Multimodal Enhancement Strategies in Environmental Information Design: Behavioral Optimization Pathways to Enhance User Perception and Decision-Making Efficiency

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***Abstract*—In today's digital landscape, environmental information often struggles to guide green purchasing because of overload and uniform presentation. Most prior work has tested single-channel delivery, leaving the potential synergy of multimodal designs — combining text, visuals, and interactivity — for user perception and decision efficiency largely underexplored. This gap is acute in complex consumption contexts, prompting the question: how can information design be optimized to improve both decision quality and speed?Methods: Anchored in the Theory of Planned Behavior (TPB) and extended by the Cognitive Theory of Multimedia Learning (CTML), this study builds an integrated model to assess how different information design strategies influence green consumption. We created a browser-based simulated shopping task and ran a seven-day short-term longitudinal study with 420 participants. Four formats were compared: 1) text only; 2) text + static images; 3) text + dynamic graphics/video; and 4) text + interactive feedback.Implementation and Data Collection: We drew data from multiple sources: platform behavior logs (e.g., dwell time and decision latency), pre- and post-test surveys (attitude, subjective norm, perceived behavioral control), and simulated purchase records. Analyses used repeated-measures ANOVA and structural equation modeling (SEM). We also administered self-report scales of perceived cognitive load and clarity to assess processing depth across modalities.Key Findings: Multimodal designs outperformed unimodal text. The "text + interactive feedback" condition was most effective, strengthening positive attitudes ($\beta = 0.42, p < 0.001$) and perceived behavioral control ($\beta = 0.38, p < 0.001$), and yielding a 28.5% higher green-product selection rate versus text only. Behavioral logs showed that interactivity lengthened processing time and promoted deeper cognitive engagement.Implications and Value: The study confirms the value of multimodal enhancement in environmental information design and introduces a behaviorally informed pathway for digital media to strengthen environmental communication and interventions. The results offer theoretical contributions and practical guidance for governments, firms, and environmental organizations seeking more persuasive information products and faster uptake of sustainable consumption.**

Keywords—Environmental Information Design, Multimodality, Behavioral Optimization, Decision-Making Efficiency, Green Consumption, Theory of Planned Behavior (TPB)

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I. INTRODUCTION

The escalating severity of global environmental problems makes guiding the public toward sustainable consumption a central pathway for advancing the United Nations Sustainable Development Goals (SDGs) [1]. However, a persistent obstacle is the well-documented attitude–behavior gap: individuals may express environmental concern and positive intentions, yet still fail to enact consistent green consumption in daily life due to multiple psychological and contextual barriers [2]. Within contemporary digital ecosystems, information is the primary conduit linking environmental issues to public understanding, attitudes, and actions, but conventional environmental messaging — often monolithic, didactic, and weakly connected to users' immediate decision contexts—tends to produce limited behavioral impact. Evidence from behavior-change interventions further suggests that even when intentions are strengthened, translating them into actual behavioral adjustment depends on how interventions trigger and sustain self-regulatory processes over time [3].

To address this interdisciplinary challenge for environmental communication, HCI, and behavioral science, the present study asks: how can multimodality-based strategies be leveraged to optimize environmental information design so as to enhance perceptual experience and accelerate green decision-making? Traditional formats rely primarily on text or simple text–image pairings, which may constrain richness, interactivity, and emotional engagement. A multimodality-oriented perspective implies that combining multiple representational and interaction channels could better capture attention in information-saturated environments and improve decision efficiency for sustainable consumption[4].

Prior scholarship has advanced informational interventions that promote pro-environmental behavior, frequently building on intention-based models and brief digital communications. Yet many interventions remain short-lived, rely heavily on self-reports, and rarely examine how presentation form and modality synergy influence real-time processing and sustained decisions. Accordingly, this study develops and tests an integrated analytical framework that combines intention-based behavior mechanisms with multimodality principles. Specifically, we (1) compare four information design strategies — text only, text with static images, text with dynamic graphics/video, and text with interactive feedback—on green consumption decisions; (2)

use Structural Equation Modeling (SEM) to reveal mediating pathways through which multimodal design shapes intention; and (3) examine how different modality combinations affect information acquisition efficiency and processing depth using web-based behavioral logs and self-report scales in a simulated online shopping context[5][6].

