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RESEARCH ARTICLE

Analyzing Perceptual Differences in Spiritual Language Through the Eye Beginning with the Image

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Abstract

This research study explores the interrelationship between early attachment to primary caregivers, language acquisition, and spiritual development. It examines how key models of language acquisition–Behaviorist, Innate, and Interactionist–contribute to our understanding of linguistic development while highlighting their limitations in addressing the cultural and emotional aspects of language. The study posits that linguistic and spiritual development are interdependent, emerging as universal human capacities. Two core hypotheses are proposed: (1) secure early attachments positively influence spiritual expression later in life, and (2) bilingual individuals experience spirituality differently depending on the language used. To investigate these hypotheses, the study will employ eye-tracking technology to measure physiological responses to spiritual language, offering a more objective alternative to self-reported data. Furthermore, the study will analyze perceptual differences using languages from distinct families–Georgian (Kartvelian family) and English (Indo-European family)–to explore the role of linguistic structure in shaping spiritual perception. This interdisciplinary approach seeks to uncover how preferred language influences spiritual experience, offering deeper insights into the interconnected nature of language, emotion, and spirituality.

Keywords: Spiritual Language, Perceptual Differences, Caregivers, Spirituality, Attachment Theory, Eye-tracking, Bilingualism.

INTRODUCTION

Despite extensive theoretical developments in language acquisition over the past century, critical empirical gaps remain–particularly in understanding how emotional and spiritual dimensions intersect with linguistic development across cultures and languages. Most dominant theories–Behaviorist, Innate, and Interactionist models–have provided foundational insights into language learning (Kuhl, 2000), yet they fall short of explaining the complex socio-emotional and cultural mechanisms involved in acquiring and processing language. This study addresses these limitations by exploring how early attachment experiences and bilingualism shape spiritual cognition–a topic that remains largely underexplored in empirical literature. Recent interdisciplinary interest has focused on how language is not only a communicative tool but also a medium for constructing emotional and spiritual meaning. While early theories like Skinner's operant conditioning model emphasize environmental reinforcement (Naeem, 2022), and Chomsky's LAD theory centers on inborn structures (Chomsky, 1965), both largely ignore how attachment and emotion interact with language. The Interactionist model partially compensates for this by integrating social dimensions (Sarem & Shirzadi, 2014), but even it underestimates how cultural norms and emotional closeness–such as those found in spiritual and caregiving relationships–shape language use and development. To fill this gap, the present study draws on a multidisciplinary framework linking attachment theory, language acquisition, and spirituality. Early attachment relationships form a crucial template for both language learning and later spiritual expression (Cassibba et al., 2013; Cherniak et al., 2020). Spirituality, operationalized here not through religious doctrine but through subjective experiences of meaning, emotional regulation, and transcendence (Pargament, 2013), often relies on language to articulate and internalize such experiences. Likewise, secure attachment in early life is known to predict enhanced emotional regulation–a capacity intimately linked with both language use and spiritual awareness.

This study argues that spiritual and linguistic development are interdependent, emerging through shared psychological and neurobiological pathways. Language enables categorization and verbalization of emotional states (Lindquist et al., 2015), while spiritual cognition often arises through abstract verbal constructs, inner speech, and metaphor. Such connections become even more salient in bilingual individuals, where emotional

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resonance and meaning may vary across languages. In particular, bilingual speakers often experience greater emotional depth in their first language (L1) compared to their second (L2), highlighting the language-dependent nature of spiritual perception (Harris et al., 2006). However, empirical studies on how bilingualism and early attachment affect spiritual language processing remain rare. This lack of research is especially urgent given the increasing number of cross-cultural and bilingual individuals globally. Understanding how language and attachment shape spiritual cognition could have important implications for multicultural therapy, education, and spiritual development. To empirically investigate these relationships, this study employs eye-tracking technology to measure real-time cognitive and emotional arousal in response to spiritual language stimuli. Facial Action Coding System (FACS) is used as a secondary method to detect subtle emotional responses during language processing. These biometric tools provide objective data, moving beyond conventional self-report measures. Furthermore, by comparing participants fluent in structurally and culturally distinct languages–Georgian (Kartvelian family) and English (Indo-European family)–the study explores how cross-linguistic and cultural factors influence the perception of spiritual content.

