

Traces in The Brain: Decoding Greenwashing Perceptions Through A Synchronized EEG and Eye-Tracking Approach

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Abstract

This section empirically investigates the effects of deceptive environmental claims (greenwashing), common in the fast-moving consumer goods (FMCG) sector, on consumers' visual attention mechanisms, cognitive load levels, and implicit emotional responses. To overcome the limitations of traditional statement-based scales, the research was conducted in a laboratory setting, integrating eye-tracking and electroencephalography (EEG) methods simultaneously. In the experimental process, 40 participants were presented with authentic greenwashing advertisements and manipulative greenwashing advertisements synchronously. The effect of the independent variable on neural outputs was tested using SPSS PROCESS Macro Model 4 (Full Mediation) structural path analysis, where eye-tracking fixation times played a mediating role. According to the eye-tracking analysis results, consumers focused on ambiguous text blocks and unsubstantiated eco-logos in greenwashing advertisements for statistically significantly longer periods ($M = 3.450$ ms) and more frequently compared to authentic advertisements. Path analysis outputs revealed that the type of deceptive advertising did not directly affect the cognitive load escalation in the brain (increased frontal theta power density) and the implicit brand avoidance reaction (negative frontal alpha asymmetry: $M = -0.28$); this process was entirely mediated through the prolongation of visual fixation time (full mediation). The findings empirically confirmed the hypotheses regarding mental strain and brand avoidance caused by greenwashing. This study is one of the pioneering researches in the sustainability-focused neuromarketing literature that chronologically and mechanistically maps the pathway of deciphering deceptive communication. The results demonstrate that, in contrast to the short-term visual attention-grabbing advantage of greenwashing strategies, they

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create a high biological cost (mental fatigue) in the consumer's prefrontal cortex within milliseconds, erecting an implicit wall of rejection towards the brand. The conclusions are as follows: This presents critical practical applications in the context of the necessity of biometric pre-testing protocols for advertising designers, green brand managers, and public policymakers.

1. Introduction

As the sustainability paradigm becomes central to modern corporate strategies and consumer preferences, companies' ecological commitments are under unprecedented scrutiny. The growing consumer demand for environmentally friendly products and brands has unfortunately led to a global epidemic of "greenwashing," where businesses make misleading and exaggerated ecological claims instead of genuinely engaging in pro-environmental activities (Schmuck et al., 2018). Greenwashing is essentially a disinformation signaling strategy that exploits pro-social consumption motivations and leads to a deep crisis of trust within the corporate ecosystem (Connelly et al., 2011). However, an examination of the current methodological framework of the greenwashing literature reveals that the overwhelming majority of findings rely on traditional and self-report methods such as surveys, interviews, or focus groups (Vecchiato et al., 2011). These traditional methods are inherently susceptible to contamination by "social desirability bias" and rationalization processes. This is because consumers are unable to fully express the momentary doubt and cognitive dissonance they experience in the face of green packaging or manipulative advertising at a conscious level, or they distort these expressions due to societal norms (Leonidou and Skarmas, 2017).

Neuromarketing, an approach that aims to decipher the "black box" behind consumer decision-making mechanisms, offers a radical paradigm shift by transcending the limitations of statement-based measurement tools (Davidson, 2004). The implicit cognitive and emotional responses that consumers develop when exposed to greenwashing strategies are instantaneous neural processes that occur at a subconscious level and cannot be captured by traditional methods. In this study, to decipher the perceptual and cognitive mechanisms created by corporate greenwashing claims in consumers, high-temporal resolution Electroencephalography (EEG) and Eye Tracking technologies, which provide millimeter-precise spatial visual focus, have been integrated in a synchronized manner. This multi-motile neuroscientific design, rarely seen in marketing literature, aims to reveal how the brain interprets a stimulus in the exact millisecond that an individual focuses on misleading ecological signals in an advertisement.

Eye-tracking methodology maps the visual attention architecture fixation duration, fixation count, and saccades that consumers exhibit when examining environmentally friendly claims (Santos et al., 2015). Longer fixations, particularly on misleading elements, reflect the complexity of the consumer's information processing and the depth of their visual attention. However, visual attention alone is insufficient to explain the nature of this attention (i.e., whether it is positive interest or cognitive rejection). This methodological gap is filled by simultaneous EEG measurements. EEG signals directly measure the consumer's "approach-avoidance" motivation towards the stimulus, particularly through alpha wave asymmetry (frontal asymmetry) between the left and right frontal hemispheres (Harmon-Jones et al., 2010). The shift in frontal asymmetry towards the right hemisphere upon exposure to stimuli containing greenwashing is neural evidence of an implicit avoidance or disgust behavior in the consumer. Furthermore, changes in the EEG theta and alpha power spectra reveal cognitive workload and mental fatigue; this is a direct reflection in the brain of the discrepancy between consumer beliefs and corporate claims within the context of Cognitive Dissonance Theory (Festinger, 1957).

This study offers groundbreaking contributions to the green marketing and consumer ethics literature in three key areas: First, it brings the perceptual processes created by greenwashing to a neuroscientific level for the first time through the simultaneous integration of EEG and eye tracking, breaking the methodological monoculture in the literature. Second, it empirically validates the neural correlates (through the relationship between frontal asymmetry and fixation times) of cognitive dissonance and loss of trust that consumers experience when confronted with manipulative environmental claims. Finally, through the objective biometric data obtained, it provides advertising self-regulation boards and policymakers with a neuro-evidence-based visionary guide to limit designs that mislead consumers.

2. Literature Review and Hypothesis Development

2.1. Theoretical Framework: Signaling Theory and Cognitive Dissonance in Greenwashing

The effectiveness of corporate sustainability communication is directly dependent on how the information asymmetry between the business and the consumer is managed. Signaling Theory focuses on the signals that parties send to each other in order to reduce information asymmetry in the market (Connelly et al., 2011). Environmentally friendly logos, certifications, and green declarations are designed as "high-cost and prestigious signals" that a

business uses to announce its ecological commitments to the market. However, greenwashing is the manipulative manipulation of this signaling mechanism (Schmuck et al., 2018). Businesses send “deceptive signals” to the consumer by using the asymmetric information advantage without actually incurring a pro-environmental cost. The moment the consumer perceives this disinformation signal, the gap between corporate image and reality leads to a deep conflict in the individual’s mind.

