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A Study on the Behaviour of Heart Rate Variability (HRV) with the aid of Markov Chains Theory and Transition Probability Matrices

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Heart Rate Variability (HRV), as recorded by biofeedback equipment, can be very informative about some of the aspects of the emotional, cognitive and physiological states of an individual. In this study we recorded HRV for eight (8) participants under different modalities (meditation, listening to a reading and visioning) via the use of an emWave system (commercial product) (Quantum Intech, Inc., 2010), that measures heart rhythms in a non-invasive (free of risk) way. This measurement presumably captures heart-brain and autonomic nervous system dynamics in general, that reflects changes of coherent, relaxed or stressed states encoded in different heart rhythms. We analysed the results using a methodology described in previous research work (Davis & Schübeler, 2019) based on Markov Chain Analysis, in order to determine the transition probability matrices between three states: Coherent (0), Relaxed (1) and Stressed (2) for the different modalities. The results show clearly that the highest levels of coherence were achieved during meditation, followed by listening to reading material and visioning. We posit that biofeedback equipment combined with the methodology applied for analysing the data can be a powerful tool in discriminating and modelling different states of consciousness and inner peace directly related to psychophysiological coherence, particularly valuable when masterfully generated at will.

Keywords - *Heart Rate Variability (HRV), Psychophysiological Coherence, Coherence Scores, Euclidean Distance, Semi-Markov Processes, Markov Chain Analysis, Markov Probability Transition Matrices, Inner Peace.*

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INTRODUCTION

Planetary peace and social harmony require that each person within the human family attain a way of life that is conducive to inner peace. This is a challenge that is solely the responsibility of each adult, whether it be in personal connection with The Creator or in an impersonal interaction with the field of Universal Values via meditation, for example. In previous work (Zhuang et al., 2016) (Gillett & Davis, 2015) (Davis & Walling, 2018) we presented the reader with ways to understand a peace propagation process that starts with the attainment of individual inner peace and then potentially and ideally propagates in human interactions, describing the system dynamics that include presumably causal loops which connect, amongst other factors, the rate at which an individual grows spiritually modulated both by stress levels, as well as the quality of a spiritual practice (Thayer et al., 2012). In this paper we present experimental results and analysis based on HRV data that shows the different levels of psychophysiological coherence associated to different daily activities (modalities) like meditation, listening to reading material, presumably spiritually uplifting and conducive to inner peace, and finally we measure HRV in a community process of envisioning which includes dialogues and expositions towards a shared vision for the community.

With the raw data obtained with the emWave system, a biofeedback system used to monitor heart rate variability and psychophysiological coherence, (Quantum Intech, Inc., 2010), we calculated the transition probability matrices based on coherent states, also associated to coherence scores (Davis & Schübeler, 2019) which show the effectiveness of prayer and meditation as a spiritual practice that can help to reduce stress more than inspirational reading does. We also show that mentally energy consuming tasks may lead to lesser coherence and more stress, however, when balanced with activities that contribute to coherent states, we can improve the quality of human life and thus provide biological environments more conducive to inner peace (van der Eijk, 2007), particularly when the energy-consuming tasks are geared towards a learning process that, in the long-term, contributes to the mastery of psychophysiological coherence and inner peace.

Here we present an initial study to show the discriminative power of our methodology in order to characterize three (3) different states: Coherent (0), Relaxed (1) and Stressed (2) for eight (8) of ten (10) participants that took part in The Embassy of Peace Vision 2017 Heart Rate Variability (HRV) and Coherence Study, where the data was collected and then analysed estimating transition probability matrices that are usually described in detail in the common literature available on Markov Processes and Markov Chains (Ross, 1983) (Howard, 1971).

Heart Rate Variability has been defined as "…..the change in time intervals between adjacent heartbeats; an emergent property of interdependent regulatory systems that operates on different time scales to adapt to environmental and psychological challenges" (McCraty & Shaffer, 2015) and is a measure of neuro-cardiac function that reflects heart-brain interactions and autonomic nervous system dynamics (McCraty et al., 2006) (McCraty & Shaffer, 2015) (Tiller et al., 1996). It is expected that changes in HRV due to particular breathing patterns (breathing techniques), together with the experience and embodiment of positive emotions, would lead to different coherent or stressed states (Childre & McCraty, 2001) (Heck et al., 2017) (Pribram & Melges, 1969). We are interested in studying the transitions between states (0, 1 and 2) that may give us the means to calculate coherence Scores (S), coherence Cumulative Scores (CS) and transition probability matrices (TPM). The first two (S & CS) will allow us to compare the different modalities via a measure of distance (Euclidean Distance) between an ideal score and the actual score. The third (TPM) will allow us to characterize the different individuals under different modalities via their respective transition probability matrices, which in turn we intend to use in modelling and simulating (Law & Kelton, 1991) complex systems like social interactions between individuals in different coherent states and in so doing, better describe the peace propagation process in communities of different sizes and mixtures of individuals with different levels of mastery for psychophysiological coherence and inner peace (Zhuang et al., 2016).