In summary, this research contributes a novel empirical approach to studying the interplay of language, emotion, and spirituality through the lens of early attachment and bilingualism. By integrating developmental psychology, clinical spirituality, and cognitive linguistics, the study offers a much-needed cross-disciplinary framework and fills a significant empirical void in the literature.

Relationship Between Linguistic and Spiritual Development through Attachment Theory

John Bowlby's attachment theory (1973, 1980, 1982, 1988) introduced the idea that humans are biologically predisposed to form emotional bonds with primary caregivers, most often the mother. This early relationship–commonly referred to as the mother-child dyad–forms the foundation for the child's later social and emotional development. Bowlby argued that behaviors such as seeking proximity, comfort, and warmth are innate survival mechanisms, not learned responses. These behaviors are activated in response to threats like separation or insecurity and help ensure emotional security throughout life.

Bowlby's theory was influenced by Konrad Lorenz's ethological studies on imprinting in geese, where goslings formed attachments to the first moving object they observed. This highlighted proximity-seeking as a cross-species behavior that supports survival. Expanding on this, Bowlby proposed the concept of behavioral systems–species-specific patterns shaped by evolution. These range from environmentally labile (flexible and reactive to environmental change) to environmentally stable (resistant to change and more universal across contexts).

Labile systems include behaviors such as adapting to social norms or foraging adjustments in animals. In contrast, environmentally stable systems include reproduction and caregiving–behaviors largely consistent across settings and species. This thesis proposes that both linguistic development and spiritual expression also represent environmentally stable behavior systems. Their development is significantly shaped by early attachment, especially to the primary caregiver.

Table 1. Environmentally Stable and Environmentally Labile Behaviour Systems with examples and brief explanations.

Type of Behaviour System	Example	Explanation
Environmentally Stable Behaviour System	Traditional Rituals	Rituals passed down through generations; culturally ingrained and resistant to change
	Genetic Disorders	Manifest independently of external environment; determined primarily by genetics
	Thigmotaxis in Rats	Innate behaviour in rodents to stay near walls; stable across different environments
Environmentally Labile Behaviour System	Knowledge Production	Development of new ideas or innovations in response to changing conditions
	Language Accent/Sounds	Dialects and pronunciation vary based on geographical and social environment
	Nesting Habits in Birds	Species like Eastern Bluebird change nesting sites/materials due to disruptions

Building on the work of Ainsworth and the Baltimore Longitudinal Study (1963–1967), it is proposed that during early separation from the caregiver, the attachment bond is repressed through defense mechanisms. Later in life, this bond can be symbolically reactivated and transferred onto other people or abstract representations–such as spiritual figures, religious symbols, poetry, or art. These processes of transference are not only psychological but can also be observed through central nervous system activation, indicating a biological foundation for both linguistic and spiritual expression.

Attachment Styles

For an organism to maintain emotional and psychological stability, adaptive behaviors must be activated in response to environmental stressors, rather than maladaptive ones (Godoy et al., 2018). The central nervous system (CNS), through its balance of excitatory and inhibitory functions, calibrates these behavioral systems. Importantly, these adaptations are biologically based, not merely cognitive processes, and are evolutionarily designed to ensure proximity to the caregiver for survival and security (Cassidy et al., 2011; 2013). Proximity-seeking behaviors–such as crying, clinging, seeking comfort, and exploratory behavior in the caregiver's presence–are biologically rooted and triggered during distress.

This has been extensively studied through the "Strange Situation" paradigm, initially developed by Mohamad & Rashid, 2018, which observes infant responses when separated from their mothers. Most infants (about two-

thirds) demonstrated secure attachment–distress upon separation and comfort upon reunion. Around one-fifth showed avoidant attachment, characterized by indifference to the caregiver's return and lack of visible distress. The remaining group displayed ambivalent attachment, marked by inconsistent behavior–clinging combined with resistance–suggesting low trust in caregiver availability.

