*	.04	-15.52
VALID	-2.24*	.06	-37.16
FNNxVALID	.97*	.08	11.78
EMOTIONAL REACTIVITY	-.09*	.04	-2.51
NEGATIVE EVENTS	-.07*	.01	-5.08
REACTIVITY x NEGATIVE EVTS	.04*	.02	2.22

Note: * $p < .05$, emotional reactivity and average daily negative event variables centered at their means.

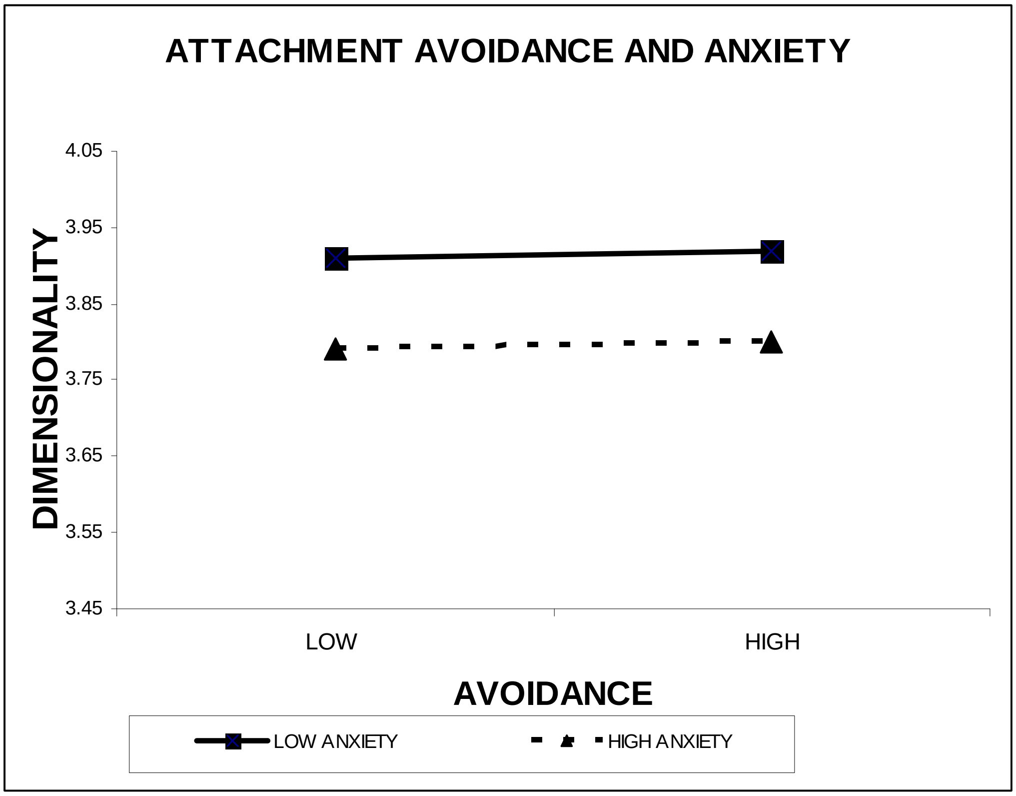

Figure 1*.* Interaction between attachment anxiety and avoidance predicting embedding dimensionality of negative affect. Variables are plotted at 1SD above and 1SD below their respective means.