We foresee that these tools will allow us to study and comprehend brain-heart-respiration dynamics and their implications in the mastery of coherent states, which are conducive to or generated by inner peace and their associated cognitive states (Davis et al., 2016) (Davis et al., 2017). This in turn will also potentially enable us with tools and applications to better model both inner peace and social harmony (Davis & Schübeler, 2018). We further conjecture that HRV and psychophysiological coherence measures should be related to positive emotions and their associated cognitive states which are derived from the creation of knowledge and meaning and the subjective space or inner being (Gillett, 2008) in mind-brain and environment interactions (Davis & Kozma, 2013) (Davis et al., 2015) (Davis, 2018) (Crivellato & Ribatti, 2007) (Kozma & Davis, 2018).

DESCRIPTION OF EXPERIMENTS

During ten (10) sessions held over a period of seven (7) days, we conducted a set of activities where each participant wore a HRV sensor on the ear lobe that was provided by the research team, a friend or a personally owned device. All participants had their devices set to the lowest challenge level ("Challenge: Low") as described in the emWave2 Quick Start Guide for PC and Mac (Quantum Intech, Inc., 2014). The duration of each session was an hour that included either meditation (Activity 1) and listening to a reading (Activity 2) or visioning (Activity 3).

This series of ten (10) experiments, denoted as Sessions 0 to 9, included three (3) males and five (5) females out of the ten (10) participants since two (2) of them presented either a large amount of artefacts or non-exportable data. The age range of the participants, all healthy, was from thirty-one (31) to fifty-eight (58) years. Participants predominantly sat in chairs (with the exception of Participant 1 who sat on the floor) in a circular arrangement. Each session started and ended for all participants at around the same time with latencies of at most 50 seconds. Since every participant has mastered to a good degree how to enter a state of psychophysiological coherence at will, all participants were asked to get to a coherent state prior to commencing each session. Once everybody was in a coherent state (state 0), identified by 'green' in the emWave system, the experiment was started. As stated above, the study included three (3) different modalities as follows:

- Activity 1 (Sessions: 0, 2, 3, 5, 7, 8 and 9)
- Activity 2 (Sessions: 0, 2, 3, 5, 7, 8 and 9)
- Activity 3 (Sessions: 1, 4 and 6 treated as two (2) sessions each)

Activity 1 consisted of a particular form of meditation, comprised of an element of collective singing of an ancient prayer, listening to reading from a spiritual revelation (Paradise Landing, 2000) (read by Participant 4) and toning (a form of chanting). In our analysis we will refer to Activity 1 also as

Crown Modality (CM). Activity 2, Reading Modality (RM) entailed one (1) person (Participant 1) reading a presumably inspirational spiritual text, while the rest of the participants were listening. Activity 3, Visioning Modality (VM) was an interactive session of visioning future developments of the community, including listening (all participants), talking and taking notes (Participant 1 and 3 only).

METHODOLOGY

Raw data from all sessions from all participants was exported from the emWave system and imported into computer spreadsheets for a total of seven (7) datasets for CM and RM and six (6) data sets for VM. All the data was pre-processed to ensure quality and precision, for synchronization and period length. In some cases some parts of the data were left out when necessary, due to artefacts or technical faults in the recording. Generally speaking, the majority of the data sets were very good. The raw data consists of scores exported from the emWave system, which records "sessions_ZoneScores" (in our study simply called scores) that are calculated every five (5) seconds via a native algorithm based on spectral analysis (McCraty & Atkinson, 1996) (Tarvainen & Niskanen, 2012) (McCraty & Shaffer, 2015) (Medicore, n.d.) (McCraty et al., 2001) during each session. For this study we identified the possible states of the system as $X_t = \{0, 1, 2\}$ associated to green (coherent state), blue (relaxed state) and red (stressed state) respectively. The Zone Scores as provided by the emWave system are: zero (0) for red, one (1) for blue and two (2) for green, which is the inverse order than X_t in our study.

The one-step (discrete time) transition probability matrix (TPM) $P_{ij} = P\{X_{t+1}=j \,/\, X_t=i\}$ for this system (Markovian property assumed) can be written as:

$$P_{ij} = \begin{pmatrix} P_{00} & P_{01} & P_{02} \\ P_{10} & P_{11} & P_{12} \\ P_{20} & P_{21} & P_{22} \end{pmatrix} \quad i, j = 0, 1, 2 \quad (1)$$

It is important to note that for different participants in different modalities some TPM could be more conducive to green states than others and some other times the TPM could be more conducive to red states or any probabilistic distribution reflected in the limiting probabilities (Ross, 1983) associated to each matrix.

For example, we could have matrices associated to different tendencies of coherent, relaxed or stressed states; Green (G), Blue (B) and Red (R) where:

$$G_{ij} = \begin{array}{c} \\ 0 \\ 1 \\ 2 \end{array} \begin{array}{c} \begin{array}{ccc} 0 & 1 & 2 \end{array} \\ \begin{pmatrix} 0.9 & 0.05 & 0.05 \\ 0.8 & 0.1 & 0.1 \\ 0.7 & 0.2 & 0.1 \end{pmatrix} \end{array} \quad \text{Dominant Coherent (Green)}$$

$$B_{ij} = \begin{array}{c} \\ 0 \\ 1 \\ 2 \end{array} \begin{array}{c} \begin{array}{ccc} 0 & 1 & 2 \end{array} \\ \begin{pmatrix} 0.3 & 0.6 & 0.1 \\ 0.05 & 0.9 & 0.05 \\ 0.05 & 0.7 & 0.25 \end{pmatrix} \end{array} \quad \text{Dominant Relaxed (Blue)}$$