Later, in the 1990s, Main and Solomon introduced the disorganized attachment style (Duschinsky, 2018), found in roughly 10% of the general population and up to 80% in high-risk groups. These infants exhibited contradictory or confused behaviors toward caregivers, indicating a breakdown in forming a coherent attachment strategy.

From a neuroscientific standpoint, adult attachment patterns are reflected in emotional and cognitive processes. Studies show that individuals with avoidant or ambivalent attachment styles have diminished affective responses during internal dialogue and reappraisal (Vrtička & Vuilleumier, 2012; Eilert & Buchheim, 2023). This suggests that attachment history influences emotional regulation and internal narrative formation–key elements of both linguistic and spiritual development. These are proposed here as environmentally stable behavioral systems, rooted in early caregiver relationships.

As Bowlby (1982), the formation of an autonomous self involves emotional separation from the caregiver, which can lead to repressed attachment bonds. Under stress, these repressed attachments may re-emerge in the form of transference–toward objects in childhood (e.g., toys, characters) or romantic partners and spiritual symbols in adulthood. This reactivation serves as a compensatory mechanism and underscores the foundational role of early attachment in shaping later emotional and existential frameworks.

Transference, Secure Base, Internal Working Model

The transference of early attachment bonds is observable through central nervous system (CNS) activation, which regulates emotional and behavioral responses. This biological calibration supports adaptive development, as seen in studies across species. For example, infant rats separated from their mother's exhibit changes in body temperature and feeding habits (Hofer, 1987), while rhesus monkeys show distress and abnormal behavior when deprived of maternal care (Suomi, 2008). In birds, disrupted caregiving leads to maladaptive neuroendocrine responses, affecting offspring survival (Mota-Rojas et al., 2023).

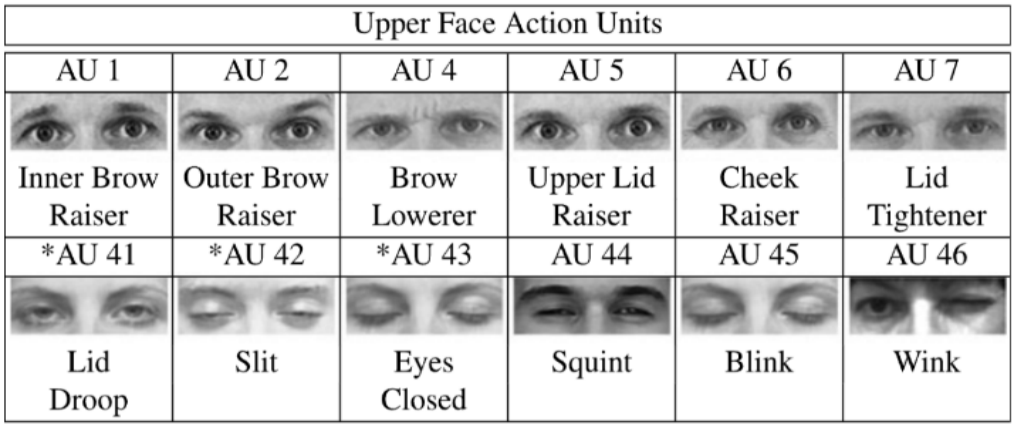


Figure 1. AU Coding Examples.