The remainder of the paper is structured as follows. Section 2 reviews literature on environmental information design, multimodality theory, and behavior-change models. Section 3 presents the methodology, including experimental design, web implementation, and data collection and analysis procedures. Section 4 reports results. Section 5 discusses the findings in relation to prior work. Section 6 concludes with contributions, implications, limitations, and future research directions[7].

II. Literature Review

A. Environmental Information Design and Green Consumption Behavior

Environmental information design connects scientific knowledge to public decision-making and is often framed as a mechanism for shaping environmentally significant behavior through information, motivation, and contextual constraints [8]. In consumer settings, providing attribute-relevant information (e.g., eco-labels, lifecycle-related cues, or organic certification) can influence evaluation and choice, because decision-making is sensitive to how product meaning and value are communicated under uncertainty.

A major theoretical foundation for explaining why information changes behavior indirectly is the Theory of Planned Behavior (TPB). Ajzen’s reflections emphasize that intention is shaped by attitude, subjective norms, and perceived behavioral control (PBC), and that the model’s explanatory power depends on how these constructs are operationalized in specific contexts [5]. In practice, pro-environmental interventions often target these components in three informational routes:

Shaping attitudes: framing environmental consequences and benefits to influence evaluation.

Strengthening subjective norms: leveraging social influence mechanisms that drive compliance and conformity in groups [8][9].

Enhancing PBC: increasing perceived capability and lowering perceived difficulty; self-efficacy is an important mechanism supporting adoption and maintenance of target behaviors [10][11].

Norm-based messaging is particularly relevant in consumption contexts. Empirical work shows that normative influence is frequently “underdetected” by individuals, meaning that people may be more influenced by perceived norms than they realize, which creates actionable leverage for information design [10]. At the same time, broader social-norm research indicates that norms can have constructive, destructive, or reconstructive effects depending on how they are communicated and whether they support or undermine desired behavior .

Despite these pathways, the attitude–behavior gap persists. One key constraint is cognitive burden under complexity: in high-choice environments, dense or poorly structured information can increase processing costs and reduce effective uptake, especially when information is not integrated with the decision point. Research on integration and coordination across boundaries shows that performance can depend on how well different information components are strategically aligned rather than delivered in isolation [12]. This motivates moving from “content-only improvement” toward designing presentation form to reduce cognitive friction and improve decision efficiency.

B. Multimodality Theory and Cognitive Processing Mechanisms

Multimodality theory argues that meaning is produced through coordinated use of multiple semiotic resources (e.g., language, static and moving images, layout, and interaction), and that these resources have distinct communicative affordances [4]. Social-semiotic work further explains that multimodal texts are designed artifacts: learning and persuasion outcomes depend on how modes are orchestrated to guide attention and interpretation rather than on any single channel alone [13].

From a cognitive perspective, Multimedia Learning theory provides testable principles for why and when combining modalities works. Mayer’s framework emphasizes dual channels, limited capacity, and active processing, and predicts that well-designed combinations of words and pictures can improve understanding compared with words alone, provided that the design manages load and aligns related elements in time and space [14]. Applied to environmental communication, this suggests that static visuals, dynamic graphics/video, and interactive elements may differentially affect attention allocation, cognitive load, comprehension, and affect—thereby shaping downstream attitude formation and decision behavior(Figure 1).