$$R_{ij} = \begin{array}{c} \\ 0 \\ 1 \\ 2 \end{array} \begin{array}{c} \begin{array}{ccc} 0 & 1 & 2 \end{array} \\ \begin{pmatrix} 0.1 & 0.3 & 0.6 \\ 0.1 & 0.1 & 0.8 \\ 0.1 & 0.2 & 0.7 \end{pmatrix} \end{array} \quad \text{Dominant Stressed (Red)}$$

$$\forall\, i = 1,3 \;\&\; j = 1,3$$

Our Markov chain analysis required us to determine which state participants were in for each time period, where each unit of time t (t=1,2,3,.....n) represents a five (5) second period 5, 10,.....5*t, ... 5*n respectively. A transition was computed between time t and time t+1. States i and j could take the values of 0, 1 or 2 and the proper counting computations were carried out to arrive to the empirical probability distributions for each row of the TPM. P_{ij} for all i,j = 0,1,2 describes the transition probabilities between all possible states. There are nine (9) of them in total (P00, P01,.....P11,P12,.....P22) as described in equation (1).

In order to differentiate between modalities and participants, we calculated the Euclidean Distance (ED) index for each data set, based on two (2) different variables as follows: the Cumulative Coherence Score (CS_t) and the Score, S_t = 2,1 or-1, based on state variable, X_t = 0,1 or 2 respectively, where:

$$X_t = \begin{cases} 0, \text{ for a coherent state, green} \\ 1, \text{ for a relaxed state, blue} \\ 2, \text{ for a stressed state, red} \end{cases} \qquad \forall\, t = 1, 2, 3, \ldots\ldots$$

$$S_t = \begin{cases} 2 \text{ when } X_t = 0 \\ 1 \text{ when } X_t = 1 \\ -1 \text{ when } X_t = 2 \end{cases} \qquad \forall\, t = 1, 2, 3, \ldots\ldots$$

Each value of any of these two (2) variables (CS_t or S_t) is compared to an ideal outcome vector corresponding to a maximum coherence score which we have termed Ideal Cumulative Score (ICS_t = 2*t) or Ideal Score (IS_t = 2) as shown in Figure 1. We expect that the ED index from the ideal score will be different for each transition probability matrix. The variables of the system involved in the comparison of the different modalities are: Ideal Cumulative Score (ICS_t), Euclidean Distance (ED) and Cumulative Score (CS_t). The equations for the different variables of the system are as follows:

$$CS_t = S_0 + \sum\nolimits^{N}_{(t=1)} S_t \qquad (2)$$

$$ICS_t = \sum\nolimits^{N}_{(t=1)} IS_t \text{ where } IS_t = 2 \;\forall\; t \qquad (3)$$

$$ED = \sqrt{\left(\sum\nolimits^{N}_{(t=1)} (ICS_t - CS_t)^2\right)} \qquad (4)$$

It is important to note that the system variable S_t stands for the score that is assigned to each physiological state X_t where, for example, if X_3=0 then the score S_3=2. The reader should observe that coherent states have a greater score than relaxed states and that relaxed states have a greater score than the stressed ones.

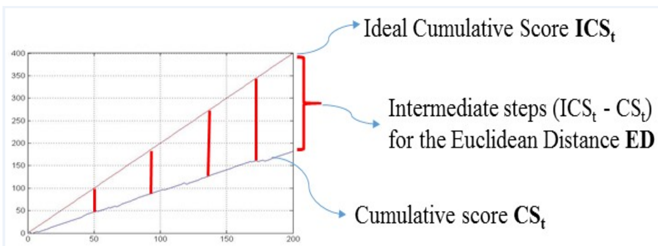

Figure 1.
shows an illustration for the evolution of CS_t and ICS_t with different moments in time, shown in red, where ED is calculated based on ICS_t-CS_t.

It is important to note that ICS_{final} is always computed for a period of time to suit the needs for the analysis and therefore can vary between sessions, modalities and participants. The IS_t in contrast is always equal to the value of two (2) and can be described as follows:

- IS_t = 2 for all t = 1, 2, ..., N
- ICS_t = 2, 4, 6, ... 2*(N-1), 2*N

where N is equal to the number of time points and ICS_N is equal to ICS_{final}. All of the above implies that we can compute two (2) other forms of ED as shown in equation (5) and (6).

$$ED_{final} = (ICS_N - CS_N) \quad (5)$$

$$ED = \sqrt{\left(\sum_{(t=1)}^{N} (2 - S_t)^2\right)} \quad (6)$$

GENERAL ANALYSIS AND RESULTS

We have analysed the data of the eight (8) participants in the three (3) modalities by calculating the Euclidian Distance (ED) for the Scores (S) and the Cumulative Score (CS). We computed the confidence intervals (CI) for the mean EDs and also generated corresponding box plots. We further computed the means, standard deviations and confidence intervals for the scores. All CI were calculated for 95% confidence.

