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A Statistical Analysis Algorithm for Brain Waves' Quality Assessment

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ABSTRACT: Beat produced in the brain as soon as two nearly equivalent pure tones with slightly different frequencies come together. This paper aims to test, examine and visualize such phenomena through utilizing the objective assessment method which based upon using Structural Similarity Index Metric (SSIM) and Structural Dissimilarity Metric (DSSIM) variations with carrier frequency. Results showed a various variations for the binaural beat in its types; a descending relation appeared in Delta and Theta curves, while a progressive state occurred in the case of Alpha and Beta curves. A Gaussian shape had been resulted for certain series in Gamma relationship with carrier frequency. After all, the best SSIM value can be found in Delta and a range of (1028.5-1029) Hz for Gamma waves. The series (1028.5-1034.5) Hz of Gamma brain wave witnessed a reverse relationship of SSIM and DSSIM with increasing the carrier frequency and this effect coincide with that presented in previous studies of carrier-beat frequencies relation for Gamma brain wave.

KEYWORDS: Binaural beat; Delta wave; Theta wave; Alpha wave; Beta wave; Gamma wave; the Carrier frequency

INTRODUCTION

The simultaneous presentation of two nearly equivalent pure tones with a slight difference in frequencies produced a 'beat' in the brain. This beat in this case constructed within the brain and is referred to as a 'binaural beat' [1,2]. As an example, when a tone of 610 Hz presented to the left ear and a 620 Hz one to the right ear, then a beat of 10 Hz shall be perceived in the brain with a carrier frequency equal to 615 Hz [2,3].

In general, the binaural beat can occur if the carrier frequency of the two stimulus tones is no longer than 1500Hz with a difference not exceed 50Hz [4,5]. In 1839, H. W. Dove discovered the concept of such phenomena and then outlined it with more details by G. Oster over five decades ago [6-8]. R. Padmanabhan et al. found that the binaural beat audio has an effective role in decreasing an acute pre-operative anxiety [8]. N. Jirakittayakorn and Y. Wongsawat suggested that 6-Hz binaural beat on a 250 Hz carrier tone can be considered as a good stimulus for a meditative use [1], while T. Mihajloski et al, adopted an adaptive method of evoking transient Auditory Evoked Potentials to binaural beats by using frequency-modulated stimuli [4]. F. E. M. Al-Obaidi and A. J. Mohamed Ali investigated the role of beat-carrier frequencies for Delta and Theta binaural beats and discussed its effect upon the brain [9] while A. J. Mohamed Ali and F. E. M. Al-Obaidi had been used the Gamma brain wave to study the effect of beat-carrier frequencies inside the brain [10]. They found that carrier frequency produced a meaningful explanation than beat frequency. This paper presents an investigation toward such waves. The importance comes from analyzing the binaural beats digitally by using an automated algorithm for wave quality assessment. To summarize such waves, Table (1) illustrates brain waves with their full descriptions.

Table 1. Brain waves types [3]

Brain Wave	Frequency Range (Hz)
Delta	0.5-4
Theta	4-7.5
Alpha	7.5-14
Beta	14-40
Gamma	>40

MATERIALS AND METHODS

In this study, an attempt to examine brain waves had been tested here by using the methods of quality assessment. The latter related to signal differences assessment between left and right waves [11,12]. The method of quality assessment can be measured throughout two ways; subjective and objective methods. The objective method is more preferable than the subjective one due to certain reasons related to its cost and hence the objective assessment method shall be handled here

Objective Quality Assessment

The objective assessment method can be defined as an automatic algorithm for quality assessment in which one could test and analyze signals without the need for human perception. This type of quality assessment made use of two main approaches; simple correlation-based metrics and Human Visual System (HVS) feature-based metrics [13].

