Measuring Hypnosis: Relating the Subjective Experience to Systematic Physiological Changes

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1. Introduction

Clinical hypnosis is a mind-body technique that operates at the intersection of subjective perceptions and objective physiological changes. A fundamental problem with hypnosis research is that the subjective mental state of patients during hypnosis cannot be measured directly. Experimental paradigms that neglect to measure changes in mental state at best yield a correlation between the treatment procedure and outcomes but cannot demonstrate a causal link. Current practices rely on the subjective reports of the subject to distinguish whether a negative experimental outcome arises because the patient never achieved the hypnotic state or because hypnosis was an ineffective treatment. The purpose of this research is to bridge this gap between the subjective perception of the hypnotic state and objective measurement of concomitant physiological changes. In addition, we seek a technique that can estimate depth of hypnosis during the course of a hypnosis session, on a time scale of less than a minute.

2. Background

2.1. Previous attempts to identify physiological changes specific to hypnosis

Hypnosis is commonly thought to be associated with EEG alpha frequencies but reproducibility has been difficult to demonstrate (Perlini and Spanos 1991). PET and fMRI studies have found significant but inconsistent differences during the hypnotic state (Maquet and al. 1999), (Rainville 1999), (Ulrich, Meyer et al. 1987). The hypnotic state can also be monitored by examining variability in the heart rate

measured between subsequent beats of the heart – the heart rate variability (HRV) signal. The heart rate exhibits spontaneous fluctuations even at rest that reflect the continuous influence of the autonomic nervous system (ANS) on the heart's pacemaker cells (Akselrod and al. 1981). The HRV signal typically contains a high-frequency (HF) component near respiratory rate (≅0.25 Hz). The spectral power in the HF component has been shown to increase during conscious relaxation compared with rhythmic breathing at 0.25 Hz (Sakakibaba, Takeuchi et al. 1994). Peng et al. found exaggerated heart rate oscillations associated with slow breathing during meditation that were significantly different from metronomic breathing and from spontaneous nocturnal breathing by normal adults or elite athletes (Peng, Mietus et al. 1999). There are accounts in the hypnosis literature that HRV is affected by mental absorption (Zachariae, Jogensen et al. 2000) and by the hypnotic state (DeBenedittis and Cigada 1994). These studies show that parameters calculated from HRV change in specific ways during meditation, mental absorption and hypnosis.

2.2. Experimental hypotheses

1. A single parameter can be calculated from HRV that will change systematically during the hypnotic state when compared with a control condition that is commensurate with the hypnotic state.
2. The average values of such a parameter would increase when more hypnotic phenomena are experienced thereby providing evidence for a hypnosis-specific measure.
3. Dynamic self-rating of hypnotic depth during hypnosis will also correlate with a single dynamic HRV parameter. A dynamic HRV parameter that correlated with dynamic self-rating would enable real-time monitoring of hypnotic depth.

2.3. Need for dynamic HRV parameterization

The HRV signal is complex due to the many sources of physiological variation with varying degrees of interdependence. Sources of variation include vagal tone, baroreflex mechanisms, circadian rhythms, respiration, and stress levels. These multiple sources of variation are embedded within the single HRV time series. This matter is further complicated because the variation introduced by each source is dynamic. Lumped statistics such as mean and variance fail to distinguish between sources of variance. Power spectrum analysis requires many minutes of HRV data to achieve reasonable frequency resolution and is therefore incapable of tracking dynamic HRV frequency dynamics that occur on the order of seconds.

3. Methods

3.1. Proposed dynamic HRV model

Since HRV is sampled only once per heart beat, dynamic parameterization of HRV on the time scale of seconds requires that parameters are extracted from just a few data

points. By treating HRV as a single oscillator, a sinusoid model with an offset and additive noise can be applied.

$$HRV = a(t)\sin\left[w(t)t + f(t)\right] + d(t) + n(t) \quad (1)$$

In this model, the amplitude *a*, frequency *w*, phase angle *f*, offset *d* and noise *n* are allowed to vary on a larger time scale than the sampling rate.