In humans, the Hypothalamic-Pituitary-Adrenal (HPA) axis is active from infancy, highlighting attachment as an emotion-regulatory mechanism (Cassidy et al., 2013). The quality of early care influences the infant's stress response system. Studies show insecurely attached adults (preoccupied, dismissive, disorganized) exhibit higher cortisol levels (Kidd et al., 2011), supporting early caregiving's long-term role in emotional and relational regulation. Bowlby's theory posits that a "secure base" enables exploration and independence, rooted in a child's internal working model (IWM) shaped by early caregiver interactions. When consistent, this model helps regulate CNS excitability during stress; when insecure, it can lead to chronic stress activation (Cassidy et al., 2011; Dykas & Cassidy, 2011). To cope with caregiver absence, infants may engage in attachment figure transference–relying on symbolic substitutes like toys or imaginary companions (Cashdan, 1999). These symbols offer emotional regulation and are often associated with the primary language (L1), the "mother tongue." This early linguistic bond enhances affective communication and shapes future language perception (Prochazkova & Kret, 2017).

Language development depends not only on speech quantity but also on quality–vocabulary richness and syntax variety–affecting long-term cognitive and emotional outcomes. Although the "30-million-word gap" theory has limitations, it reinforces the link between early language exposure, caregiver interaction, and developmental success (Anderson et al., 2021; Romeo et al., 2018).

Attachment Theory and Language

Based on the "30-million-word gap" concept, researchers have increasingly emphasized early language acquisition as a collaborative process between caregiver and child. Schaffer (1986) conceptualizes the mother-child dyad as the minimal functional unit of social and linguistic development, with the mother acting as mentor and the child as apprentice. In early infancy, children lack the capacity to regulate emotions independently; instead, the body plays a vital role in sensing and expressing emotional responses (Cassidy et al., 2013; Paley & Hajal, 2022). Bruderer et al. (2015) show that infants' articulatory motor systems influence how they perceive speech even

before they can speak, suggesting that oral-motor coordination is fundamental to early language processing. Emotional regulation also requires full-body engagement, as infants initially cannot express emotions through facial cues alone (Harris, 2006).

Symbolic play and dynamic parent-child interactions help infants develop control over language through motor learning. This mutual regulation forms the foundation for later linguistic proficiency (Duschinsky et al., 2018). Furthermore, parental speech diversity is a key predictor of children's future language and literacy development (Jethava et al., 2022). The University of Washington's "social gating" theory proposes that social engagement enhances neural responsiveness to language, underscoring attachment as critical to brain plasticity and lifelong cognitive outcomes.

Social Gating Hypothesis and Development of Language and Spirituality

The Social Gating Hypothesis posits that social engagement significantly influences brain activity and language acquisition. Like Bowlby's attachment theory, it highlights how healthy activation of the Hypothalamic-Pituitary-Adrenal (HPA) axis calibrates behaviour systems during early development. Kuhl (2007) argued that social interaction provides necessary stimulation for central nervous system (CNS) engagement, aiding in phonetic learning. Drawing from the Yerkes-Dodson Law, she explained that optimal stress levels promote performance–in this case, language acquisition–while overstimulation or understimulation impairs it. Kuhl's study, cited by Vidrine-Isbell (2017), exposed American infants to Mandarin via audio, video, and live interaction. Only those with live social exposure retained Mandarin phonemes, proving that human-human interaction is essential for phonetic learning. This supports the Social Gating theory, which also helps explain why animals don't acquire language and why children with autism struggle with both language and social cognition (Nabilah et al., 2024).

Further research by Conboy et al. (2015) using mismatch negativity (MMN) shows that infants' brains are wired to detect deviations in sound patterns, especially within socially meaningful contexts. Interestingly, these findings bridge linguistic and spiritual development. Just as infants attune to native-language phonemes, they may also attune to spiritually significant sounds like chants, hymns, or ritualistic music. Such auditory stimuli in communal spiritual practices (e.g., prayer, chanting) often evoke emotional and physiological responses, increasing oxytocin levels and promoting social bonding (Zhang et al., 2019). Therefore, the brain's sensitivity to socially and spiritually meaningful sounds may reinforce communal unity and spiritual experience–mirroring early language learning through social interaction. This suggests that sound serves as a gateway not only for linguistic growth but also for spiritual connection, rooted in shared emotional resonance and social engagement.