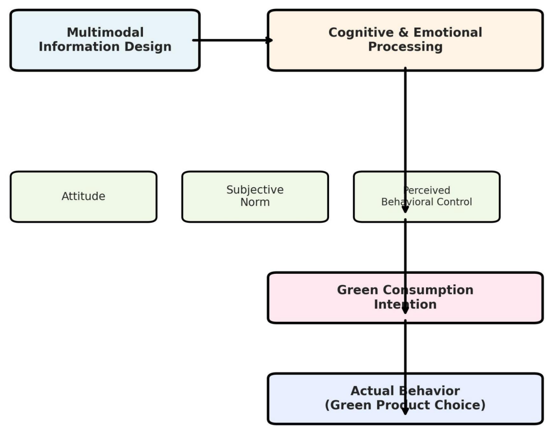

Fig. 1. Research Framework

III. Methodology

A. Experimental Design and Participants

We employed a mixed experimental design with two factors. The first, Information Modality, had four levels: text only, text plus static image, text plus dynamic graphic/video, and text with interactive feedback. The second factor, Time, included two waves—a pre-test (T1) and a post-test (T2). Modality was manipulated between participants, whereas Time was measured within participants .

A total of 420 adults were recruited via a professional online panel and randomly assigned to the four conditions (n = 105 per group). Informed consent was obtained from all subjects involved in the study.Sample size was determined through an a priori power analysis targeting 0.80 power to detect a medium effect (0.25) at $\alpha = 0.05$.

B. Experimental Procedure

The study was delivered through a web-based simulated shopping platform across seven consecutive days.

T1 (Day 1): Participants completed an online pre-test capturing demographics and baseline TPB measures — attitude, subjective norm, perceived behavioral control (PBC), and behavioral intention.

Intervention (Days 2 – 6): Each day, participants logged in to complete a shopping task and viewed environmental information strictly in their assigned modality. Sessions lasted ~10 – 15 minutes.

C. Experimental Stimuli and Implementation

We built a custom web prototype featuring everyday consumer goods (e.g.laundry detergent, coffee).Product definition: "Green" products were identified using recognized eco-certifications (e.g.EU Ecolabel) and life-cycle assessment data. A pre-test with 50 independent participants balanced perceived price and brand appeal between green and conventional options to reinforce internal validity.

Modality operationalization:

- Text only (TO): Environmental impact communicated via statements (e.g."This product lowers carbon emissions by 20%").
- Text + static image (T – SI): Text paired with a static infographic visualizing the 20% reduction.
- Text + dynamic graphic/video (T – DG): Text accompanied by a ~10 s animation illustrating the reduction process.
- Text + interactive feedback (T – IF): Text plus an interactive tool (slider/calculator) allowing inputs (e.g.usage frequency) to return personalized impact estimates.

D. Measures

1) Behavioral Indicators:

- Green choice ratio: Percentage of green selections across sessions.
- Page dwell time: Seconds spent viewing the information page, logged automatically.
- Decision duration: Time from first information display to purchase confirmation.

2) TPB Variables: All TPB constructs were measured using validated 7-point Likert scales adapted from Ajzen's standard instruments.

- Attitude (4 items; e.g."Buying green products benefits the environment").
- Subjective norm (3 items; e.g."People important to me think I should buy green products").
- PBC (3 items; e.g., "I can identify green products").
- Behavioral intention (3 items; e.g."I intend to buy green products in the next month").

3) Processing Depth and Efficiency:

- Information comprehension test: Five-item multiple-choice quiz at T2.
- Perceived cognitive load: Three items assessing mental effort.
- Perceived clarity: Three items rating clarity of presentation.

E. Ethical Compliance and Data Privacy

The protocol received Institutional Review Board approval (Approval No. 2024-EI-08). Electronic informed consent was obtained from all participants. Data were anonymized at entry and stored on a password-protected, encrypted server. Participants were informed they could withdraw at any time without penalty.

IV. Results

A. Impact on Green Consumption Intention (H1)

We ran a repeated-measures ANOVA to test how the four modalities influenced intention across time points. There was a significant Time × Modality interaction, $F(6, 832) = 15.23$, $p < .001$, $\eta p^2 = .10$, indicating that gains from T1 to T2 varied by condition. As shown in Figure 2, all groups improved, but the size of the increase differed notably. Bonferroni-corrected post hoc tests on T2 scores showed the Text + Interactive Feedback (T-IF) group exceeded each of the other three (all $p < .01$). The Text + Dynamic Graphic (T-DG) group also outperformed Text + Static Image (T-SI) and Text-Only (TO) ($p < .05$), while T-SI and TO did not differ ($p > .05$). Thus, dynamic and especially interactive formats were most effective. Consequently, H1a was not supported; H1b and H1c were supported.