Fitting the parameters within the temporal window to the proposed model is difficult because of its nonlinearity and potential for aliasing. Conventional optimization algorithms are sensitive to noise and often converge to higher frequency alias solutions. A least-squares method was devised to fit the model parameters thereby increasing the computational speed and noise rejection.

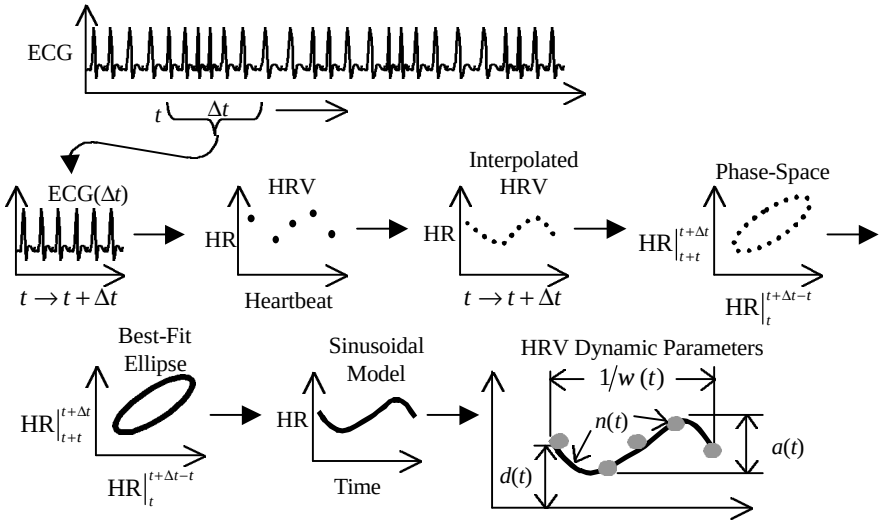

Figure. 1. Least-squares fit of parameters to the proposed dynamic HRV model. A sample of ECG data of length Δ*t* is extracted from an ECG record. The heart rate per heartbeat (HRV) is calculated by taking the inverse of the beat-to-beat times. HRV is then interpolated to a regularly sampled time series. The time series is plotted in pseudo-phase space verses itself at a time lag of *t*. Sinusoidal oscillations in HRV become an ellipse in this phase-space. The quadratic coefficients for an ellipse are fit to the data in phase-space using a least squares method. The quadratic coefficients are mathematically transformed back to the sinusoidal model. The resulting HRV dynamic parameters (*HRVdp*) are the amplitude *a*, frequency *w* offset *d* and a goodness of fit parameter that is inversely related to the additive noise *n*(*t*); the phase angle *f* is not used.

The chosen size of the temporal window was Δ*t* = 6 sec. so that typically 5 estimates of the heart rate were contained within the window. To correct the irregular sampling rate of HRV, the heart rate estimates for each heartbeat were dropped onto the nearest time point of a 10Hz temporal grid and intermediate data points were interpolated with a cubic spline. The phase-space transformation used a time lag of *t* = 1 sec. yielding a frequency range of 0 to 0.5 Hz. Once the parameters were estimated at time *t* the temporal window was advanced by 1 sec. and then the process was repeated, yielding a 1 Hz moving estimate of the model parameters.