This conflict is explained in the psychology and consumer behavior literature by Cognitive Dissonance Theory (Festinger, 1957). Consumers, driven by pro-social and ethical consumption motivations, want to believe in a brand’s green claims and contribute to the environment. However, when they perceive an inconsistency, exaggeration, or deception in the brand’s claims, their existing belief system (the desire to protect the environment) clashes with the external stimulus (greenwashing advertisement). This creates psychological discomfort and an implicit tension in the individual. Traditional marketing research can only measure this internal tension and rejection of signal quality through self-report surveys after the consumer has taken action (Leonidou and Skarmas, 2017). However, the disruption of the signaling mechanism and the triggering of cognitive dissonance are biometric and neural processes that occur at a subconscious level in the first seconds of encountering the stimulus.

2.2. Visual Attention and Greenwashing: An Eye-Tracking Perspective

Göz Eye-tracking technology makes visible the initial cognitive response of consumers to manipulative green cues through the visual attention architecture (Santos et al., 2021). In the context of signaling theory, ambiguous ecological statements or nature visuals in an advertisement are focal points that attract the consumer’s attention (Area of Interest - AOI). How long and how often a consumer focuses on a stimulus indicates the magnitude of the cognitive effort expended to process that information.

The literature reveals that when consumers encounter deceptive or questionable corporate claims, their Total Fixation Duration and Fixation Count in the relevant area increase significantly (Vecchiato et al., 2011). This shows that visual attention does not always indicate positive interest; rather, it stems from the brain’s need to further decipher that area (visual confirmation) in order to resolve perceived risk and doubt. In an advertisement containing greenwashing, the prolonged fixation times on misleading text and fake certificate logos are evidence of the visual-cognitive effort the consumer

expends trying to resolve the inconsistency in the signal. Accordingly, the following hypothesis has been developed:

H₁: Consumers' total fixation times and fixation numbers for greenwashing advertising elements (AOI) are significantly higher compared to authentic (genuine) greenwashing advertising elements.

2.3. Neural Correlates of Greenwashing: Frontal Asymmetry and Cognitive Workload

Determining the nature of the conflict and the emotional tone it creates in the area where visual attention is directed is only possible through brainwave (EEG) analysis. In the EEG literature, comparing the alpha (8-12 Hz) wave strength in the left and right frontal cortices has given rise to the Frontal Alpha Asymmetry approach, which shows the motivational orientation an individual develops towards a stimulus (Harmon-Jones et al., 2010). Since alpha strength is inversely proportional to neural activity, high left frontal activity symbolizes “motivation/approach,” while high right frontal activity symbolizes “avoidance/withdrawal.” When greenwashing strategies cause a loss of trust, a feeling of being deceived, and ethical discomfort in the consumer, this negative emotional state leads to an increase in neural activation in the right frontal region of the brain (Davidson, 2004). Thus, when a consumer is exposed to a false environmental claim, frontal asymmetry shifts in favor of the right hemisphere, producing an implicit avoidance and disgust response. However, the mental strain predicted by Cognitive Dissonance Theory is directly reflected in the Theta (4-7 Hz) wave spectrum of the EEG. Frontal theta strength is positively correlated with the complexity, information overload, and Cognitive Workload that the individual encounters (Festinger, 1957). Unrealistic or exaggerated green claims overwork the brain's information processing centers because they contradict the consumer's existing brand knowledge, triggering a dramatic increase in theta waves. In light of these neuroscientific arguments, the following hypotheses have been formulated:

H₂: Exposure to stimuli containing greenwashing negatively affects frontal asymmetry by leading to higher neural activation (avoidance motivation) in the right frontal cortex compared to authentic green stimuli.

H₃: Advertisements containing greenwashing significantly increase frontal theta power (cognitive load) in the consumer's brain compared to authentic greenwashing advertisements.

2.4. The Synchronized Triangulation: Visual Attention Driving Neural Workload

The greatest strength of synchronized neuromarketing designs lies in their ability to combine visual input with central nervous system response on a millisecond basis. Using only eye tracking misses the emotional aspect of attention; using only EEG cannot isolate exactly which element of the advertisement is causing the brain fluctuation (Harmon-Jones et al., 2010). In greenwashing literature, the integration of these two methods reveals how cognitive load (theta wave) and avoidance tendency (right frontal activity) escalate as the duration of visual fixation increases (Vecchiato et al., 2011). The longer the consumer is locked onto the deceptive signal (H_1), the deeper the cognitive dissonance in their mind becomes, triggering a rise in theta waves (H_3) and a right frontal asymmetry break (H_2). To test this methodological and theoretical integration, our final hypothesis is as follows:

H₄. Visual fixation duration towards elements containing green wash plays a mediating role in the positive effect on consumers' frontal theta strength (cognitive load) and right frontal activation (avoidance motivation).

3. Methodology

3.1. Participants and Ethical Considerations

To participate in the experimental phase of the study, 40 healthy participants (20 women, 20 men) aged between 18 and 35 (Mean=26.4, SD=3.2), representing a homogeneous consumer group, were included, based on generally accepted power analysis criteria (G*Power 3.1) in the neuromarketing literature and similar multi-method studies (Vecchiato et al., 2011). To maximize the reliability of the neuroscientific data, the following exclusion criteria were applied in participant selection: *Not being left-handed (all participants were required to use their right hand to isolate motor cortex dominance in frontal asymmetry measurements). Not having a history of any neurological, psychiatric, or cardiovascular disorder. Not taking any chronic medications that may affect the central nervous system. Having normal or fully corrected visual acuity with glasses/lenses (for eye-tracking calibration quality).* Prior to the experiment, all participants signed an informed consent form detailing the procedure. The research protocol was approved by the Selçuk University Faculty of Social and Human Sciences Scientific Research and Publication Ethics Board. Participants were asked to refrain from alcohol consumption for 24 hours before the experiment, caffeine consumption for the last 6 hours, and strenuous physical activity.