To compare certain signals, one can utilize the HVS feature-based metrics by using the following metrics:

Structural Similarity Index Metric (SSIM)

This measure compares two signals using information about luminous, contrast, and structure as follow [11,12]:

$$l(I) = \frac{2\mu_x(I)\mu_y(I) + C_1}{\mu_x^2(I) + \mu_y^2(I) + C_1} \quad \ldots\ldots\ldots\ldots\ldots \tag{1}$$

$$c(I) = \frac{2\sigma_x(I)\sigma_y(I) + C_2}{\sigma_x^2(I) + \sigma_y^2(I) + C_2} \quad \ldots\ldots\ldots\ldots\ldots \tag{2}$$

$$s(I) = \frac{\sigma_{xy}(I) + C_3}{\sigma_x(I)\sigma_y(I) + C_3} \quad \ldots\ldots\ldots\ldots\ldots \tag{3}$$

Where I= 0…..length of the wave, x and y are two different positions in the right and left signals respectively, μx, σx, μy, σy and σxy are the average of x, the standard deviation of x, an average of y, the standard deviation of y and the covariance of x and y respectively where [14]:

$$\mu_x(I) = \sum_{p=-P}^{p} w(p)x(x+p) \quad \ldots\ldots\ldots\ldots\ldots \tag{4}$$

$$\mu_y(I) = \sum_{p=-P}^{p} w(p)y(y+p) \quad \ldots\ldots\ldots\ldots\ldots \tag{5}$$

$$\sigma_x^2(I) = \sum_{p=-P}^{p} w(p)[x(x+p) - \mu_x[\![(I)]\!]]^2 \quad \ldots\ldots\ldots\ldots\ldots \tag{6}$$

$$\sigma_y^2(I) = \sum_{p=-P}^{p} w(p)[y(y+p) - \mu_y(I)]^2 \quad \ldots\ldots\ldots\ldots\ldots \tag{7}$$

$$\sigma_{xy}(I) = \sum_{p=-P}^{p} w(p)[x(x+p) - \mu_x(I)][y(y+p) - \mu_y(I)] \quad \ldots\ldots\ldots\ldots\ldots \tag{8}$$

Where w(p) is a Gaussian weighting function equal to the next expression:

$$\sum_{p=-P}^{P} w(p) = 1 \quad \ldots\ldots\ldots\ldots\ldots \tag{9}$$

And C_1, C_2, and C_3 are constants such that [14,15]:

$$C_1 = (K_1 L)^2 \quad \ldots\ldots\ldots\ldots\ldots \tag{10}$$

$$C_2 = (K_2 L)^2 \quad \ldots\ldots\ldots\ldots\ldots \tag{11}$$

$$C_3 = \frac{C_2}{2} \quad \ldots\ldots\ldots\ldots\ldots \tag{12}$$

L is the dynamic range for the sample data and $K_1 \langle\langle 1$ and $K_2 \langle\langle 1$ are two scalar constants. A value of 0.01 and 0.03 is set to parameter K_1 and K_2 respectively [14]. The structure similarity index metric can be written as [15]:

$$SSIM(I)=[l(I)].[c(I)].[s(I)] \quad \ldots\ldots\ldots\ldots\ldots \tag{13}$$

The value of SSIM is a decimal value between (-1,1) [16].

DSSIM

It is a structural dissimilarity metric and it is derived from SSIM as in the next expression [16]:

$$DSSIM(I) = \frac{1}{1 - SSIM(I)} \quad \ldots\ldots\ldots\ldots\ldots \tag{14}$$

The values of SSIM and DSSIM give us a sign of the similarity between the signals. The greater values of SSIM and DSSIM refer to the greater similarity between signals and visa versa [12].

RESULTS AND DISCUSSION

Regarding to the description of the carrier frequency that mentioned previously, several sine tones had been generated here by using the website in [3].

An assumption had been taken into account such that the first and second waves presented in Table (2) can be modeled as the two tones which will work together to generate the binaural beat in mind. These tones include Delta, Theta, Alpha, Beta, and Gamma brain waves. The SSIM and DSSIM metrics had been calculated here with their variations expressed in Table (3). This variation can be shown clearly in Figures (1-2) respectively. A general preview to the figures realized the similarities in SSIM and DSSIM behaviors for each brain wave except for Gamma binaural beat relations. A decreasing state appeared in Delta and Theta SSIM's and DSSIM's relations expressed clearly in Figures (1a,1b,2a,2b) respectively, while an increasing relation resulted in Alpha and Beta binaural beats with separated series curves shown in Figures (1c, 1d, 2c, 2d) respectively. Specifically, in Gamma binaural beat relations, the variation of SSIM with carrier frequency takes a Gaussian shape reaching its highest value in series (1028.5-1029)Hz as shown in Figure (1e) while an alternative attitude seems to the rest series of DSSIM variation in Gamma binaural beat is shown in Figure (2e). Regarding to previous studies [9,10] related to the topic of interest and among the whole wide series that had been used for Gamma binaural beat, one can realize that a decreasing state appeared in SSIM and DSSIM variations with increasing carrier frequencies at series (1028.5-1034.5)Hz which coincides with the reversal relationship found in [10] between carrier-beat frequencies. After all, the best value for SSIM can be found in Delta and a series of range (1028.5-1029)Hz for Gamma waves respectively.