The transformed interpolated HRV from time t to $t+\Delta t$ expressed in phase space with the time lag t is given by:

$$\begin{aligned} x &= HRV\left(t \in (t_i, t_i + \Delta t - t)\right) = a\sin\left(wt + f\right) + d + n \\ y &= HRV\left(t \in (t_i + t, t_i + \Delta t)\right) = a\sin\left(w(t+t) + f\right) + d + n \end{aligned} \tag{2}$$

If the noise component of the HRV signal is small, then the geometric representation of the HRV data in the *xy*-plane is an ellipse that can be described by the generalized quadratic form

$$Ax^2 + Bxy + Cy^2 + Dx + Ey + F = 0 \tag{3}$$

where the quadratic coefficients are related to the HRV model parameters as

$$\begin{aligned} A &= \frac{1}{4a^2}\left(\tan^2\tfrac{wt}{2} + 2 + \frac{1}{\tan^2\frac{wt}{2}}\right) & D &= \frac{-d}{a^2}\left(\tan^2\tfrac{wt}{2} + 1\right) \\ B &= \frac{1}{2a^2}\left(\tan^2\tfrac{wt}{2} - \frac{1}{\tan^2\frac{wt}{2}}\right) & E &= D \\ C &= A & F &= \frac{D^2}{2A+B} - 1. \end{aligned} \tag{4}$$

From equations (4) it is apparent that if the quadratic coefficients could be estimated for the HRV data then the amplitude, frequency and offset parameters could be calculated with the inverse relationship,

$$a = \sqrt{\frac{4A}{4A^2 - B^2}} \qquad w = \frac{2}{t}\operatorname{atan2}\sqrt{\frac{2A+B}{2A-B}} \qquad d = \frac{-D}{2A+B}. \tag{5}$$

Pilu et al. describe a method for direct least squares fitting of an ellipse that is ideally suited to this application (Pilu, Fitzgibbon et al. 1996). Pilu's method is constrained to yield the quadratic coefficients subject to the elliptical constraint of $B^2 - 4AC < 0$ and it is computationally efficient. The HRV dynamic parameters (HRVdp) *a*, *w*, *d*, and *n* are calculated using equation (5) from the best-fit quadratic coefficients.

3.2. Normalizing the HRV dynamic parameters

In order to make inferences based upon *HRVdp*, the values must be statistically compared to a control condition. Statistical properties of the control condition *HRVdp* can also be used to normalize *HRVdp* values for both the control and experimental conditions. Subtracting the control condition means and then dividing by the control standard deviation scales the distributions of the control *HRVdp* values to the standard normal distribution and makes all of the parameters dimensionless. This also places all of the experimental *HRVdp* values onto the same normal distribution axis. Averaging the four scaled *HRVdp*'s yields a single normalized HRV dynamic parameter (*nHRVdp*). When averaging the four scaled *HRVdp*'s, sign changes can be used to normalize the expected direction of parameter change during the experimental condition. In this study, the sign of all the parameters was flipped so that a decrease in *a*, *w*, *d*, and *n* all result in a more positive *nHRVdp* on the standard normal distribution scale. The significance of the experimental condition *nHRVdp* values can now be statistically tested with the null hypothesis that the mean is zero.

The 1Hz-sampling of nHRVdp enables reasonable comparisons to be made with 10 to 30 seconds of historical data.

3.3. Experimental Proceedure

Eleven subjects participated in the study (5 male, 6 female, mean age 21). Two subjects reported having some familiarity with hypnosis. None of the subjects had any history of psychological disorders, trauma or cardiac health problems. None of the subjects were currently taking medications.

During the hypnosis condition, subjects were instructed to sit comfortably with their eyes closed while listening to a hypnotic induction and suggestions spoken by the experimenter. Subjects were instructed to move a lever periodically to indicate how hypnotized they felt on a scale of 1 to 5 during the experiment. Subjects were reminded to move the lever every 1 to 2 minutes. The hypnotic suggestions encouraged focus on imagined sights, sounds and feelings. During the control condition subjects were instructed to sit comfortably and relax with their eyes closed while listening to the experimenter. Subjects were asked a series of true or false questions designed to ensure that the subjects stayed awake and focused. The content of the questions had minimal emotional content and required only commonly held knowledge. Subjects indicated their responses by moving the same lever used to indicate hypnotic depth.