It is important to note that while more points were available for most participants and modalities, for this analysis we limited the number of points used to 200, since this is the maximum number of points available for some participants' CM sessions. This was necessary in order to compare the ED between modalities, which requires an equal sample size unless a normalization factor is applied that would allow us to compare data samples of different sizes and take advantage of all the data collected (Davis & Schübeler, 2019a). However, this would introduce a complexity that is beyond the scope of this paper.

CM and RM consisted of seven (7) sessions each, however due to artefacts and recording failures, some participants are lacking data for single sessions as follows:

- Participant 3 - Session 5 (CM & RM)

- Participant 4 - Session 0 (CM & RM)
- Participant 5 - Session 0 (CM & RM)
- Participant 8 - Session 2 (CM only)

In Figure 2, we can observe that the participants in CM tend to yield greater CS and therefore more coherent states than in the other two (2) modalities (RM and VM). This is true for all participants, with the exceptions of Participant 4, for whom all modalities tend to produce very similar low CS results, and particularly Participant 6, being the only participant with a significantly smaller CS in CM than in the other modalities.

For a more comprehensive comparison we then computed the ED of S_t and CS_t in relation to IS and ICS_t. Here we generated two (2) sets of graphs, one (1) showing the ED with its respective CI for α = 0.05, the other box plots for the ED, both for all modalities and all participants. In Figures 3 and 4, we display these results, which allow for a clear visual discrimination between participants and modalities.

With the aid of the displayed Euclidian Distances in Figure 3, we can classify the coherence achievements of each participant in each modality and also between participants. For example, we can see that the ED of the CS for most participants is lower during CM than RM and VM and therefore generally speaking most participants were more coherent during CM, and that Participant 3 in particular shows much greater coherence during CM than in RM and VM. As already derived from the visual inspection of Figure 2, Participant 6 displays the opposite tendency with a much higher coherence during RM and VM than CM. The EDs of Participant 4 are rather large in comparison to the other participants, something we can expect given the very small CS we already observed in Figure 2 for all modalities. It is interesting to note that Participant 7 displays very similar ED and CI results for all modalities, with the exception of the CI for RM being significantly larger. This can be easily understood when looking at Figure 2, which shows the obvious outlier (orange line).

While it is important to mention that Participant 1 was the reader during RM and perhaps we might expect this to have an impact on the coherence performance, no statistically significant effect showed as evident. From the ED values of Participant 1 observed in Figures 3 and 4, it is clear that they remain relatively similar to the values of other participants across the modalities of RM and CM, which may indicate that both reading

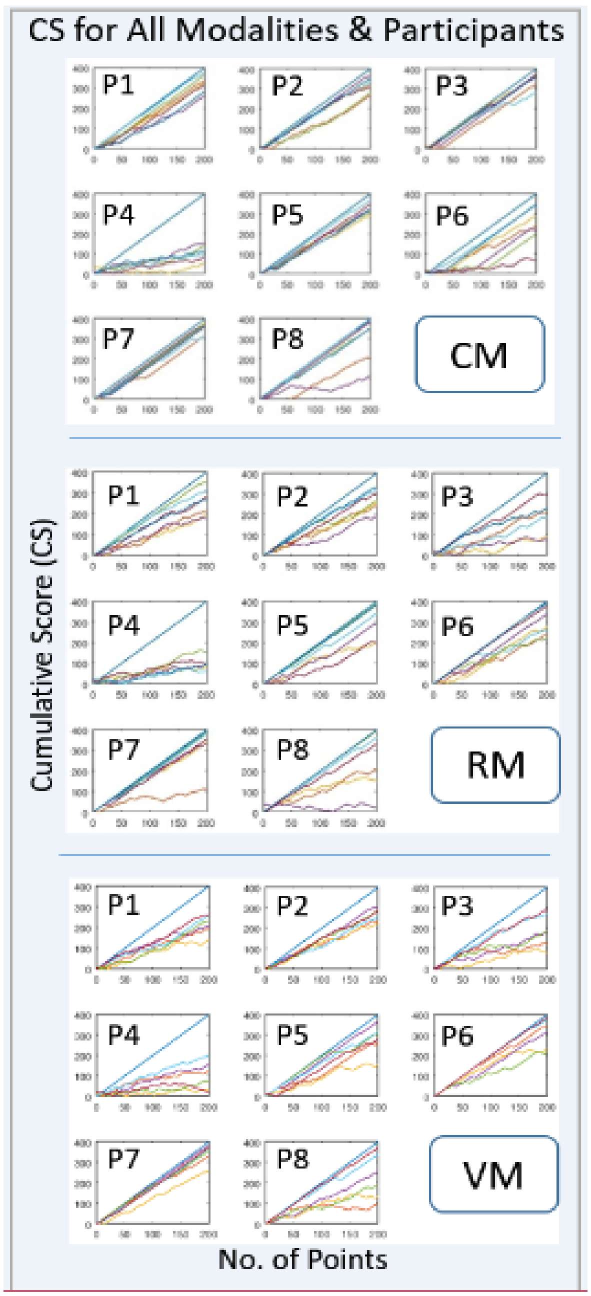

Figure 2.
illustrates the CS of all sessions, 200 points each, for all participants (Participant 1 to 8) and all three (3) modalities (CM top, RM centre and VM bottom).