Table 2. Brain waves generated by [3]

Brain Wave	1st Wave Hz	2nd Wave Hz	Carrier Frequency Hz
Delta	1001	1002	1001.5
		1003	1002
		1004	1002.5
		1005	1003
	1000.5	1001	1000.75
		1002	1001.25
		1003	1001.75
		1004	1002.25
Theta	1001	1006	1003.5
		1007	1004
		1008	1004.5
Alpha	1011	1000.5	1005.75
		1001	1006
		1002	1006.5
	1014	1000.5	1007.25
		1001	1007.5
		1002	1008
		1003	1008.5
Beta	1020	1005	1012.5
		1004	1012
		1003	1011.5
		1002	1011
		1001	1010.5
		1000.5	1010.25
	1023	1005	1015
		1004	1014.5
		1003	1014
		1002	1013.5
		1001	1013
		1000.5	1012.75
	1030	1005	1017.5
		1004	1017
		1003	1016.5
		1002	1016
		1001	1015.5
		1000.5	1015.25
	1035	1005	1020
		1004	1019.5
		1003	1019
		1002	1018.5
		1001	1018
		1000.5	1017.75
Gamma	1045	1000.5	1022.75
		1001	1023
		1002	1023.5
		1003	1024
		1004	1024.5
	1050	1000.5	1025.25
		1001	1025.5
		1002	1026
		1003	1026.5
		1004	1027
		1005	1027.5
	1055	1000.5	1027.75
		1001	1028
		1002	1028.5
		1003	1029
		1004	1029.5
		1005	1030
		1006	1030.5
		1007	1031
		1008	1031.5
		1009	1032
	1060	1000.5	1030.25
		1001	1030.5
		1002	1031
		1003	1031.5
		1004	1032
		1005	1032.5
		1006	1033
		1007	1033.5
		1008	1034
		1009	1034.5

Table 3. SSIM and DSSIM values for brain waves

Brain Wave	Carrier Frequency Hz	SSIM value	DSSIM value
Delta	1001.5	0.998	979.967
	1002	0.995	233.743
	1002.5	0.989	99.145
	1003	0.981	53.379
	1000.75	0.999	4164.618
	1001.25	0.997	444.771
	1001.75	0.993	153.088
	1002.25	0.986	74.642
Theta	1003.5	0.969	32.751
	1004	0.954	21.815
	1004.5	0.935	15.408
Alpha	1005.75	0.842	6.32
	1006	0.852	6.769
	1006.5	0.872	7.856
	1007.25	0.715	3.517
	1007.5	0.727	3.669
	1008	0.751	4.026
	1008.5	0.776	4.475
Beta	1012.5	0.461	1.858
	1012	0.437	1.776
	1011.5	0.414	1.706
	1011	0.393	1.6470
	1010.5	0.373	1.596
	1010.25	0.364	1.573
	1015	0.119	1.135
	1014.5	0.111	1.124
	1014	0.103	1.115
	1013.5	0.09714	1.107
	1013	0.0912	1.100
	1012.75	0.0885	1.097
	1017.5	0.00524	1.005
	1017	0.00497	1.005
	1016.5	0.00473	1.004
	1016	0.00451	1.004
	1015.5	0.00430	1.004
	1015.25	0.0042	1.004
	1020	0.221	1.284
	1019.5	0.208	1.262
	1019	0.196	1.244
	1018.5	0.185	1.227
	1018	0.175	1.213
	1017.75	0.171	1.206