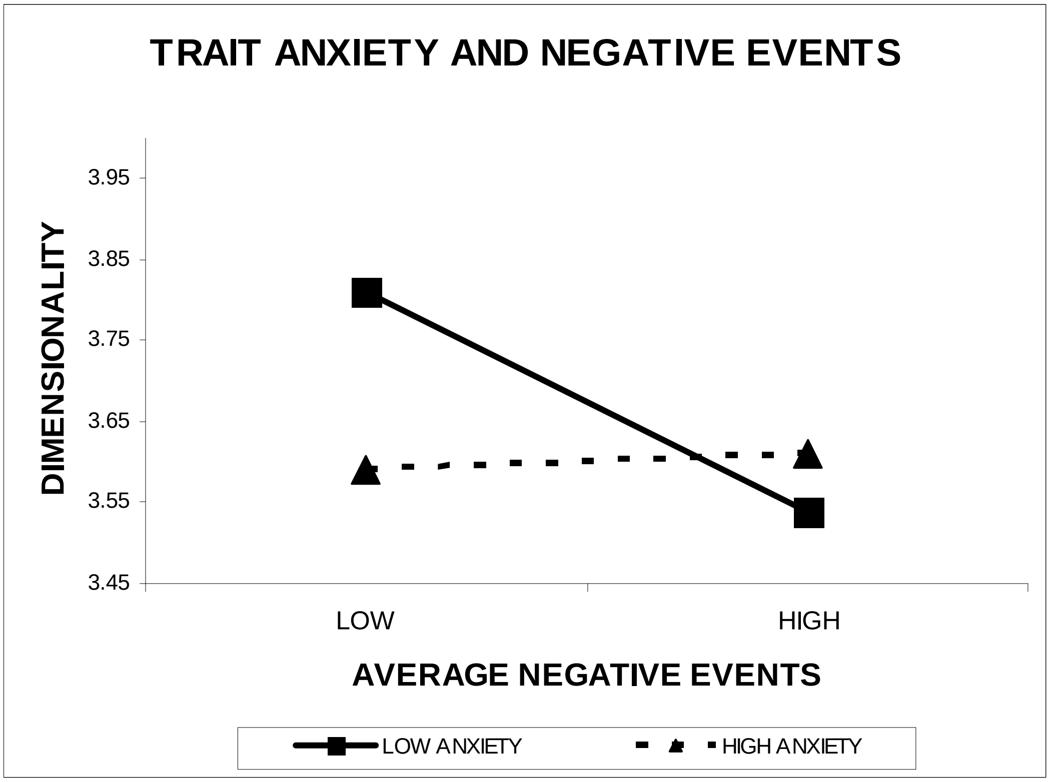

Figure 2. Interaction between trait anxiety and daily negative events averaged over 21 days predicting embedding dimensionality of negative affect. Variables are plotted at 1SD above and 1SD below their respective means.