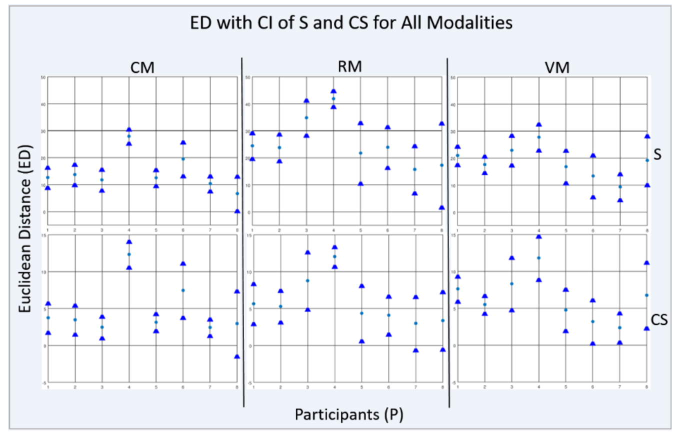

Figure 3.
shows the ED with the CI for all Participants (1 to 8) and all three (3) activities (CM left, RM centre and VM right).

and listening have similar effects. However, this remains the subject of another study.

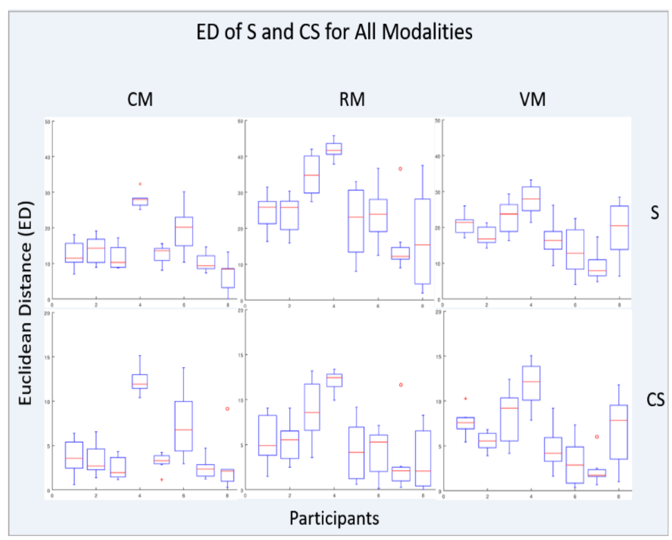

Figure 4.
shows the box plots of the ED for all Participants (1 to 8) and all three (3) activities (CM left, RM centre and VM right).

Examining VM we can see that Participant 1, 3 and 8 display slightly higher values for ED compared to the other participants. For Participant 1 and 3 we possibly have a simple explanation in that they were actively engaged in facilitating the vision process, while the other participants were more passive and predominantly listening. The higher ED of Participant 8 can be explained by the unique characteristic of their data set where the first sessions were very incoherent, while the following sessions were substantially more coherent (a learning process). Again, Participant 4 displays clearly the largest ED.

In Figure 4 we present the box plots of the ED, which confirm the results we already derived from the analysis of the ED with their CI in Figure 3.

In Table 1 we summarize the above analysis by ranking the performance of each participant for the three (3) modalities based on the mean ED. We see that Participant 7 performed overall the highest and Participant 4 the lowest.

However, it is important to mention that several of the CI around ED for CS for each participant, for each modality tend to overlap, meaning that statistically they would be considered the same mean. For example, Participant 1, 2 and 3 in CM show

Participant	CM	RM	VM	Rank
1	6	5	7	18
2	4	4	4	12
3	1	7	6	14
4	8	8	8	24
5	5	3	1	9
6	7	6	3	16
7	3	2	2	7
8	2	1	5	8

Table 1.
ranks participants by their mean ED based on CS derived from Figure 3, from the lowest value (1) to the highest (8) in each modality and the Rank being the sum of all modalities for each participant.

overlapping CI as well as Participant 5, 6, 7 and 8 in RM. Overall we can classify participants in two (2) groups, showing low coherence and high coherence tendencies. For CM, Participant 4 and 6 display significantly lower coherence than the rest of the participants. For RM, Participant 4 and 3 display significantly lower coherence than the rest of the participants. For VM, again Participant 4 and 3 display lower coherence than the rest of the participants. However, this time Participant 1 and 2 show lower coherence than Participant 5, 6 and 7, while Participant 8 displays such a large CI that their coherence state is indeterminate in ranking. The reader must note that statistically speaking Participant 4 is significantly lower in coherence than the rest of the participants for all modalities, while

Participant 7 is statistically significantly higher in coherence than most participants for all modalities.

While our analysis shows that the ED serves as a very good discriminator between participants' performance across modalities and amongst each other, we have also produced a set of matching plots that display the means of the Scores (S) and their corresponding confidence intervals. When compared with the above analysis we find very similar results, suggesting that while the ED is preferred, the mean with CI may also serve as a suitable analysis tool for coherence measures, as can be seen in Figure 5, which displays very similar results when compared to the ED in Figure 3 with the advantage that this method includes all the points for all sessions, giving us a larger sample size per participant and therefore smaller CI.