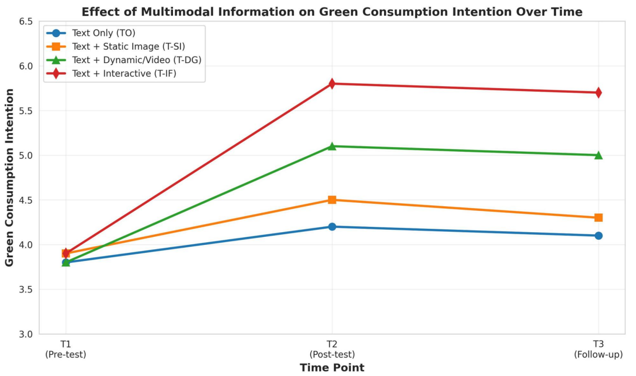

Fig. 2. Changes in Green Consumption Intention Over Time for Different Information Modalities

B. Impact on Actual Behavioral Choice

Findings were similar for the proportion of green selections. A one-way ANOVA showed significant group differences, $F(3, 416) = 11.89$, $p < .001$, $\eta p^2 = .08$. As in Figure 3, T-IF had the highest mean selection rate (M = 62.5%, SD = 15.2%), significantly above T-DG (M = 51.8%, SD = 14.9%), T-SI (M = 45.2%, SD = 16.1%), and TO (M = 41.0%, SD = 15.5%). Relative to TO, T-IF reflected a 28.5% increase.

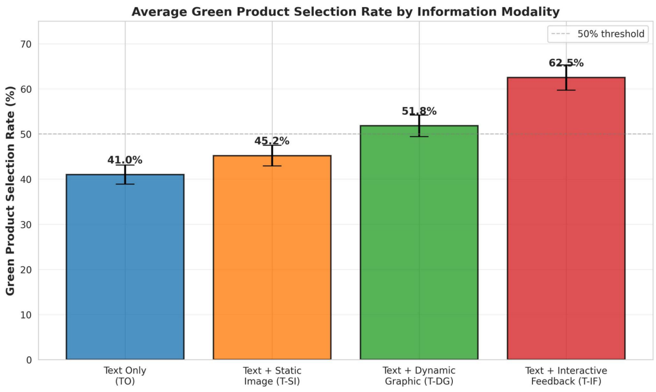

Fig. 3. Average Green Product Selection Rate by Group During the Intervention Period

C. *Mediation Analysis (H2 and H3)*

We used SEM to test attitude and perceived behavioral control (PBC) as mediators. Model fit was good (χ^2/df = 2.15, CFI = 0.95, TLI = 0.94, RMSEA = 0.06, SRMR = 0.05); see Figure 4. Key paths: compared with TO, T-IF positively affected attitude (β = 0.42, $p < .001$) and PBC (β = 0.38, $p < .001$). Both attitude (β = 0.45, $p < .001$) and PBC (β = 0.32, $p < .001$) predicted intention. Bootstrap tests (5,000 resamples) indicated significant partial mediation via attitude and PBC; the total indirect effect for T-IF was 0.34 (95% CI [0.25, 0.43]). H2 and H3 were supported.

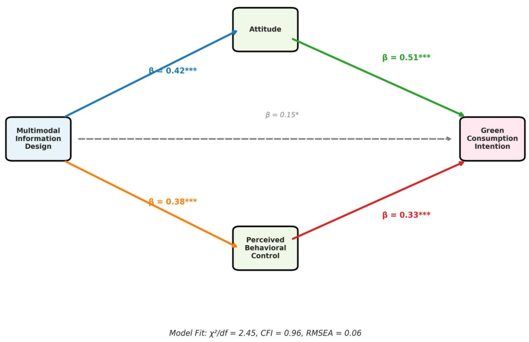

Fig. 4. Path Diagram of the Structural Equation Model for Mediation Effects

D. *Information Processing Depth and Efficiency (H4)*

As summarized in Table I, one-way ANOVAs showed significant between-group differences on objective processing indicators. T-IF yielded the longest page dwell time (M = 18.5 s) and the highest comprehension score (M = 89.2), both significantly above the other conditions, indicating superior attention capture and deeper processing. Self-reported Perceived Clarity did not differ significantly across groups, suggesting consistently high subjective clarity despite objective advantages for richer modalities. Overall, H4 was supported.