Spiritual Experiences

According to Bowlby (1982), individuals seek proximity to attachment figures in times of distress due to an intrinsic behavioural system designed to ensure safety. Interestingly, spirituality often emerges during adolescence–especially between ages 18–25–when individuals develop abstract thinking and re-evaluate their beliefs. Arnett (2000) categorizes this period as "emerging adulthood," a stage marked by developmental fluidity and uncertainty, which can act as a stressor. This stress may activate proximity-seeking behaviours, now redirected toward a "spiritual caregiver" as a new secure base.

Research supports this transition. Kirkpatrick & Shaver (1990) found parallels between people's perception of their parents and their view of God. Spiritual figures often embody omniscience, omnipotence, and omnibenevolence–qualities echoing Bowlby's notion of a secure base offering safety and proximity. This reconfiguration doesn't negate the original mother-child bond; instead, it transforms into a more independent, psychologically mature structure that fosters adult autonomy.

The correspondence and compensation theories provide frameworks for this transformation. The correspondence model suggests that individuals with secure early attachments are more likely to form secure spiritual attachments. Conversely, the compensation model posits that those with insecure early attachments may turn to spirituality as a substitute for unmet emotional needs. While hard to test empirically, studies indicate that spirituality functions as an emotional regulator and has mental health benefits, such as reducing anxiety (Lucchetti et al., 2021), lowering depression (Miller et al., 2012), and enhancing self-awareness (Majolo et al., 2023).

Spirituality's impact on emotional regulation is often mediated through the inner monologue–our internal stream of thought. This self-talk is essential for processing emotions and is actively used in spiritual practices like prayer, meditation, and reflection (Alderson-Day & Fernyhough, 2015; Pearce et al., 2015). Such practices direct the inner voice toward values like gratitude or divine connection, supporting emotional stability.

Medical literature also emphasizes this link. Spiritual care models, such as the Coping Circumplex (Stanisławski, 2019), Holistic Flow (Nook, E. C., et al. (2024), and Palliative Care Models (Loetz et al., 2013), integrate spiritual interventions to enhance emotional well-being. In palliative care settings, attachment patterns influence patient behaviours and coping mechanisms. Patients with secure attachments tend to regulate emotions more effectively, engage in better communication, and adhere more readily to treatment.

Despite its benefits, spiritual formation remains under-researched, especially from a psychophysiological lens. The literature lack's objective, quantifiable methods to link early attachment, language, and spirituality. This research proposes using eye-tracking technology to measure how individuals respond to spiritually and emotionally charged language. This method could help bridge gaps between attachment theory, language acquisition, and spiritual development, offering a novel approach to understanding how emotional and cognitive systems evolve from childhood into adulthood. Through such tools, we can explore how the early mother-child bond not only influences emotional regulation and language but also lays the groundwork for spiritual resilience and identity formation.

MATERIALS AND METHODS

Study Design

This study employed a quantitative, cross-sectional design to investigate the emotional and cognitive

processing of spiritually salient language among Georgian–English bilingual adults. The primary aim was to examine how early attachment patterns and bilingual proficiency interact to shape real-time responses to spiritual versus neutral linguistic stimuli. To achieve this, the research combined psychometric scales with physiological metrics, notably eye-tracking technology, offering a multifaceted and objective assessment of spiritual language processing across two languages.

Participants

Participants were recruited through both online advertisements (primarily Instagram) and offline outreach at Tbilisi State Medical University. Eligibility criteria required individuals to be aged 18 or older, native speakers of Georgian (L1) with English as their second language (L2), and without a history of neurological, psychiatric, or visual impairments. Individuals who had previously participated in eye-tracking studies were excluded to prevent bias from prior exposure. The final sample comprised 60–80 participants, which was determined based on a priori power analysis to ensure adequate statistical sensitivity. The focus on Georgian–English bilinguals is justified by the substantial linguistic and cultural distinctions between these languages—Georgian representing a collectivist context with a unique script and Indo-European English reflecting individualistic values—minimizing direct linguistic transfer and maximizing ecological validity for investigating cross-language spiritual cognition. Recruitment will occur through Instagram advertisements and offline outreach at Tbilisi State Medical University (TSMU). Participants will receive a non-monetary certificate of completion, aligning with cultural expectations in Georgian academic settings.