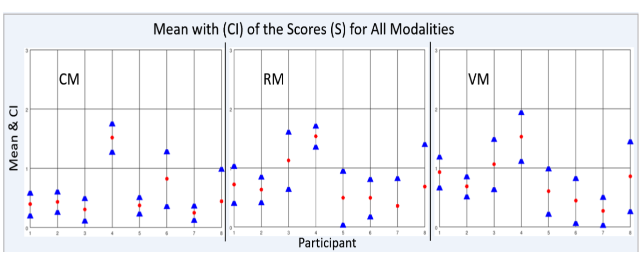

Figure 5.
shows the means (calculated as 2-S, and displayed in red) for all Participants (1 to 8) and all three (3) activities with their corresponding confidence intervals (blue).

It is important to note, that of the three (3) measures we prefer the mean ED of CS since it better captures the cumulative trajectory compared to the ideal trajectory for each session and significantly reduces the standard deviation for each sample due to its cumulative nature. However, a final verdict regarding the power of these measures will require a thorough mathematical and statistical analysis, beyond the scope of this work.

MARKOV CHAIN ANALYSIS - EXPERIMENTAL VS ANALYTICAL

For the second part of the analysis we created transition probability matrices (TPM) by comparing the state of the system in time t with the state of the system in time t+1. We then counted the occurrence of each possible transition for each state: N_{00}, N_{01}, N_{02} and N_{10}, N_{11}, N_{12} and N_{20}, N_{21}, N_{22}. From these counts we derived the empirical probability of transition from one state to another, for example, 01 represents all cases where the system transitioned from state 0 to state 1. The probabilities were then computed as follows:

$$P_{00} = \frac{N_{00}}{N_{00} + N_{01} + N_{02}}$$

$$P_{01} = \frac{N_{01}}{N_{00} + N_{01} + N_{02}}$$

$$\vdots \qquad (7)$$

$$P_{22} = \frac{N_{22}}{N_{20} + N_{21} + N_{22}}$$

With these probabilities we then generated the TPM for each session and participant, see equation (1). Next we computed the average of all TPM per participant per modality and then we raised the average TPM to the power of 1000 in order to obtain the limiting probabilities (LP).

$$LP = \overline{TPM}^{N} \text{ with } N=1000 \qquad (8)$$

These results give us the limiting probabilities for all participants and modalities.

For the sake of illustration we provide the reader with one (1) example, where we computed the average TPM for Participant 1 in Modality 1 and then we derived the limiting probabilities resulting in a second matrix:

$$P_{ij}^{1} = \begin{matrix} & 0 & 1 & 2 \\ 0 & 0.66 & 0.25 & 0.09 \\ 1 & 0.18 & 0.55 & 0.27 \\ 2 & 0.02 & 0.13 & 0.86 \end{matrix}$$

$$P_{ij}^{1000} = \begin{matrix} & 0 & 1 & 2 \\ 0 & 0.078 & 0.159 & 0.763 \\ 1 & 0.078 & 0.159 & 0.763 \\ 2 & 0.078 & 0.159 & 0.763 \end{matrix}$$

$$P_{ij}^{1000} = LP = F(X_t)$$

As we can see the transition probabilities have now stabilized for each row providing us with the probability distribution $F(X_t)$ for the states of the system (any row of the matrix) enabling us to calculate the analytical (derived from average TPM) expected value and standard deviation of the system which we will refer to, from now on, as analytical expected value and standard deviation.

We compare the experimental means versus the analytical expected values, and we can observe that for CM both are very close for all participants, while for RM and VM some participants display a larger distance between the two (2), whereas for others their values remain very close.

In order to determine whether the two (2) values (analytical and experimental) can be considered to be statistically equal, we plotted the analytical expected values together with the CI of the experimental mean. Both in Figure 6 and Table 2 we can observe that most analytical expected values are within the CI of the experimental means for most participants and modalities.

We further tested for the null hypothesis H_0 that experimental and analytical expected values are statistically equal, where **H_0=0** (analytical expected values fall **within** the **CI** around the experimental mean) when the hypothesis was **accepted** and **H_0=1** (analytical expected values fall **outside** the **CI** around the experimental mean) was **rejected**.

In Table 2 we present the actual values for all means, standard deviation (SD) and CI of the experimental data together with the analytical expected values and their associated SD. The last column shows the results of the hypothesis test, where we can see that in most cases our visual impression, derived from Figure 6, holds true.

While H_0 was rejected for Participant 1 in CM and Participant 3 in VM, we must note that both are so close to the lower bound that we would be inclined to accept H_0 to avoid incurring a statistical rejection error. Similarly, Participant 5 in RM shows an analytical expected value which falls outside and a little bit further (but still relatively close) from the CI. We consider this an unusual outcome since we are unable at this stage to find any reason for such an exception, for the analytical expected value of that participant to fall outside the CI of the experimental mean. The analytical expected values for Participant 8 in both CM and RM are also outside, relatively far from the CI. However, we can understand this when examining the individual sessions, since this participant displayed very low CS for the first sessions, before being introduced to some basic breathing techniques, and on implementation, very quickly reached highly coherent states with their respective very high CS for the following sessions.