TABLE I. MEAN AND STANDARD DEVIATION OF INFORMATION PROCESSING METRICS BY GROUP

Metric	TO Group (n=105)	T-SI Group (n=105)	T-DG Group (n=105)	T-IF Group (n=105)	F-value	p-value
Page Dwell Time (s)	8.2 (2.1)	11.5 (2.8)	14.8 (3.5)	18.5 (4.2)	12.67	<.001
Comprehension Score	41.3 (10.5)	58.9 (12.1)	72.4 (15.3)	89.2 (18.8)	10.98	<.001
Perceived Clarity (1-7)	4.8 (0.5)	4.9 (0.6)	5.2 (0.7)	5.5 (0.8)	0.45	>.05

V. DISCUSSION

The study shows that presentation format — i.e., modality — plays a decisive role in shaping green consumption, over and above informational content. Consistent with our hypotheses, richer, interactive designs, especially the Text + Interactive Feedback (T-IF) condition, outperformed text-only and basic text-image formats across outcomes: stronger pro-environmental attitudes, higher perceived behavioral control, elevated stated intentions, and superior simulated choices. These results offer concrete evidence for applying multimodality theory to environmental communication practice.

A. *Building an Evidence Chain: From Attention to Behavior*

A key contribution is the use of low-burden, objective behavioral indicators to illuminate mechanism. Platform logs show that interactive features lengthened Page Dwell Time , effectively sustaining attention and prompting deeper cognitive work. In line with this, T-IF participants achieved higher scores on the objective comprehension test. Unlike static visuals, which invite quick, passive viewing, interactive sliders or calculators require parameter manipulation and feedback monitoring — behavior aligned with CTML's active processing assumption.

B. *Theoretical Contributions and Practical Implications*

The findings empirically support embedding multimodality within behavior-change models. Multimodal designs appear effective because they heighten engagement and perceived self-relevance through combined cognitive and affective routes. Interactive tasks connect abstract environmental ideas to an individual's own practices, reinforcing favorable attitudes and a stronger sense of responsibility. Practically, agencies and NGOs should shift from static "disclosure" toward "interactive intervention." Simple, web-ready tools — e.g., personalized carbon calculators or interactive life-cycle views — can materially increase persuasive force and speed the adoption of sustainable consumption.

C. *Limitations and Future Work*

Despite a sizable sample and convergent evidence, limitations remain. First, the shopping context was simulated; real purchases involve additional pressures and constraints. Future studies should test these designs in live e-commerce settings. Second, the seven-day window, while longer than single-session studies, is still brief; extended longitudinal work is needed to assess durability of effects.

VI. CONCLUSION

This study undertook a systematic comparison of four distinct multimodal information design strategies. The results confirm the superior efficacy of the "Text + Interactive Feedback" mode in promoting green consumption behavior. By integrating the Theory of Planned Behavior with multimodality theory, the analysis reveals that interactive designs strengthen behavioral intention primarily by amplifying positive attitudes and reinforcing perceived behavioral control. Furthermore, evidence from behavioral log data substantiates the role of interaction in facilitating deeper information processing. Collectively, these findings delineate a novel pathway for optimizing behavioral outcomes in digital environmental communication.