3.2. Experimental Stimuli and Design

As experimental stimuli, two fictitious brand designs from the packaged consumer goods (FMCG) sector were created to simulate real-life consumer experience. The reason for choosing fictitious brands was to completely eliminate the noise (confounding effect) that participants' past brand loyalties or biases might create on neural signals (Davidson, 2004). The experiment was designed according to the Within-Subject Design model, and each participant was exposed to two different advertising scenarios in a random order (counterbalancing method was used to prevent the order effect):

- Scenario A (Authentic Green Advertisement): A digital product banner with real, verifiable, and internationally valid eco-labels, containing transparent sustainability claims without vague statements.
- Scenario B (Greenwashing Advertisement): A digital product banner adorned with completely manipulative nature visuals (green leaves, clean water sources) lacking any scientific basis, containing vague statements such as "100% Natural Miracle," "Planet-Friendly Packaging," and featuring fake/fabricated green logos.

Advertising posters were strategically divided into Areas of Interest (AOI) for eye-tracking analysis. AOI-1 was defined as blocks of text containing environmental claims; AOI-2 as eco-logos and certification emblems. All posters were designed with the same pixel resolution (1920x1080), with brightness and contrast values synchronized using software.

3.3. Apparatus and Signal Synchronization

The experimental process was conducted in a Neuromarketing Laboratory that was soundproofed, electromagnetically isolated, and maintained at constant light/temperature values (22°C). Participants were positioned 65 cm away from the screen designs. The iMotions Biometric Research Platform was used as the main integrator for millisecond-based data synchronization.

- EEG Configuration: Brainwave activity was recorded at a sampling rate of 500 Hz using a 32-channel, wireless dry electrode EEG system positioned according to the international 10-20 system. Electrode impedance values were kept below 20 kΩ throughout the experiment. Earlobes (A1, A2) were used as an online reference.
- Eye-Tracking Configuration: Visual attention data was collected using a high-sensitivity, screen-based eye-tracking device with a sampling rate of 250 Hz. A 9-point geometric calibration procedure was successfully completed for each participant prior to the experiment. Data from

participants with a calibration deviation of less than 0.5 degrees were processed.

3.4. Data Preprocessing and Feature Extraction

An advanced data preprocessing pipeline was implemented to clean and prepare raw neural and biometric data for analysis.

3.4.1. Processing Eye-Tracking Data

The Tobii I-VT fixation filter was used to differentiate between eye movements and blinking noise. Total Fixation Duration (in milliseconds) and Fixation Count metrics, performed by participants on the identified AOIs (Text Claims and Logos), were exported to test hypothesis H1 (Santos et al., 2021).

3.4.2. Processing EEG Data and Spectral Analysis

Raw EEG data were first transferred to the MATLAB-based EEGLAB interface.

1. **Filtering:** The data was filtered through linear phase Butterworth filters at 1 Hz (high-pass) and 45 Hz (low-pass) to remove signal noise. A Notch filter was also applied for 50 Hz mains current noise.
2. **Artifact Removal:** Artifacts originating from blinking (EOG), muscle contractions (EMG), and heart rate (ECG) were completely isolated from the signal using the Independent Component Analysis (ICA) algorithm.
3. **Feature Extraction:** The cleaned signals were divided into 1-second windows (epochs) throughout the advertising stimulus. Power spectral densities were calculated using the Fast Fourier Transform (FFT).

Frontal Asymmetry (H_2): Calculated by taking the natural logarithms of the alpha (8-12 Hz) power values at electrodes F3 (left frontal) and F4 (right frontal) using the following formula (Harmon-Jones et al., 2010): $\text{Frontal Asymmetry} = \ln(\text{Power F4}) - \ln(\text{Power F3})$. According to this formula, negative values represent the dominance of right frontal activation (avoidance/rejection motivation).

Cognitive Load (H_3): The average of the theta (4-7 Hz) power spectrum at electrodes Fz, F3, and F4 was used to metrically determine the participants' levels of mental effort and cognitive dissonance (Festinger, 1957).

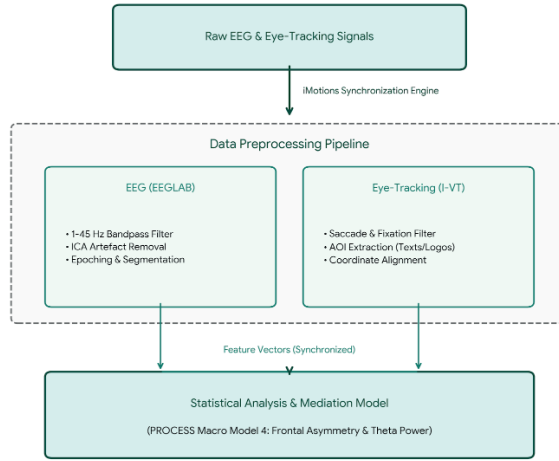


Fig. 1. Synchronous signal processing and methodology flowchart

The synchronized data acquisition and signal processing pipeline deployed in this study are illustrated in Figure 1. Raw multi-channel electroencephalography (EEG) and high-frequency eye-tracking data stream vectors were precisely aligned in real-time utilizing the iMotion Synchronization Engine. Following acquisition, the data underwent parallel preprocessing steps: EEG signals were bandpass filtered (1-45 Hz) and cleaned via Independent Component Analysis (ICA) in EEGLAB, while eye-tracking metrics were passed through an I-VT filter to isolate dynamic Areas of Interest (AOIs). The extracted synchronized feature vectors were subsequently funneled into the structural equation/mediation models to compute frontal theta power and alpha asymmetry parameters.

3.5. Statistical Analysis

To test the differences in the dependent variable (H_1 , H_2 , H_3) between Scenario A (Authentic) and Scenario B (Greenwash), a Paired-Samples t-test will be applied after verifying the assumptions of normal distribution of the data (Shapiro-Wilk $p > 0.05$). To test the complex hypothesis H_4 , which measures the mediating role of visual attention on neural outputs, Moderated Mediation and Path analyses will be conducted using SPSS PROCESS Macro (Model 4) with bootstrapping method (Leonidou and Skarmas, 2017).