It is also important to note that in two (2) sessions, state 2 was entirely absent for this participant. We may therefore interpret these dynamics as a non-stationary process, where the matrices are better understood to define a growth process based on a learning experience, rather than the stable states seen with the other participants. All of these unusual events could indicate the presence of semi-Markov processes for some participants in some modalities, something that falls outside the scope of this work and that requires further investigation. However, in the case of Participant 1 and 3 as mentioned above, and perhaps even for Participant 5 we are inclined to assume a Markov process since the analytical expected value is reasonably close to the lower bounds of the CI which could indicate that we are in the situation where we may reject H_0 while the hypothesis, {H_0: analytical expected value is equal to experimental mean}, is actually true.

To conclude our analysis we present Figure 7, where the reader can appreciate the limiting probabilities or probability distribution $F(X_t)$ associated with the states of the system for each modality and participant. Again it is evident that most participants spend more time in coherence (state 0) in CM than they do in RM and VM. The previous results from the ED analysis regarding the similarity of RM and VM in terms of coherence levels is also confirmed in Figure 7. We further see that the

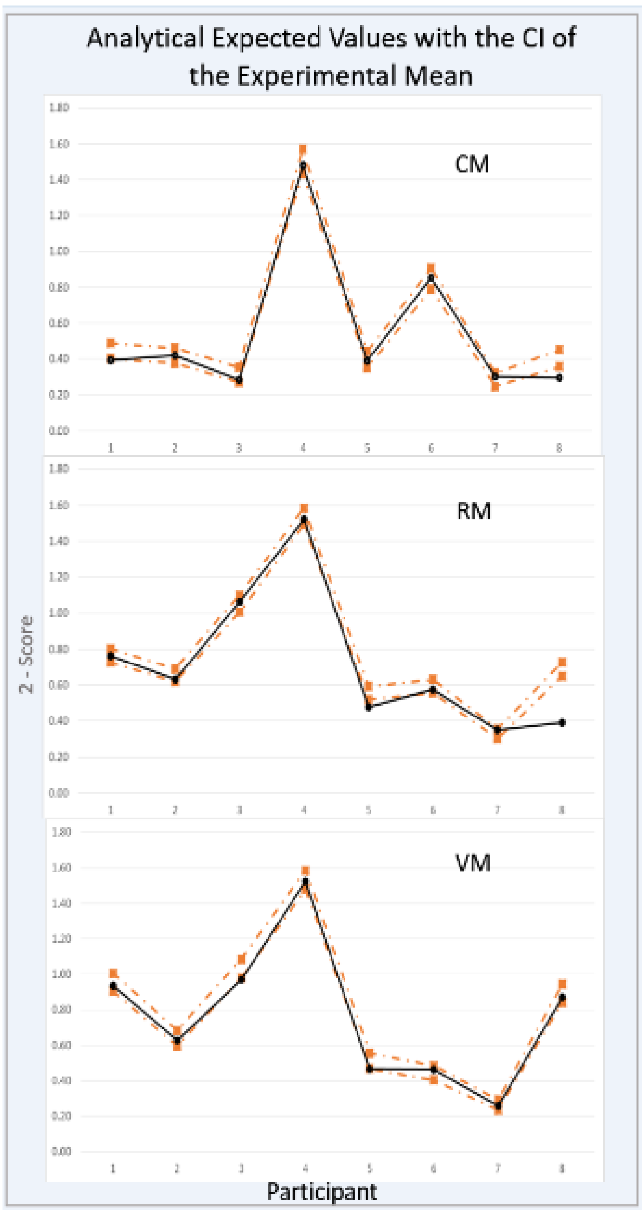

Figure 6.
depicts the confidence intervals (orange) for the experimental means of all participants for all modalities plotted together with the analytical (derived from average TPM) expected values (black).

	M_Expt	SD_Expt	LB	UB	M_Ana	SD_Ana	H_0
P1 CM	0.45	0.90	0.40	0.49	0.39	0.84	1
P2 CM	0.42	0.90	0.38	0.46	0.42	0.88	0
P3 CM	0.31	0.79	0.27	0.35	0.28	0.75	0
P4 CM	1.50	1.28	1.44	1.57	1.48	1.27	0
P5 CM	0.40	0.85	0.35	0.44	0.39	0.84	0
P6 CM	0.85	1.21	0.79	0.91	0.85	1.19	0
P7 CM	0.29	0.77	0.25	0.32	0.30	0.78	0
P8 CM	0.40	0.88	0.36	0.45	0.30	0.69	1
P1 RM	0.76	1.09	0.73	0.80	0.76	1.09	0
P2 RM	0.65	1.05	0.62	0.69	0.63	1.03	0
P3 RM	1.05	1.30	1.01	1.10	1.06	1.30	0
P4 RM	1.54	1.27	1.49	1.58	1.52	1.27	0
P5 RM	0.55	1.05	0.52	0.59	0.48	0.98	1
P6 RM	0.59	1.08	0.56	0.63	0.58	1.07	0
P7 RM	0.33	0.82	0.30	0.36	0.35	0.82	0
P8 RM	0.69	1.15	0.65	0.73	0.39	0.85	1
P1 VM	0.95	1.20	0.90	1.01	0.94	1.19	0
P2 VM	0.64	1.03	0.60	0.68	0.63	1.02	0
P3 VM	1.03	1.25	0.98	1.08	0.97	1.22	1
P4 VM	1.53	1.27	1.48	1.59	1.52	1.27	0
P5 VM	0.51	1.01	0.47	0.56	0.47	0.98	0
P6 VM	0.44	0.95	0.40	0.48	0.46	0.96	0
P7 VM	0.26	0.67	0.24	0.29	0.26	0.65	0
P8 VM	0.89	1.20	0.84	0.94	0.87	1.17	0