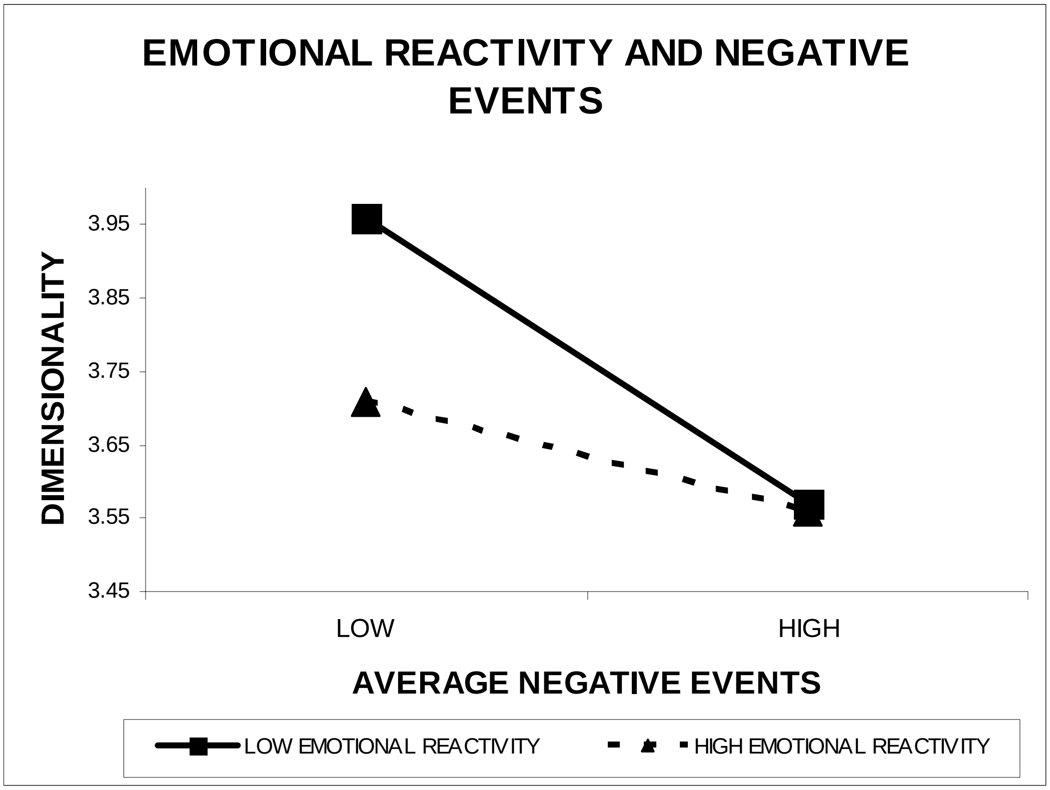

Figure 3. Interaction between emotional reactivity and daily negative events averaged over 21 days predicting embedding dimensionality of negative affect. Variables are plotted at 1SD above and 1SD below their respective means.

DISCUSSION

I proposed that the temporal dynamics of affect can be described and related to trait level descriptions of affect regulation using an estimate of the embedding dimension of individual time series'. Consistent with historical traditions of dynamical systems and social psychological research I sought to bridge levels of description of the affective system. I linked trait level reports of anxiety, emotional reactivity, and attachment anxiety with daily reports of negative affect by describing macroscopic temporal dynamics (embedding dimensionality). I showed that individuals can be differentiated in terms of embedding dimensionality based on whether one is high or low in negative emotionality. Dimensionality was high for low negative emotionality individuals except when they reported high levels of negative events over the 21-day period. These findings are consistent with literature on the normative and functional experience of anxiety and emotional reactivity; the differentiating feature is not the absence of negative events or threatening stimuli but rather the flexible response and being able to regulate one's affective experience.

The measure of embedding dimensionality can be thought of as both the number of unique equations of change required to describe the evolution of a system in time, and the active degrees of freedom or coordination dynamics of the system. I found evidence that the dimensional volume required to depict the dynamics of negative affect was larger than that of positive affect. This finding is consistent with the broader literature on differential processing of negative and positive stimuli, and the preferential activation of various neural substrates in response (Cacioppo, Gardner, & Berntson, 1999; Ohman, Flykt, & Esteves, 2001; Smith, Cacioppo, Larsen, & Chartrand, 2003; Taylor, 1991). Negative affect is composed of more potential inputs and thus requires a larger volume, compared to positive affect, to be fully depicted.

I failed to find variability in the dimensionality of positive affect and thus was unable to examine any relationships between trait level descriptors and its dimensionality. This does not mean that all time series' of positive affect were the same for every individual but rather that their active dynamics in phase space could be represented in the same dimensional volume. This would imply that all individuals could be described as having the same functional configuration of positive affect. The absence of variability in positive affect dimensionality could be due to the measure of affect used (PANAS) or the timescale of its report. Consistent with prior literature (Cacioppo, Larsen, Smith, & Berntson, 2004; Taylor, 1991), the finding may imply that there is simply more action with negative affect; it is 'hotter' and therefore more easily measured and depicted.

The pattern of findings regarding attachment anxiety and avoidance suggested that the measure of embedding dimensionality was particularly sensitive to molar descriptions of negative emotionality but not able to differentiate attachment dimensions or find a relationship between avoidance and dimensionality. Within the context of this study (healthy established couples) the classic findings of avoidance relating to negative affect may more be a function of what is and is not focused on rather than how much.