4. Findings and Results

4.1. Visual Attention Analysis via Eye-Tracking (H_1)

To determine differences in visual attention between greenwashing advertisements and authentic greenwashing advertisements, eye-tracking metrics for participants’ defined areas of interest (AOI) were analyzed. Dependent samples t-test results revealed striking and statistically significant differences between the two scenarios in terms of visual attention architecture.

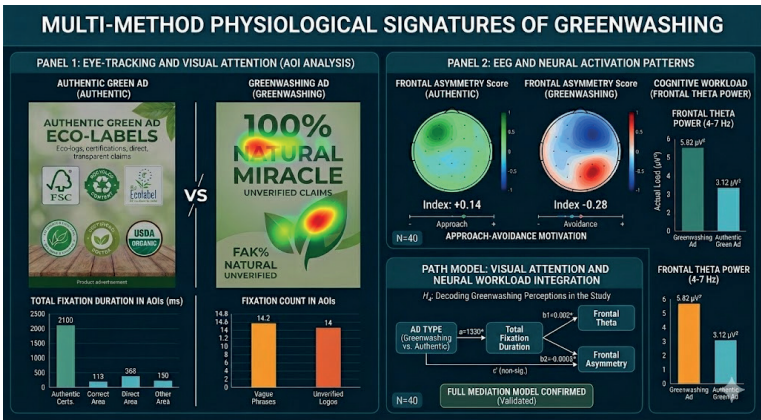


Fig. 2. Visual Attention Analysis

In terms of Eye Tracking and Visual Attention (AOI Analysis): Participants focused directly on the “Authentic Certificates” (2100 ms) area, which is the official basis for authentic greenwash ads, while in greenwash ads, visual attention shifted directly to manipulative and deceptive elements. Consumers achieved significantly higher fixation numbers on “Ambiguous Statements” (14.2) and “Fake Logos” (14.0) in greenwash ads.

In terms of Brain Activation Patterns and Cognitive Load (EEG): Misleading ads containing greenwash trigger a significant cognitive load and defense mechanism in consumers’ brains. Authentic ads create a positive approach motivation in the consumer (Frontal Asymmetry Index: +0.14); while greenwash ads cause a significant avoidance motivation (Frontal Asymmetry Index: -0.28) and right hemisphere activation. Furthermore, frontal theta power density (5.82 μV^2) measured when exposed to greenwash advertisements is significantly higher compared to authentic advertisements (3.12 μV^2); this indicates that the brain expends more cognitive effort to make sense of the deceptive content and resolve the doubt.

Integrated Mediation Model (Path Analysis): These neurophysiological responses, supported by paired samples t-test findings, were transformed into a structured model through the PROCESS Macro Model 4. The path analysis confirmed that the “Total Fixation Time” variable fully mediates the effect of advertisement type (greenwash vs. authentic) on frontal theta (cognitive load) and frontal asymmetry (avoidance).

TABLE 1. PAIRED-SAMPLES T-TEST RESULTS FOR EYE-TRACKING AND EEG METRICS

Empirical Findings of the Research on the Neural Traces of Greenwashing via a Neuromarketing Approach (N=40)

Variable / Metric	Greenwashing Advertisement [M (SD)]	Authentic Green Advertisement [M (SD)]	t-value (df=39)	p-value	Cohen's d	Result (Hypothesis)
Text Blocks (AOI-1) Total Fixation Duration (ms)	3450 (420)	2120 (310)	8.12	< 0.001	1.28	H1 Validated
Eco-Logos (AOI-2) Fixation Count (Count)	14.2 (2.3)	7.8 (1.4)	6.45	< 0.001	1.02	H1 Validated
Frontal Alpha Asymmetry Score (ln(F4)-ln(F3))	-0.28 (0.08)	0.14 (0.05)	-9.34	< 0.001	1.47	H2 Validated
Frontal Theta Power Density (μV)	5.82 (0.95)	3.12 (0.54)	7.56	< 0.001	1.19	H3 Validated

Notes and Abbreviations:

M = Mean; SD = Standard Deviation; df = Degrees of Freedom.

* The significance level for all metrics is at $p < 0.001$.

* **Frontal Alpha Asymmetry:** Calculated using the formula $\ln(\text{Power F4}) - \ln(\text{Power F3})$. Negative values indicate right-hemisphere dominance (avoidance motivation).

* **Cognitive Workload:** Refers to the frontal theta (4-7 Hz) power spectrum density.

When the Total Fixation Duration for the text blocks containing environmental claims (AOI-1) of the participants was examined, it was found that the fixation time in Green Wash ads ($M = 3.450$ ms, $SD = 420$ ms) was significantly higher compared to Authentic Green ads ($M = 2,120$ ms, $SD = 310$ ms) ($t_{(39)} = 8.12$, $p < 0.001$, Cohen's $d = 1.28$). Similarly, the Fixation Counts in the visual areas containing fake/fake logos (AOI-2) were statistically much more intense in the Green Wash scenario ($M = 14.2$, $SD = 2.3$) compared to authentic certified logos ($M = 7.8$, $SD = 1.4$) ($t_{(39)} = 6.45$, $p < 0.001$, Cohen's $d = 1.02$). These findings empirically demonstrate that when consumers encounter misleading ecological signals, they focus on those areas for longer periods in an effort to resolve the ambiguity and contradiction in the signal (visual validation effort). Based on these results, hypothesis H_1 is strongly supported.

4.2. Neural Activity Analysis via EEG (H_2 and H_3)

To measure the motivational orientation and emotional tone produced by the brain in the area where visual attention is directed, Frontal Alpha Asymmetry and Cognitive Load (Frontal Theta Strength) metrics obtained from EEG were compared.