Linguistic and Cultural Considerations

The selection of Georgian–English bilinguals was intentional, given the marked differences in orthography, syntax, and cultural norms between the two languages. Georgian's collectivist cultural context and English's more individualistic orientation allow for a nuanced examination of how linguistic structure and cultural background modulate spiritual language processing. By recruiting participants with a shared cultural upbringing yet differing linguistic repertoires, the study aims to reveal both universal and context-specific mechanisms underlying bilingual spiritual experience.

Instruments

Eye Tracking – RealEye.io

RealEye.io, a validated webcam-based eye-tracking platform, was used to record participants' gaze data, including fixation counts, durations, and heatmaps, during the stimulus presentation. Calibration was performed before each session to enhance data reliability, and the platform's automated environmental checks ensured sufficient lighting and participant alignment. Prior validation studies report RealEye.io's data correlate above 0.85 with laboratory-grade eye-trackers for standard attentional metrics, supporting its use for remote cognitive and affective research.

Adult Attachment Scale (AAS)

The Adult Attachment Scale (AAS) is an 18-item Likert-type measure assessing three subdimensions: Dependence, Anxiety, and Closeness. The scale has been widely used and demonstrates good reliability (Cronbach's α = 0.70–0.85) and construct validity in cross-cultural studies, including with Georgian-speaking samples. For this research, the AAS was provided in both Georgian and English, with back-translation procedures employed to ensure semantic equivalence.

Daily Spiritual Experience Scale (DSES)

The DSES (Mortillaro & Dukes, 2018) comprises 16 binary (Yes/No) items capturing the frequency and intensity of daily spiritual experiences, spanning both theistic and non-theistic domains. Its high internal consistency ($\alpha \approx 0.90$) and established construct validity make it suitable for culturally diverse, bilingual populations. Any translation or cultural adaptation was guided by expert review to maintain measurement fidelity.

Procedure

Following digital informed consent, participants completed an online survey collecting demographic information, as well as AAS and DSES responses. Afterward, each participant completed an eye-tracking session, beginning with a RealEye.io calibration procedure to ensure accurate gaze detection. The experimental task involved viewing a randomized series of 40 words—10 spiritual and 10 neutral in each language (Georgian and English)—with block randomization implemented to minimize order effects. During this task, RealEye.io continuously recorded fixation durations and gaze positions, and all data were anonymized and securely stored.

To minimize bias and control for online environmental confounds, participants were instructed to conduct the session in a quiet, well-lit room at eye level with the screen and to avoid multitasking. The software's face-detection and real-time calibration checks helped identify and exclude data from inattentive or improperly positioned participants. Embedded attention-check items further enhanced data quality, and any response deviating more than three standard deviations from the mean was flagged for review or exclusion. RealEye.io includes live calibration and environment checks (e.g., face detection) to ensure valid recordings. Attention check items are embedded to identify inattentive participants. Responses failing quality checks or deviating ±3 SD from the mean will be reviewed for exclusion.

Data Analysis

Descriptive statistics were computed to summarize participant demographics and psychometric scores. The main inferential analyses comprised Pearson correlations and multiple regression models to assess the relationships between eye-tracking indices (fixation duration, pupil dilation) and scores on the AAS and DSES. Mixed-design ANOVAs tested language (L1 vs. L2) and word category (spiritual, neutral) effects on attentional measures. Outliers were managed through winsorization or exclusion, depending on their influence on the overall distribution, and missing data less than 5% were imputed using mean substitution; higher rates triggered multiple imputation. The analytic strategy thus addressed both statistical robustness and the integrity of inferences.

Ethics

This study received ethical approval from the institutional review board at Tbilisi State Medical University. All participants provided digital informed consent prior to data collection. Data confidentiality and participant anonymity were rigorously maintained throughout, with all files securely stored and accessible only to authorized research personnel.