The study also sought to disentangle parallel aspects of heightened negative emotionality. Trait anxiety is reflected in an over interpretation of stimuli as threatening (Bar-Haim, Lamy, Pergamin, Bakermans-Kranenburg, & van Ijzendoorn, 2007; Mogg & Bradley, 1998) thus the individual high in anxiety is both being perturbed by many features of the environment and recruiting stimuli into a cognitive-affective pattern of appraisal and response that characterizes the psychological rigidity of anxiety (Fresco, Williams, & Nugent, 2006). Emotional reactivity captures the extent to which a person becomes easily aroused as well as the tendency to remain emotionally aroused. The inertia associated with emotional reactivity is a more rigid affective response pattern and associated with various maladjustment outcomes (see Kuppens, Van Mechelen, Nezlek, Dossche, & Timmermans (2007) for a review). High reactivity and anxiety were associated with low dimensionality; the results were interpreted to mean that embedding dimensionality is sensitive to rigidity in affect dynamics that correspond to trait-level descriptions.

Bernstein (1967) argued that the process of motor development consists of a reduction in dynamic or active degrees of freedom, even while the number of actual mechanical degrees of freedom may increase *or* decrease. From this perspective the change in dynamic degrees of freedom occurs unidirectionally where coordination is a reduction in active degrees of freedom that generates a class of possible behavioral outcomes. Bernstein’s approach did not address the notion of flexibility at the level of which behavioral configuration actually manifests. Kay (1988) and others (Newell & Vaillancourt, 2001) have argued that there is a hierarchy of system element constraints that occur as one moves from micro-components of the system (e.g., affective neuroscience) to the coordinative structure (the affect system), and finally to observable behavior or dynamic degrees of freedom (subjective affect, trait level descriptions of affect regulation). Further, the particular configuration of system elements at the level of coordinative structure is what allows the dynamic degrees of freedom or behavior to be functionally flexible and adaptable to novel contexts (if one can walk on concrete one can likely make the functional adjustments to walk on sand, however different the surface-step interface may be). This is a direct analog to affect.

In the context of affect the behavior we observe in a particular individual, or the qualia experienced, is the result of the coordinative structure of their idiosyncratic or even species specific affect system. How the affect system is activated and functionally brought to bear in a given task or context is unique. This study examined whether trait level descriptions of negative emotionality corresponded with an *increase* (hypersensitivity), *or* a *decrease* (hyperfocus) in the dynamic degrees of freedom of affect temporal dynamics and found support for the anxiety-affective relationship being consistent with a hyper-focus pattern. While the literature on motor coordination frequently observes decreases in dimensionality as a function of practice or learning, this is more analogous to affect regulation over development, and potentially less useful for understanding affect in smaller-scale context. Newell & Vaillancourt (2001; Vaillancourt & Newell, 2002; Newell, Broderick, Deutsch, & Slifkin, 2003) describe increases *and* decreases in dimensionality of motor behavior that are dependent on task demands. Thus functionally adaptive processes such as affect may require increases or decreases in dynamic degrees of freedom. This is consistent with affect regulation and healthy psychological functioning (Kuppens, et al., 2007).

Becoming anxious when faced with a threat is normative and guides a behavioral or cognitive response to facilitate reducing the threat. Displaying an appropriate response and recovering from emotional arousal is central to affect regulation. This study showed that individuals low in negative emotionality had higher dimensionality except when they had reported a high average number of daily negative events. Anxious and reactive individuals did not appear different in their embedding dimensionality whether negative events had occurred or not, suggesting that negative emotionality is associated with overly constrained negative affect dynamics. Those low in negative emotionality displayed a functional shift in dimensionality in response to negative events. In essence, being in an environment with many negative events was indistinguishable from an individual high in trait anxiety, as they both represent focusing in on a few things from the environment that are perceived to matter.