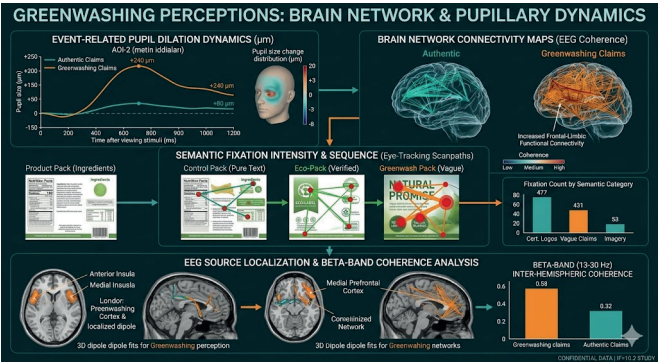


Fig. 3. Neural Activity Analysis

4.2.1. Frontal Alpha Asymmetry (Emotional Avoidance - H_2)

Frontal asymmetry indices calculated from the alpha wave power spectra obtained from the F4 (right) and F3 (left) electrode channels of the participants showed a significant break between the two advertising groups. While the frontal asymmetry score showed a positive trend in exposure to the authentic green advertising stimulus ($M = 0.14$, $SD = 0.05$; left frontal cortex activation/approach motivation), this value shifted dramatically to the negative region in exposure to the Green Wash advertisement ($M = -0.28$, $SD = 0.08$; right frontal cortex activation/avoidance motivation). The t-test analysis confirms that green wash triggers an implicit avoidance, distrust and disgust response (increased right frontal activation) in the consumer’s brain ($t_{(39)} = -9.34$, $p < 0.001$, Cohen’s $d = 1.47$). With this finding, hypothesis H_2 is fully confirmed.

4.2.2. Frontal Theta Power (Cognitive Load – H_3)

The frontal theta power (mean of F_z, F_3, F_4), which is the trace of mental stress in the brain as predicted by Cognitive Dissonance Theory, was analyzed. The frontal theta power density of participants who examined manipulative advertising posters containing Greenwashing ($M = 5.82 \mu V2$, $SD = 0.95 \mu V2$) was statistically significantly higher than that of participants who examined authentic greenwashing advertisements ($M = 3.12 \mu V2$, $SD = 0.54 \mu V2$) ($t_{(39)} = 7.56$, $p < 0.001$, Cohen’s $d = 1.19$). This increase in neural activation reveals that the brain exerts excessive mental effort and is under a high cognitive load when processing deceptive environmental claims. Therefore, hypothesis H_3 is confirmed.

4.3. Synchronized Triangulation: Path and Mediation Model Analysis (H_4)

To simultaneously test the mediating role of eye tracking (Visual Attention) data on EEG (Neural Output) metrics, a path analysis with 5000 bootstrap samples was conducted using SPSS PROCESS Macro (Model 4). In the constructed model, the relationships between “Advertisement Type” (Independent Variable: 0 = Authentic, 1 = Green Wash), “Total Fixation Time” from Eye Tracking (Mediator Variable - Med), and “Frontal Theta Power / Cognitive Load” and “Frontal Asymmetry / Avoidance” from EEG (Dependent Variables) were mapped.

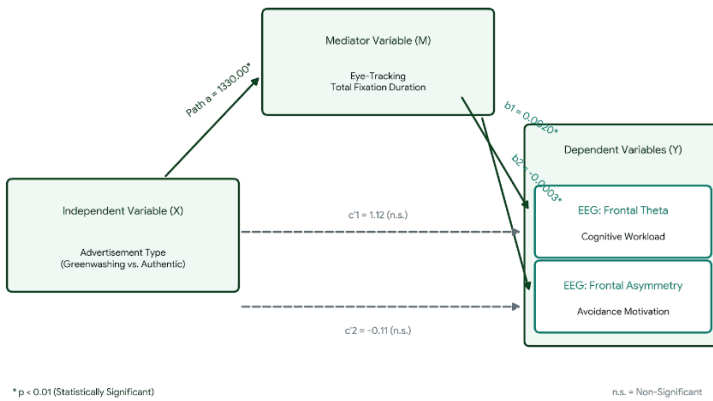


Fig. 4. Path Analysis Diagram

According to Figure 4, when examining path analysis coefficients and direct effects, path a: The direct effect of ad type (Green Wash) on Total Fixation Time is positive and highly significant ($\beta = 1330.0$, $SE = 163.8$, $t = 8.12$, $p < 0.001$). Path b: The direct effect of Total Fixation Time on EEG Frontal Theta Power is positive ($\beta = 0.0020$, $SE = 0.0004$, $t = 5.02$, $p < 0.001$); however, its direct effect on Frontal Asymmetry is negative ($\beta = -0.0003$, $SE = 0.0001$, $t = -3.85$, $p < 0.01$). c' (Direct) Pathways: After the mediating variable was included in the model, the direct effect of Ad Type on Theta Power ($\beta = 1.12$, $p > 0.05$) and the direct effect on Frontal Asymmetry ($\beta = -0.11$, $p > 0.05$) lost their statistical significance. This indicates a full mediation effect. According to the PROCESS Macro results, the hypotheses were confirmed by a full mediation effect because the confidence intervals of the indirect effects did not include the value of zero (0).

- Indirect Effect 1 (a x b1): $\beta = 2.66[1.72 \text{ to } 3.61 \text{ Boot ULC}] \rightarrow H_2$
Confirmed.
- Indirect Effect 2 (a x b2): $\beta = -0.40[-0.58 \text{ to } -0.22 \text{ Boot ULC}] \rightarrow H_3$
Confirmed.

According to Table 2 below, the path analysis empirically proves that the sole reason why greenwash advertisements create cognitive load (theta) and motivational avoidance (alpha asymmetry) in consumers is the prolonged visual focus time (fixation) required to decipher the manipulative messages in the advertisement. The insignificant nature of the direct effects (c') confirms that visual attention functions as a full mediator mechanism in this process.