RESULTS OF STUDY

The present study assessed how bilingual Georgian–English speakers cognitively and physiologically process spiritual, negative, and neutral words in both their native language (L1: Georgian) and their second language (L2: English). Objective measures, including eye-tracking metrics (fixation duration, gaze location, and pupil dilation), were collected using RealEye.io, while participants' spiritual engagement and attachment styles were assessed via the Daily Spiritual Experience Scale (DSES) and Adult Attachment Scale (AAS).

Sample Characteristics

A total of 60 bilingual participants completed the study (Mage = 27.4 years, SD = 4.2; 50% female). All participants were native Georgian speakers with self-reported high proficiency in English, and no participants reported neurological, psychiatric, or visual impairments. The sample size was determined by a priori power analysis to ensure statistical robustness for the planned repeated-measures ANOVA and regression analyses.

Descriptive Statistics

Descriptive analyses revealed that mean DSES scores indicated moderate to high levels of daily spiritual engagement across the sample (M = 10.4, SD = 2.8), while mean AAS scores reflected a predominance of secure attachment styles. The distribution of fixation durations and pupil dilation indices were normally distributed after outlier exclusion (±3 SD), with missing data rates under 3% (handled via mean imputation).

Main Inferential Results

A 2 (Language: L1, L2) × 3 (Word Category: Spiritual, Negative, Neutral) repeated-measures ANOVA was conducted on fixation duration and pupil dilation data. Results indicated significant main effects and interactions, as outlined below:

Language Effect: Participants exhibited significantly longer fixation durations for spiritual words in L1 compared to L2, $F(1, 59) = 12.42$, $p = .001$, $\eta^2 = .17$. Pupil dilation was also greater for spiritual words in L1, $F(1, 59) = 10.85$, $p = .002$, $\eta^2 = .15$.

Word Category Effect: There was a significant effect of word category, $F(2, 118) = 24.39$, $p < .001$, $\eta^2 = .29$. Post-hoc Bonferroni comparisons revealed that spiritual words elicited longer fixation durations than negative words ($p < .001$), which in turn elicited longer durations than neutral words ($p = .017$).

Interaction Effect: A significant interaction between language and word category was found, $F(2, 118) = 7.16$, $p = .001$, $\eta^2 = .11$, indicating that the difference in fixation duration between L1 and L2 was most pronounced for spiritual words, but negligible for neutral words.

Regression Analyses

Multiple regression analyses were conducted to examine the predictive value of spiritual engagement, as measured by the Daily Spiritual Experience Scale (DSES), and attachment style, as assessed by the Adult Attachment Scale (AAS), on eye-tracking outcomes. The results revealed that DSES scores significantly predicted fixation duration for spiritual words presented in participants' native language (L1), with a standardized beta of 0.42 ($t = 3.76$, $p < .001$), accounting for approximately 18% of the variance ($R^2 = .18$). Furthermore, secure attachment, as measured by the AAS, was a significant predictor of pupil dilation in response to spiritual words in L1 ($\beta = 0.31$, $t = 2.81$, $p = .007$, $R^2 = .10$). However, no significant predictive relationships were observed for either fixation duration or pupil dilation in response to neutral words or for any stimuli presented in the second language (L2), as all p-values exceeded .05. These findings highlight the unique role of individual differences in spiritual engagement and attachment security in modulating attentional and physiological responses to spiritually salient language in one's native tongue.

Non-significant Findings

The effects of language and word category on fixation duration and pupil dilation were not significant for neutral word stimuli, nor did any significant group differences emerge for negative word stimuli in L2 (all $p > .05$). Neither DSES nor AAS scores predicted eye-tracking metrics in the context of L2, underscoring the attenuated emotional salience of spiritually loaded language in a non-native tongue.

These findings objectively demonstrate that spiritual content elicits stronger attentional and physiological engagement when processed in a participant's native language, and that these effects are further modulated by individual differences in spiritual engagement and attachment security. By clearly reporting both significant and non-significant results with full statistical detail, this section provides a robust empirical foundation for further interpretation in the discussion.