Brain Wave	Carrier Frequency Hz	SSIM value	DSSIM value
Gamma	1022.75	0.740	3.855
	1023	0.751	4.020
	1023.5	0.772	4.401
	1024	0.794	4.868
	1024.5	0.816	5.449
	1025.25	0.907	10.841
	1025.5	0.914	11.725
	1026	0.927	13.865
	1026.5	0.939	16.646
	1027	0.950	20.200
	1027.5	0.959	24.507
	1027.75	0.976	43.468
	1028	0.978	47.273
	1028.5	0.981	53.120
	1029	0.981	53.945
	1029.5	0.979	48.427
	1030	0.974	39.271
	1030.5	0.966	29.975
	1031	0.955	22.352
	1031.5	0.940	16.692
	1032	0.920	12.599
	1030.25	0.981	54.768
	1030.5	0.979	47.678
	1031	0.971	35.682
	1031.5	0.962	26.692
	1032	0.950	20.172
	1032.5	0.935	15.499
	1033	0.917	12.113
	1033.5	0.896	9.620
	1034	0.871	7.763
	1034.5	0.842	6.349

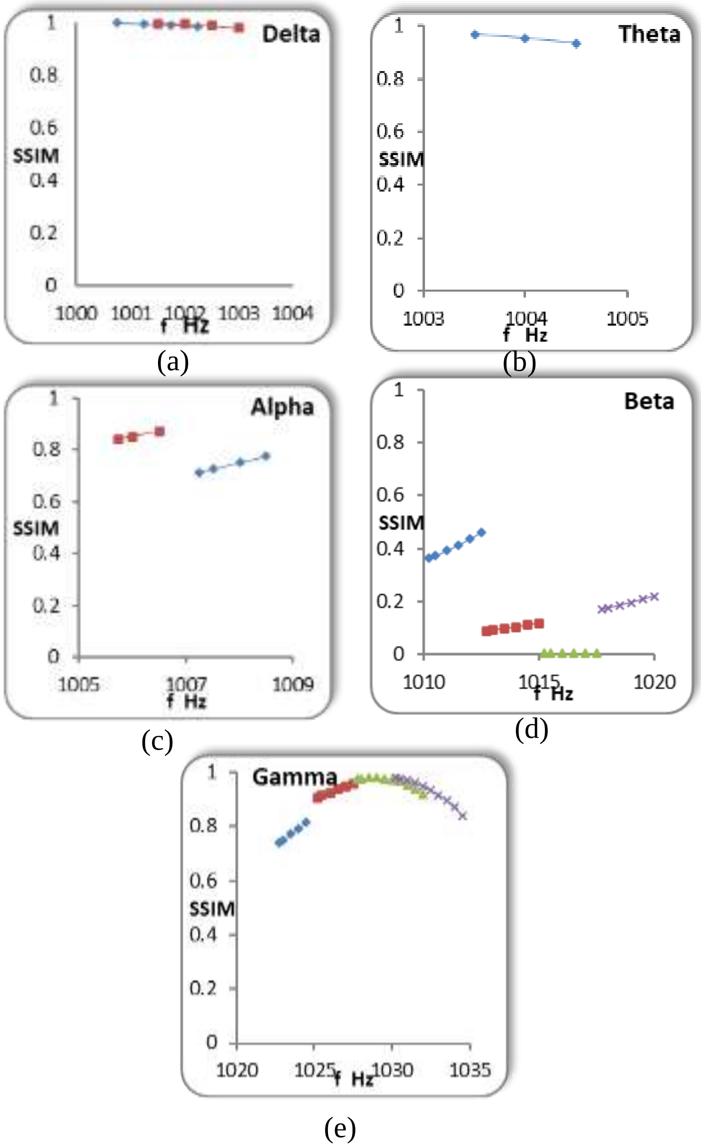

Figure 1. The variation of SSIM with carrier frequency for all brain waves.

(a) Blue series for range (1000.75-1002.25) Hz, Red series for range (1001.5-1003) Hz [9]
(b) Blue series for range (1003.5-1004.5) Hz [9]
(c) Blue series for range (1007.25-1008.5) Hz., Red series for range (1005.75-1006.5) Hz.
(d) Blue series for range (1010.25-1012.5) Hz., Red series for range (1012.75-1015) Hz., Green series for range (1015.25-1017.5) Hz., Magenta series for range (1017.75-1020) Hz.
(e) Blue series for range (1022.75-1024.5) Hz, Red series for range (1025.25-1027.5) Hz, Green series for range (1027.75-1032) Hz, Magenta series for range (1030.25-1034.5) Hz [10]