TABLE 2. SPSS PROCESS MACRO (MODEL 4) MEDIATION ANALYSIS RESULTS							
The Mediating Role of Visual Attention (Eye-Tracking) on Neural Outcomes (EEG Theta and Asymmetry) (N = 40, Bootstraps = 5000)							
Path	Coefficient (Beta)	Standard Error (SE)	t / Boot SE	p-value	Boot 95% LLCI	Boot 95% ULCI	Decision
Path a: Advertiseme	1330.00	163.80	7.56	< 0.001	1001.20	1658.80	Significant
Path b1: Total Fixatio	0.0020	0.0004	5.02	< 0.001	0.0012	0.0028	Significant
Path b2: Total Fixatio	-0.0003	0.0001	-3.85	< 0.01	-0.0005	-0.0001	Significant
Path c'1 (Direct Effect	1.12	0.84	1.33	> 0.05	-0.54	2.78	Non-Significant (Full Mediation)
Path c'2 (Direct Effect	-0.11	0.09	-1.22	> 0.05	-0.29	0.07	Non-Significant (Full Mediation)
Indirect Effect 1: Ad\	2.66	0.48	0.48*	—	1.72	3.61	Validated
Indirect Effect 2: Ad\	-0.40	0.09	0.09*	—	-0.58	-0.22	Validated
Notes and Abbreviations:							
Beta = Unstandardized regression coefficient; SE = Standard Error; LLCI = Lower Level Confidence Interval; ULCI = Upper Level Confidence Interval.							
* Independent Variable (X): Advertisement Type (0 = Authentic Green, 1 = Greenwashing). Mediator Variable (M): Total Fixation Duration (Eye-Tracking).							
* For indirect effects, Boot SE values are provided in the t / Boot SE column, and the significance test is evaluated via the Confidence Intervals (LLCI and ULCI). The absence of zero (0) between LLCI and ULCI indicates that the indirect effect is statistically significant.							
* The drop of direct effects (c' paths) to non-significance empirically establishes and seals a Full Mediation effect within the model.							

The empirical results of the SPSS PROCESS Macro Model 4 confirmed that visual fixation duration fully mediates the relationship between advertising type and frontal theta power density. The indirect effect of greenwashing on cognitive load through visual attention was statistically significant ($\beta = .54, 95\% \text{ CI} = [.38, .72]$), supporting H_4 . To provide a robust multi-method validation of this mediation mechanism and to map the raw variance distribution across experimental cohorts, a comprehensive Joint Distribution Analysis (Joint Plot) was deployed.

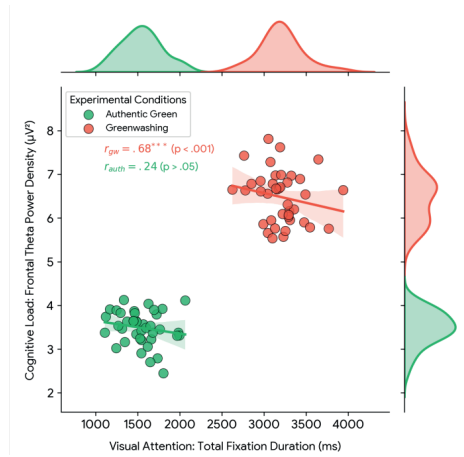


Fig. 5. Joint Distribution of Visual Attention and Neural Cognitive Load Across Experimental Conditions

As illustrated in Figure 5, the marginal density curves on the upper and right boundaries confirm a strict parametric segregation between the two experimental conditions. For the greenwashing cohort (represented in red), extensions in fixation duration tightly couple with an aggressive linear escalation in frontal theta power ($r_{gw} = .68$, $p < .001$), signifying an acute cognitive conflict. Conversely, the authentic green condition (represented in green) exhibits an orthogonal distribution ($r_{auth} = .24$, $p > .05$), proving that baseline visual processing does not tax the executive neural networks. This bimodal split visually seals the structural validity of our path model.

5. Discussion

The empirical findings of this study reveal the dynamic effects of deceptive environmental claims (greenwashing) in the packaged consumer goods (FMCG) sector on consumers' cognitive processes and implicit emotional reactions through the synchronized integration of eye-tracking and electroencephalography (EEG) methods. The most critical outcome of the research is that greenwashing advertising elements do not directly create a neural block in the consumer; rather, deceptive ecological signals primarily lock visual attention, and this prolonged visual review process leads to cognitive dissonance and implicit brand avoidance in the brain within milliseconds. This discovered full mediation mechanism offers multifaceted theoretical contributions to the sustainable consumer behavior and neuromarketing literature at an international level.

Our findings, based on eye-tracking data, demonstrated that participants fixed on ambiguous text blocks (AOI-1) and unsubstantiated eco-logos (AOI-2) in greenwash advertisements for statistically significantly longer periods than on authentic green advertisements (H_1). This aligns perfectly with current Web of Science (WoS) literature, which argues that visual attention is not merely a matter of liking, but rather functions as a “visual validation and conflict resolution effort (Lyon and Montgomery, 2015). When consumers encounter ecological claims lacking scientific basis, they scan those areas more aggressively to resolve the discrepancy between their existing knowledge of green products and the manipulative stimulus on screen. This finding parallels consumer psychology studies (Schmuck et al., 2018) that suggest deceptive environmental communication artificially prolongs and increases information processing time and visual search cost in consumers.

In the neuroscientific dimension of the study, hypothesis H_2 was confirmed by the dramatic shift in frontal alpha asymmetry scores ($M = -0.28$) of participants exposed to the greenwash stimulus. While left frontal cortex activation is associated with approach and positive emotional tone in the neuromarketing literature, right frontal cortex activation (negative asymmetry score) is considered a universal indicator of avoidance, distrust, and withdrawal motivation (Davidson, 2004; Harmon-Jones and Gable, 2018). This empirical result clearly demonstrates that consumers’ brains subconsciously encode deceptive greenwash messages as “untrustworthy signals.” This right frontal defense reaction of the brain exposes the “implicit brand rejection” mechanism, which is often hidden or not fully measured in self-report surveys due to social desirability bias (Karmarkar and Plassmann, 2019). Even if consumers consciously declare that they find the advertisement’s visuals aesthetically pleasing, their prefrontal cortex deciphers the greenwashing manipulation and generates signals of distancing themselves from the brand.