After giving informed consent, subjects were questioned about their previous experiences with hypnosis. The Hypnotic Induction Profile (Speigel and Speigel 1978) was used to measure subjects' hypnotizability. Subjects were then prepared for data logging sampled at 200Hz with an ECG (HP 78354A) and respirometer (custom). Data was recorded for 10 minutes of the control condition followed by 10 minutes of the hypnosis condition. After the hypnosis session, subjects were asked how hypnotized they felt and if they experienced various hypnotic phenomena.

4. Results

4.1. Hypnotizability and hypnotic phenomena

Of the 11 subjects tested with the Hypnotic Induction Profile, 10 were determined to have intact hypnotic ability and 1 was not responsive to the hypnotizability test. Data from this subject was subsequently excluded from the analysis.

Table. 1. Overall self-rating of hypnotic depth (n=10)

Subjective Self-Rating	1	2	3	4	5
Number Reporting	0	2	5	2	1

Table. 2. Hypnotic phenomena reported by subjects immediately after hypnosis (n=10)

Hypnotic Phenomenon	Num. Subj.	Hypnotic Phenomenon	Num. Subj.
Vivid mental imagery	9	Imagined textures	6
Heaviness/sinking into chair	8	Drifting sensations	5
Time distortion	8	Tingling sensations	4
Floating sensations	7	Imagined smells or tastes	4
Clear mental sounds	6	Unusual temperature changes	3

4.2. Differences in mean *nHRVdp* during hypnosis

The mean *nHRVdp* was found to be significantly greater during hypnosis than control for all 10 subjects. Mean *nHRVdp* values ranged from 0.17 to 0.62. A one-tailed t-test comparing the control and hypnosis *nHRVdp* was significant for all subjects ($p<0.000001$ in all cases, $7.3 < t < 24.9$).

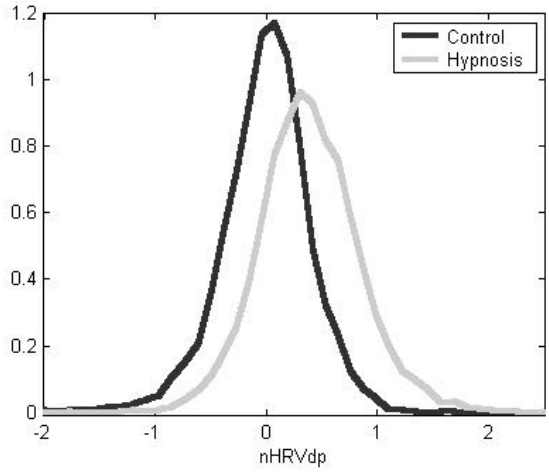

Figure. 2. Control and hypnosis *nHRVdp* distributions. An averaged distribution of all 10 subjects is shown. Two-way ANOVA between experimental condition and subject shows that the separation of the composite HRV parameter distributions is highly significant ($F=2601$, $p<0.000001$, $n_c=6054$, $n_h=6000$).

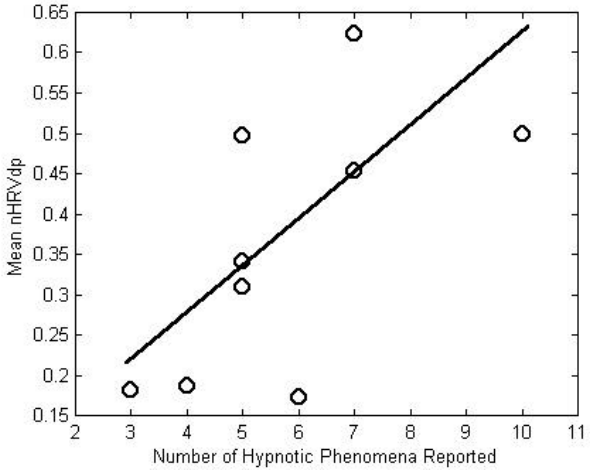

Figure. 3. The number of hypnotic phenomena from Table 2 reported by each subject was totaled and correlated with the mean *nHRVdp* during hypnosis ($R^2=0.42$, $F=5.79$, $p=0.043$, $n=10$). Data points for individual subjects are shown (circles) with the regression line.