A challenge for future research will be to develop experimental approaches that allow for shifts in active degrees of freedom to be observed in response to task demands. For example, Gable and Harmon-Jones (2005) found that attentional broadness associated with positive affect is only found when the affect induction occurs in the context of avoidance goals rather than approach goals. Thus, examining both positive and negative affect in functionally specific contexts of attentional focus or shifting may yield insight into how and when embedding dimensionality change occurs.

Limitations

The time series used in this study were quite short for estimating dimensionality, thus the estimates themselves may be somewhat inaccurate compared to what they might be given more measures in time or a different affect measure. That said, finding a relative difference between individuals allowed for patterns of affect and individual differences in emotionality to be examined, indicating that the calculation was sensitive to differences across people.

The sample in this study was largely homogenous and high-functioning meaning there was likely a restriction of range in the constructs investigated. Healthy couples give us a good sense of healthy coordination but not necessarily information about the risky ranges of emotionality associated with clinical disorders or outcomes. By taking daily measures I may have had a poor representation of the dimensional volume because I was examining dynamics of daily epochs rather than the within the moment-to-moment circumstance. Further, the measure of daily affect may be limited in its psychometric properties and the retrospective nature of the affect reports. Finer grained measurements may have allowed a clearer interpretation and increased power within time series.

Future directions

Developing an understanding of how dimensionality shifts in time in response to various domains of events, across different timescales, is important to further the understanding of the index. Kay cited the need and utility of a dimensionality analysis at all levels of system functioning to better understand the full range of system geometries. Newell and Vaillancourt's (2001) research examines the way that dimensionality shifts up or down depending on the functional constraints of the task itself (Newell, Broderick, Deutsch, & Slifkin, 2003; Vaillancourt & Newell, 2002). Certainly it would make sense in terms of affect regulation to be able to slip into different dimensional configurations depending on the context. Low trait anxiety individuals preattentively avoid negative or threatening stimuli until some threshold is reached and they shift in affective coordination to stimuli in the environment. The coupling of attention and affection regulation (Wadlinger & Isaacowitz, 2011) is an import area of research that may help clarify when dimensional shifts occur, in which direction, and under what circumstances.

APPENDIX

Analytical technique for calculating embedding dimension

False nearest neighbors

The concept of false nearest neighbors (FNN) and dimensionality seem distally related. FNN capitalizes on Takens' (1981) theorem by mapping a single variable through time using its constituent lags and combines it with properties inherent to a phase space representation of the system. The concept of FNN is that two points that are truly next to each other in phase space will continue to be next to each other if represented in a dimensionality above the true embedding dimension. However, two points in embedding space less than the actual embedding dimension may appear next to each other, but may not be neighbors at a higher dimensional representation because they were only folded to be next to each other (Kennel, Brown, & Abarbanel, 1992). With an automobile, for example, let us say that it takes four dimensions to constitute all the unique motions of successful driving. Plotting the points in four dimensions or all 10 dimensions will show the same properties, but plotting it in fewer than four dimensions will not. By minimizing the number of neighbors at dimension (m) that are false at dimension (m+1), we can identify when m is just enough to properly unfold a variable in time.

This approach (applied uniformly in the literature on FNN) requires the user to choose a lag (τ) to define a series of points to represent a vector. At an embedding dimension of one, each point is compared with every other point in the time series to identify the point with the closest value at m. At two dimensions (m=2) each point is represented by the value Y at time T and the value of Y at time T+τ - a vector. At three dimensions (m=3) each point is represented by a vector of three points: Y_t, $Y_{t+\tau}$, and $Y_{t+2\tau}$, and so forth. The Euclidean distance is calculated between all vectors at m, the smallest distance defines the neighbor for that data point. The distance between these same points are calculated at vector length of m+1. The neighbor is then declared false if the ratio of distances between points at m+1 to m surpass some user specified threshold (r). That is, the distance between two points increased substantially at a higher dimensionality. This is done for all points in the time series creating the proportion of false neighbors at embedding dimension (m).