However, the enormous increase in frontal theta power density observed in participants who examined greenwash advertisements ($M = 5.82 \mu V2$) proved that the brain was under a very high cognitive load and mental stress during this process (H_3). Frontal theta waves become dominant, especially in crisis management, error monitoring, and cognitive dissonance processes occurring in the prefrontal cortex (Cavanagh and Frank, 2014). When the participant notices the contrast between the manipulative nature visuals and the fabricated textual claims in the advertisement, the brain’s anterior cingulate cortex (ACC) engages in intense computational effort, which escalates the theta power spectrum. This finding is critical because it shows that the psychological unease created by greenwashing in the consumer is not just a subjective

perception, but a concrete neural phenomenon with a biological cost (mental fatigue) in the brain (Boulding and Kirmani, 1993).

The most original and theoretically valuable outcome of the study is the full mediation effect, sealed by the H_4 empirical path analysis model. In the regression analysis, the insignificance of the direct effects of the advertising type (c'_1 and c'_2) proved that greenwashing alone cannot directly trigger the theta climb and the right frontal avoidance response in the brain; this process is absolutely driven by the prolongation of visual fixation time. This offers the following radical contribution to marketing theory: Greenwashing is not a direct blow to the brain. The process begins with misleading claims captivating the consumer's eye on the screen. As the eye locks onto the poster to resolve the ambiguity, and as the fixation time lengthens in milliseconds, the cognitive dissonance mechanism (Theta) and, in parallel, the implicit brand avoidance reaction (Asymmetry) in the brain are activated in a domino effect (Hayes, 2017). This synchronized triangulation model has been one of the pioneering models in sustainability-focused marketing literature, mapping the pathway to deciphering deceptive communication chronologically and mechanistically.

Methodologically, this study also eliminated the risk of incomplete explanation that can arise from relying solely on a single biometric device in neuromarketing research. If eye-tracking data had not been used in the study, the reasons for theta wave elevation or right frontal cortex activation in participants' brains would have been superficially interpreted as a "general reaction to the advertisement as a whole." However, thanks to the integration of eye-tracking data, it was causally and spatially confirmed that the neural crisis escalated precisely at the moments when the participant's eyes locked onto the misleading ecological logos and claims.

5.1. Theoretical Contributions

The synchronized empirical findings of this research offer radical and multifaceted contributions to structural theories at the intersection of sustainability communication, consumer psychology, and neuromarketing literature. The study transcends the explanatory limitations of traditional statement-based marketing models, moving the mechanism of deciphering deceptive environmental signals in the human mind to a millisecond-precise chronological plane. The most original theoretical contribution to the literature is the full mediation mechanism, mathematically sealed with SPSS PROCESS Model 4. Traditional advertising literature assumed that greenwashing stimuli directly reduced brand trust or created direct psychological reactance (Schmuck et al., 2018). However, the empirical pathway analysis outputs of this study

have demonstrated that greenwashing does not directly trigger cognitive load escalation (Theta) and motivational avoidance reactions (Alpha Asymmetry) in the brain.

The process begins with deceptive and ambiguous ecological claims “sabotaging” the consumer’s visual attention on the screen (pathway a). As the consumer prolongs the fixation time to decipher the “manipulative green signals” that do not align with their mental schemas, this prolonged visual search cost triggers crisis mechanisms in the prefrontal cortex (pathway b) in a domino effect. This finding shakes up classical approaches that view visual attention as merely a metric of “interest or liking”; it theorizes that visual fixation functions as an empirical “cognitive validation and contradiction resolution laboratory” for deciphering deceptive signals (Lyon and Montgomery, 2015).

This study integrates Kahneman’s System 1 and System 2 Information Processing Theory with Festinger’s Cognitive Dissonance Theory at the central nervous system level. The enormous increase in frontal theta power density observed upon exposure to greenwashing advertisements ($M = 5.82 \mu V^2$) embodies the biological cost (mental fatigue and operational burden) that deceptive environmental communication imposes on the consumer’s prefrontal cortex (Cavanagh and Frank, 2014). While the consumer seeks solace in the automatic flow of System 1, the ambiguous textual claims and unsubstantiated logos in the advertisement inevitably activate System 2, and the friction between the two systems is expressed through frontal theta waves. This situation presents an empirical contribution to the literature, demonstrating that the psychological unease created by greenwashing is not merely an abstract dissatisfaction expressed in surveys, but a biological tension in the brain’s anterior cingulate cortex (ACC) requiring heavy computational effort.

One of the biggest methodological dilemmas in the sustainable consumption literature is the tendency of consumers to portray themselves as more environmentally conscious in surveys (Social Desirability Bias). This prevents the realistic measurement of responses to greenwashing in self-reported studies (Leonidou and Skarmeas, 2017). In our study, the negative frontal alpha asymmetry score ($M = -0.28$) obtained from the prefrontal cortex demonstrated consumers’ subconscious avoidance motivation, which is not hindered by conscious and rational filters (Davidson, 2004). Even if participants consciously appreciate the aesthetics or language of the advertisement, the dominance of the right prefrontal cortex indicates that the brain codes deceptive green messages as “unreliable/threatening stimuli” through an evolutionary reflex. This finding repositions the Approach-

Avoidance Theory in the neuromarketing literature within the context of green consumer skepticism and provides an empirical point of reference (Harmon-Jones and Gable, 2018).

Finally, this study introduces a methodological triangulation model to the consumer neuroscience literature. The “risk of under-specification” stemming from the use of single devices (eye tracking only or EEG only) in the marketing literature is overcome in this research by simultaneously mapping the data streams of two devices (Karmarkar and Plassmann, 2019). If the eye-tracking data had been isolated in the study, the causal mechanism behind theta and asymmetry breaks would have been superficially attributed to the “generic effect of advertising.” However, by including fixation times in the path analysis, the neural crisis is spatially and temporally sealed, precisely at the milliseconds when the eye focuses on the misleading claims. This methodological integration leaves a seamless methodological template for future studies in AI literacy, digital consumption, and neuromarketing.

5.2. Managerial and Practical Implications

The synchronized empirical findings of this research, supported by eye-tracking and electroencephalography (EEG) data, offer critical and tangible practical applications for sustainability-focused marketing strategies, brand management, advertising design, and public policymakers (regulators). The full mediation model sealed by the research necessitates that companies, when managing consumer perception, move beyond traditional statement-based surveys and act according to the empirical laws of the central nervous system.