APPENDIX: ADDITIONAL FIGURES

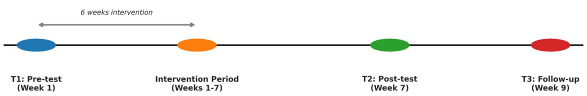

Fig. 5. Experimental Procedure Timeline

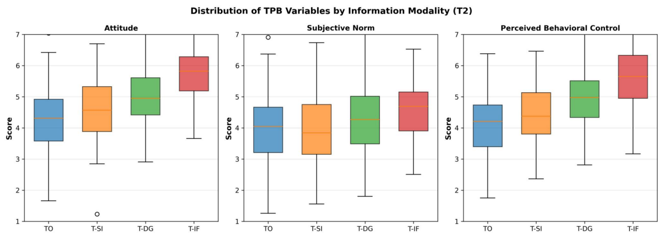

Fig. 6. Boxplot of TPB Variables Distribution by Group

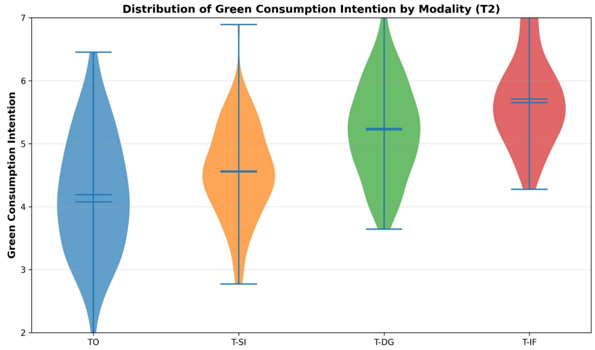

Fig. 7. Violin Plot of Attitude Distribution at T2

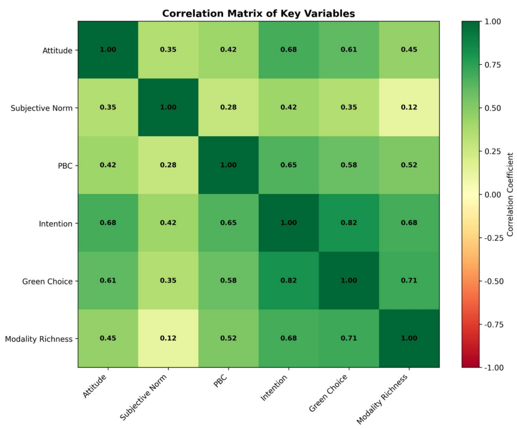

Fig. 8. Heatmap of Correlations Between Variables

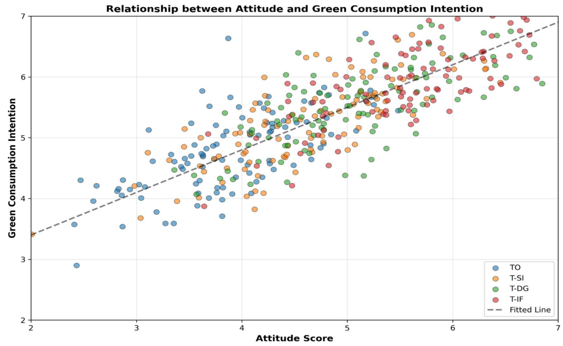

Fig. 9. Scatter Plot of Intention vs. Behavior

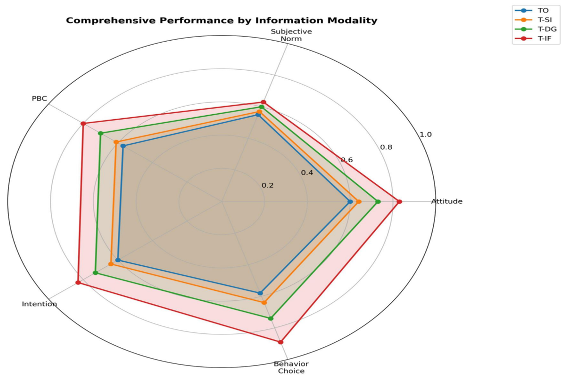

Fig. 10. Radar Chart for Multidimensional Comparison of Groups

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AVAILABILITY OF DATA

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AUTHOR CONTRIBUTIONS

Guanfeng Li contributed to conceptualization, methodology, software development, formal analysis, and writing — original draft preparation, and also oversaw supervision and project administration. Jingwen Wang contributed to investigation, data curation, validation, visualization, and writing.

COMPETING INTERESTS

The authors declare no competing interests.

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