4.3. Correlations between *nHRVdp* and dynamic self-rating of hypnotic depth.

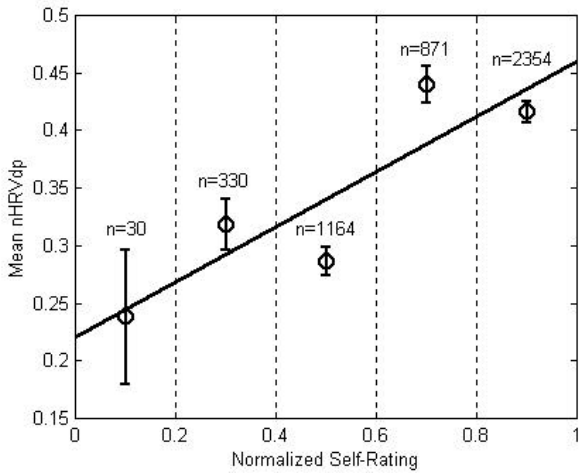

Figure. 4. The self-ratings of hypnotic depth were normalized for each subject and then divided into the five bins indicated on the horizontal axis of the figure. Mean *nHRVdp* values corresponding to the binned self-ratings are shown on the figure (circles). The error bars are standard error. Self-ratings during the first 2 minutes of the hypnosis condition are excluded because that time corresponds to the hypnotic induction period when the hypnotic state fluctuates widely but the lever was not generally moved because of logistics. A significant correlation was found between the binned normalized self-ratings of hypnotic depth and the mean composite HRV parameters in each bin (R^2=0.77, F=10.2, p=0.0497, n=5).

Although the normalized self-ratings of hypnotic depth generally increased during the experiment, there is no significant correlation between normalized self-ratings and mean normalized time in each bin (R^2=0.504, F=3.04, p=0.179, n=5). This indicates that the magnitude and timing of lever movements was significant.

5. Discussion

The first hypothesis was that a single parameter could be calculated from HRV that would change systematically during the hypnotic state. The normalized HRV dynamic parameter was found to increase significantly during hypnosis for all subjects ($p<0.000001$). The second hypothesis was that the average values of such a parameter would increase when more hypnotic phenomena are experienced. Mean *nHRVdp* was found to correlate significantly with the number of hypnotic phenomena reported by subjects immediately after the hypnotic session (p=0.043). The third hypothesis was that dynamic self-rating of hypnotic depth during hypnosis would also correlate with such a specific dynamic HRV parameter. Normalized self-rating of hypnotic depth was found to significantly correlate with *nHRVdp* (p=0.0497). The fact that no significant correlation between dynamic self-rating was found with time

during the experiment further supports the claim that the dynamic changes in self-rated hypnotic depth are systematically related to *nHRVdp*.

In the broadest sense, these results suggest that an ECG monitor together with the proposed dynamic HRV model objectively measure hypnotic depth. Such a device, a "hypnometer," could be used as a standard in clinical hypnosis to improve the reliability of hypnotic interventions. A hypnometer would also be a useful tool for the psychotherapeutic uses of hypnosis. A patient's hypnotic depth could be monitored in real time providing valuable feedback to the therapist without the need to ask the patient for self-ratings.

One of the most important issues to address with the HRV based monitoring of hypnotic depth is repeatability. Although the results presented are statistically significant, the number of subjects was small (n=10) and the same experimenter conducted all of the hypnosis sessions. Also, the overall duration and ordering of the experimental conditions was not varied in this experiment. Because of the subjective nature of the hypnotic state and the large number of influences on HRV, it is unclear exactly what is being measured by the proposed method.

The nature of hypnosis is an age-old question. This algorithm provides a new way of monitoring hypnotic depth and may help to elucidate the underlying physiology of hypnosis.

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