Table 2.
The first four (4) columns show the values of the experimental means, standard deviations and their corresponding lower and upper bounds (CI) for α = 0.05. The following two (2) columns display the analytical expected values and standard deviations. All values are presented for Participant 1 to 8 in all modalities (CM, RM & VM). The last column shows the results for the hypothesis testing of H_0, Accept H_0=0, Reject H_0=1.

results for Participant 4 are aligned with the ED analysis and again display low coherence levels and similar tendencies for all modalities. Finally, Participant 7 shows a very similar distribution of coherence states for all three (3) modalities, as we have already mentioned in the ED analysis section above.

Based on these observations and the predominant acceptance of H_0, we conclude that the analytical expected values are statistically reliable to represent the experimental data for most cases and

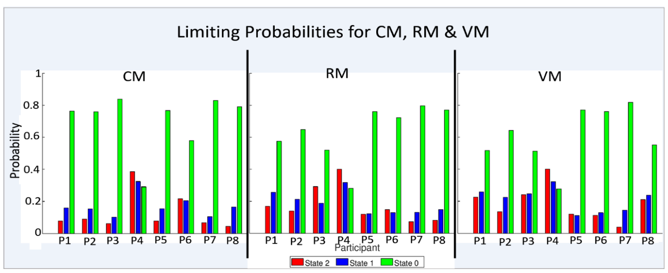

Figure 7.
displays the limiting probabilities (y-axis between 0 and 1) calculated from the average transition probability matrices (TPM) for each participant (x-axis P1 to P8) and modality (CM left, RM centre & VM right). The probability for state 2 is displayed in red, for state 1 in blue and for state 0 in green.

therefore the TPM, we conjecture, can now be used to characterize each participant in each modality for general modelling and simulation purposes. However, it is important to remind the reader that the probability distribution of the units of time that the system spends in any state once it has entered it, is ruled by the geometric probability distribution to preserve the Markovian property and if this distribution was different then we should be very careful with the modelling of the system since we would be in the face of a semi-Markov or other kind of model (Howard, 1971). A further and more in depth test will be needed here and this is outside the scope of this paper and should be the subject of another study.

CONCLUSIONS AND FUTURE RESEARCH

We have demonstrated the usefulness of Euclidean Distance as a discriminator for coherence, though with the current limitation of the requirement to have the same number of points for all data sets analysed. How to overcome this limitation when needed should be explored in another study. We have also shown that the means with corresponding confidence intervals may very well serve as a tool to derive some insight about the coherence scores and their relationship to one another.

Furthermore, we have confirmed from (Davis et al., 2019) that Crown Meditation (Activity 1) produces more coherent states for most participants consistently over all seven (7) sessions compared with Reading (Activity 2) and Visioning (Activity 3). We conjecture therefore that meditation in general, and in our case Crown Meditation, is a desirable activity in order to achieve a greater level of inner peace and psychophysiological coherence in the community of participants tested for this study, which can be achieved at will, however does require practice and a certain level of understanding and knowledge. This was notably illustrated by Participant 8 who initially, for the first three (3) sessions, produced very low coherence scores, however once familiarized with certain breathing techniques and some practice was able to achieve high levels of coherence very quickly. This observation suggests that psychophysiological coherence and possibly inner peace are attainable at will, given the commitment of the human being to learn how to attain such states, for example, via the aid of breathing techniques, meditation and biofeedback equipment.

We have demonstrated in this study that from the experimental data we can derive average TPM with their associated limiting probability matrices, together with their corresponding analytical expected values and standard deviations that are comparable and preserve the overall tendencies displayed by participants during the experiment. With this finding we are now able to use this data for simulation and generate large numbers of sessions, thereby overcoming the limitations imposed by the demands of physical experiments, such as time and other resources. We intend to apply this methodology to derive simulation models based on the average TPM to better describe the peace propagation process in communities and how the mastery of inner peace and psychophysiological coherence can positively affect such a process.

In this study HRV was measured and used in order to classify distinct states of coherence. While this is a measurement purely derived from the heart interbeat intervals (IBI), it is important to keep in mind that the results are certainly also a consequence of brain activity and respiration, where for example, different breathing patterns can strongly influence the coherence level in one or the other direction, as mentioned above for Participant 8. For a greater appreciation of the interaction between brain, heart and respiration more research is required. We foresee great benefits from a deeper understanding of the dynamics between these three (3), such as to gain insight into the role they play in attaining inner peace and social harmony. Additionally, we expect to be able to reach a better understanding of how human beings influence and affect each other, via entrainment-based coherence and entrainment between individuals (Denney, 2008) (McCraty et al., 1998) (McCraty et al., 2009) (Tomasino, 2007) and we conjecture was possibly taking place as reflected in this study in the similarities of behaviour between Participant 1 and 3 and their shared role during Activity 3 (VM). However, this requires a more in depth and certainly more challenging kind of study.

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