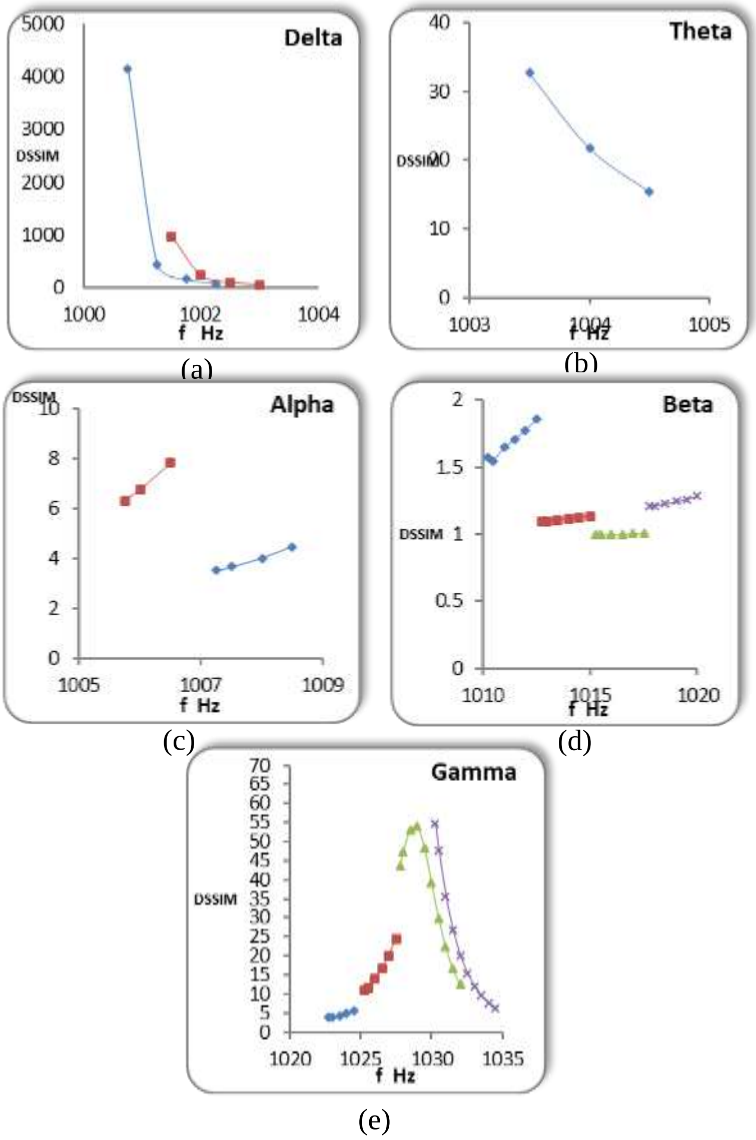

Figure 2. The variation of DSSIM with carrier frequency for all brain waves.

(a) Blue series for range (1000.75-1002.25) Hz, Red series for range (1001.5-1003) Hz [9]
(b) Blue series for range (1003.5-1004.5) Hz [9]
(c) Blue series for range (1007.25-1008.5) Hz., Red series for range (1005.75-1006.5) Hz.
(d) Blue series for range (1010.25-1012.5) Hz., Red series for range (1012.75-1015) Hz., Green series for range (1015.25-1017.5) Hz., Magenta series for range (1017.75-1020) Hz.
(e) Blue series for range (1022.75-1024.5) Hz, Red series for range (1025.25-1027.5) Hz, Green series for range (1027.75-1032) Hz, Magenta series for range (1030.25-1034.5) Hz [10]

CONCLUSION

This paper introduced an analytical study to examine brain waves through investigating their quality assessment. The latter assessment had been achieved by studying the attitude of SSIM and DSSIM variation with carrier frequency. A similar behavior for both SSIM and DSSIM had been noticed through increasing the carrier frequency for each type of brain wave. This is true for every brain wave except for Gamma one; a Gaussian shape had been constructed instead. After all and among the whole brain waves which had been used here, one can realized that the best value for SSIM can be resulted in Delta brain wave in addition to the series (1028.5-1029)Hz found in Gamma brain wave. For such wave and specially in it's particular series (i.e. 1028.5-1034.5)Hz, a decreasing state resulted in the case of SSIM and DSSIM variation with increasing the carrier frequency and this reversal relationship ensures the fact in previous studies related to the inverse relation for carrier-beat frequencies. According to authors' opinion, the latter range of gamma frequencies may be leed to further investigations in the near future.

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