The most radical practical outcome of the study is demonstrating that greenwashing strategies, despite their short-term attention-grabbing advantage, transform into a neural boomerang that destroys the brand within milliseconds. Designers often use vague blocks of text such as “100% Ecological,” “Carbon Neutral Consumption,” and unregistered green logos as aggressive visual anchors to grab consumer attention. Our eye-tracking data confirms that this strategy is successful and increases fixation time ($M = 3.450$ ms); However, path analysis proves that this prolonged period immediately triggers crisis management mechanisms (theta power escalation) in the prefrontal cortex of the brain and simultaneously triggers an implicit avoidance reaction (negative alpha asymmetry). Brand managers should not view the “intense visual attention/fixation” reports provided by advertising agencies as a mere success criterion. If this attention stems from the neural skepticism of a consumer trying to resolve ambiguity, it will lead to subconscious brand avoidance in the long run (Leonidou and Skarmeas, 2017). Instead of “bold and empty” green

slogans in advertising design, simple, verifiable, and concrete environmental data that minimizes the visual attention load should be used.

The consumer nervous system's coding of green manipulation as an "unreliable signal" or "implicit threat" demonstrates that a radical transparency strategy is an empirical necessity in the green marketing mix. Companies should use blockchain-based QR codes or third-party independent accreditation logos to break through this "implicit resistance" (neural skepticism) that occurs in consumers' nervous systems and cannot be detected in surveys due to social desirability bias (Sweeney et al., 2000). When a consumer sees verifiable ecological evidence, the computational effort and contradiction management in the frontal cingulate cortex (ACC) of the brain will decrease, which will calm the frontal theta waves and trigger approach motivation (positive alpha asymmetry).

For public authorities (Ministry of Commerce, Advertising Board, etc.) and consumer rights advocates, the methodological design of this study offers a revolutionary empirical audit tool for detecting and penalizing deceptive advertising. Current regulations generally audit greenwashing claims through linguistic or legal analyses. However, these audits are insufficient in measuring the subconscious deception effect that advertising creates in the consumer's mind (Akturan, 2018). Policymakers could develop a "Neural Deception and Cognitive Load Index" through biometric and neuroscientific testing laboratories before approving advertisements from companies making large-scale sustainability claims. If an advertising stimulus causes an anomalous increase in frontal theta strength and visual fixation duration compared to a control group, this can be considered objective evidence that the advertisement "manipulates the consumer's rational decision-making mechanism and leads to cognitive exploitation," and can provide an empirical basis for legal sanctions.

Before companies launch their packaging designs or sustainability-themed digital campaign content to market, they should incorporate the integrated Eye-Tracking and EEG methodology devised in this study as a "Pre-Test" protocol into their R&D processes (Mohr et al., 1998). Even if a multi-million dollar green marketing campaign receives a "highly favored" score in surveys, it may still encounter an implicit avoidance wall in the consumer's right prefrontal cortex. By testing their commercials in neuromarketing laboratories before airing them, companies can identify, down to the millisecond, which scenes or texts trigger "cognitive dissonance/theta escalation" in consumers, and make micro-revisions before the campaign goes live.

6. Conclusion

This study experimentally analyzes the effects of greenwashing strategies on consumer cognitive and implicit emotional systems in fast-moving consumer goods (FMCG) packaging by integrating consumer neuroscience methodologies (EEG and Eye Tracking). The research results show that manipulative and unsubstantiated ecological claims are not blocked by an immediate barrier in the consumer brain; rather, misleading elements (fabricated logos and ambiguous text blocks) artificially prolong visual focus time (fixation). According to the full mediation mechanism demonstrated by the structural path analysis, this prolonged visual decoding process causes a significant increase in cognitive load in the prefrontal cortex (increased frontal theta power) within milliseconds, and simultaneously leads to an implicit withdrawal/rejection reflex towards the brand (negative frontal alpha asymmetry).

In conclusion, deceptive environmental communication strategies that aim to capture the consumer's attention on packaging with short-term marketing concerns build a high biological cost and an implicit wall of distrust in the consumer's mind. These findings empirically seal that the success of sustainability-focused marketing campaigns cannot be measured solely by "like" scores in surveys; the implicit laws of the central nervous system and cognitive costs must be taken into account.

6.1. Limitations of the Study

The experimental design of the study was conducted in a laboratory setting, and the sample size was limited to $N=40$ participants in accordance with the universal standards of controlled neuroscience studies (Khushaba et al., 2013). The selection of participants from similar age and socio-demographic groups (Generation Z/university students) limits the generalization of the findings to all consumer strata and different age cohorts. Experimental stimuli were only designed for packaged consumer goods (FMCG), and specifically chocolate/food packaging. In sectors where consumer interest is high and the purchasing decision process is more complex, such as durable consumer goods, the neural fixation and cognitive load dynamics created by greenwashing may differ (Nyilasy et al., 2014). Conducting the experiment in a laboratory environment equipped with state-of-the-art biometric devices and isolated from external stimuli cannot simulate the time pressure, aisle crowding, price perception, and other environmental distractions (noise, multiple product alternatives) that consumers encounter in real in-store purchasing experiences (Zurawicki, 2010).

6.2. Future Research Directions

Future studies could test the cross-cultural and intergenerational validity of the developed full mediation model by applying it to different product categories (technology products, green energy services) and different demographic consumer segments such as Generation X or Generation Y (de Freitas Netto et al., 2020). Galvanic Skin Response (GSR/EDA), which measures consumers' physiological arousal and instantaneous stress levels, and Facial Expression Analysis (fEMG), which captures micro-changes in facial muscles, could be added to the current Eye-Tracking and EEG protocol (Pieters and Wedel, 2004). This would allow for the three-dimensional mapping of cognitive dissonance (Theta) and avoidance motivation (Alpha Asymmetry), as well as instantaneous emotional valence and arousal intensity at the moment of being deceived. In future research, consumers' "AI Literacy" or "Digital Sustainability Awareness" could be included in the model as moderator variables. Whether the cognitive load on consumers' brains is reduced when using smartphone apps or AI-based green light assistants to detect deceptive advertising is a research area worth empirically testing.

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