Kantz and Schreiber (1997) expanded on the FNN approach to account for a bias that some vectors are too extreme in value to have a case even qualify for having a true neighbor (or neighbor for that matter). They estimate the proportion of FNN using the following equation:

$$\mathrm{Pr}oportion_{fnn}(r) = \frac{\sum_{n=1}^{N-m-1} \Theta\left(\frac{\left| s_n^{(m+1)} - s_{k(n)}^{(m+1)} \right|}{\left| s_n^{(m)} - s_{k(n)}^{(m)} \right|} - r \right) \Theta\left(\frac{\sigma}{r} - \left| s_n^{(m)} - s_{k(n)}^{(m)} \right| \right)}{\sum_{n=1}^{N-m-1} \Theta\left(\frac{\sigma}{r} - \left| s_n^{(m)} - s_{k(n)}^{(m)} \right| \right)} \qquad (1)$$

N is the number of cases in the time series, m is the embedding dimension for calculating the FNN, S is the Euclidean distance of two nearest vectors using lag τ, r is the threshold and σ is the standard deviation of Y across the time series. This is done for all points in time. The three separate heavyside step functions (Θ) express the quantity as the proportion of false neighbors who qualify by not having vectors too extreme in value (the additional constraint comes from the second heavyside step function in the numerator where the Euclidean distance is compared to the ratio of the standard deviation and the threshold parameter r and the same function in the denominator to adjust the count – the extreme cases are excluded from the proportion). As with the previous methods of FNN, the user must identify a threshold (r), and a lag (τ) and though the approach is argued to be robust to these choices, its impact is rarely assessed (Kantz & Schrieber, 1997). The proportions of false nearest neighbors (Y-axis) are then plotted as a function of the embedding dimensions (X-axis) and the embedding dimension is chosen at the base of the elbow – consistent with the way Scree Plots are utilized in exploratory factor analysis.

Revising the FNN approach

Our approach is to break equation (1) into individual components and re-express it in a regression format. For each point in time T, we calculate two binary variables at a series of different embedding dimensions (m). These two binary variables parallel the numerator portions of equation (1). The first we will call FNN:

$$FNN_t = \Theta\left(\frac{\left| s_t^{(m+1)} - s_{k(t)}^{(m+1)} \right|}{\left| s_t^{(m)} - s_{k(t)}^{(m)} \right|} - r \right) \qquad (2)$$

This is essentially the first heavyside step function indicating if, for the individual case at time t, its nearest neighbor qualifies as false (FNN=1) or a true neighbor (FNN=0). The second equation parallels the second step function generating a binary variable we will call VALID:

$$Valid_t = \Theta\left(\frac{\sigma}{r} - \left| s_t^{(m)} - s_{k(t)}^{(m)} \right| \right) - .5 \qquad (3)$$

VALID indicates if a given vector qualifies as potentially having a true neighbor (VALID=.5) or not (VALID=-.5). In our analytic procedure we can create the identical results to Kantz and Schrieber (1997) by excluding cases where VALID equals -.5, treating them as missing data. In practice we suggest including all cases and using VALID as a variable in the model to control for the differential importance of these cases.

Using the FNN and VALID calculations, this generates a pair of binary variables for each value of Y in the time series for a range of embedding dimensions (e.g., m=1 to m=10). For simplicity, we will temporarily fix the threshold parameter and lag to exemplify our basic logic. The embedding dimension can then be estimated in a regression equation:

$$m_t = b_0 + b_1(FNN_t) + b_2(VALID_t) + b_3(FNN_t * VALID_t) + e_t \qquad (4)$$

This regression equation assumes a conditional probability of the embedding dimensions, consistent with expectations. B_0, the regression intercept, is the predicted embedding dimension when FNN equals zero and VALID equals zero. Since the FNN variable is coded as zero when it is a true neighbor, the intercept takes on the predicted embedding dimension when there are no false neighbors. Since VALID is an unweighted effects code, the intercept is also a group average between the cases Kantz and Schrieber (1997) would include and those cases that would normally be excluded. Notice that there is no ambiguity in the estimation of the embedding dimension (no need to identify the elbow in a plot). Additionally, standard errors on the intercept provide a method of generating confidence intervals on the estimate.

The regression coefficients on FNN, VALID, and the interaction between FNN and VALID are also of interest in the analytic procedure. For the main effect of FNN, the regression coefficient indicates the extent to which the embedding dimension estimate changes when FNN goes from zero to one when VALID is zero (at the group average of VALID). In other words, the coefficient on FNN (b_1) is the extent to which the embedding dimension estimate changed between having real vs. false neighbors averaged between those who potentially can have a false neighbor and those who cannot. If no change had occurred (the FNN main effect was not significant), then it would be indicative of a poor estimate in the embedding dimension either due to having too small a time series or a poor range of estimates for the embedding dimension or other parameters. Thus, a significant coefficient on the FNN variable provides evidence as to the utility of the embedding dimension estimate.

For the main effect of VALID, the regression coefficient indicates a change in the estimated embedding dimension between those cases that would normally be removed from the data analytic procedure and those that would always be included. A non-significant coefficient would be indicative of an inability to differentiate those who potentially could not have a true neighbor from those who can. Thus, it provides a second validation test for the use of the embedding dimension estimate. Ideally both the FNN and VALID coefficients would be significant to verify the embedding dimension estimate.

Under large samples, removal of cases where VALID equals -.5 would likely result in a better estimate of the embedding dimension. However, under small sample sizes these cases can still provide useful information, though not as valuable as those that would always be included. And rather than removing such cases, it provides a weighting for their estimates. Since the exclusionary rule produces large proportions of cases to be removed, the unweighted effect code essentially reduces the influence of those cases in comparison to the cases that would always be included. This trade-off creates a likely interpretation that the embedding dimension estimate may be biased, but that the validation tests would be indicative that differences in embedding dimensions could still be detected.

The interaction between FNN and VALID indicate the extent to which the test between false and true neighbors (FNN) differs between those who potentially can have a false neighbor and those who may not. The test itself is not very indicative of the validity of the embedding estimates. However, the inclusion of the interaction is necessary to get a proper estimate of the FNN and VALID coefficients since they will likely interact and regression assumes homogeneity of slopes. Given the argument for what the VALID variable is coding for, it is also possible to end up with a nested arrangement where not all possible cells of the two by two contain cases. Under this circumstance, the interaction would appear collinear with the FNN and VALID main effects and the appropriate choice is to merely drop the interaction.

Multiple people analyzed simultaneously

Since the regression procedure described thus far is conducted within person, this approach is easily expanded to multi-level modeling procedures that simultaneously examine across people. The search for false neighbors is first conducted within person for a series of embedding dimensions. The resultant values for m, FNN, and VALID are treated across individuals (i) using a level one equation paralleling equation 4.

$$m_{ti} = \beta_{0i} + \beta_{1i}(FNN_{ti}) + \beta_{2i}(VALID_{ti}) + \beta_{3i}(FNN_{ti} * VALID_{ti}) + e_{ti} \qquad (5)$$

The level two equations then include average parameters and variability in parameters across people.

$$\begin{aligned} \beta_{0i} &= \gamma_{00} + \omega_{0i} \\ \beta_{1i} &= \gamma_{10} + \omega_{1i} \\ \beta_{2i} &= \gamma_{20} + \omega_{2i} \\ \beta_{3i} &= \gamma_{30} + \omega_{3i} \end{aligned} \qquad (6)$$

The central focus is the intercept equation (β_{0i}) and one can then further expand the equation to include predictors of various coefficients: to see what individual difference factors might account for variation in the embedding dimension. It is also plausible to find variability in the validation tests (FNN and VALID) and the interaction. In each case the equations can be expanded with appropriate individual difference variables to indicate generalizability of the embedding dimension estimates to subpopulations.

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