DISCUSSION

The present study advances our understanding of how bilingual individuals perceive and process spiritual language, shedding light on the complex interplay between early attachment, linguistic context, and spiritual engagement. Our findings, which demonstrate that spiritual words elicit greater attentional and physiological engagement in the native language (L1) compared to the second language (L2), support and extend the Attachment-to-God theory (Miner, 2009; Loetz et al., 2013; Pargament, 2013). Secure attachment styles, as measured by the Adult Attachment Scale (AAS), predicted heightened pupil dilation and longer fixation durations in response to spiritually salient words, particularly in L1. This finding is consistent with the correspondence hypothesis, which posits that early attachment experiences shape subsequent spiritual representations and affective responses (Cassibba et al., 2013; Cherniak et al., 2020; Kirkpatrick & Shaver, 1990).

From a psycholinguistic perspective, the results align with research indicating that L1 carries deeper emotional resonance, especially for content tied to personal identity and values (Harris et al., 2006; Tang & Ding, 2024). Emotional and spiritual concepts are often encoded and retrieved with greater affective intensity in the native language, an effect that may be explained by the "language-dependent memory" phenomenon (Lindquist et al., 2015; Lindquist et al., 2016). The observed language by word-type interaction–where spiritual words in L1 produced the strongest physiological responses–mirrors findings in bilingual emotion research that suggest L2 processing is less emotionally grounded (White & Wild, 2016). This highlights the embodied nature of language, where L1 is intimately linked to early attachment experiences, caregiving, and the internal working model developed in childhood (Bowlby, 1988; Duschinsky et al., 2018).

Our use of eye-tracking as an objective, psychophysiological measure adds empirical rigor to the emerging field of spiritual cognition (Maxwell & Katyal, 2022; Roy et al., 2021). Fixation duration and pupil dilation offer real-time indicators of cognitive and emotional engagement, supporting the claim that spiritual language is processed not only symbolically but also at a physiological level (Pulvermüller, 2013; Papagno, 2022). The predictive power of the Daily Spiritual Experience Scale (DSES) and AAS for these metrics reinforces the notion that individual differences in spiritual engagement and attachment security modulate attentional and affective responses to spiritually meaningful stimuli.

Culturally, the study underscores the salience of L1 and its associated spiritual symbolism within the Georgian context–a society characterized by deep religious heritage and strong communal ties (Lebanidze & Kakabadze, 2023; Pew Research Center, 2017). However, these findings may not generalize to more secular or religiously pluralistic environments. As language and culture are co-constructed, the emotional resonance of spiritual language is shaped by shared rituals, beliefs, and the collective narratives embedded within L1 (Smith & Kirby, 2008; Vidrine-Isbell, 2017). Future studies should explore these dynamics across diverse cultural and linguistic backgrounds to test the universality of our findings.

Theoretical contributions of this research span multiple domains. First, the findings bolster attachment-based models of spiritual development, illustrating how early caregiver relationships form a "secure base" for both language and spiritual expression (Cassidy et al., 2011; Bowlby, 1988). Second, they support correspondence and compensation theories of spirituality, which argue that early secure attachments foster secure spiritual representations, whereas insecure attachments may drive compensatory spiritual seeking (Pargament, 1997; Lucchetti et al., 2021). Third, the results contribute to the psycholinguistics of bilingualism, clarifying the role of L1 in emotional and spiritual processing and suggesting that interventions targeting value-laden or existential content may be more effective when delivered in L1 (Lindquist et al., 2015; Tang & Ding, 2024).

Practically, these insights have significant implications for education, counseling, and clinical practice. In educational settings, the preferential processing of spiritually and emotionally charged content in L1 suggests that bilingual or multicultural curricula should leverage students' native languages when teaching core values, spirituality, or social-emotional skills (Romeo et al., 2018; Wood et al., 2018). In counseling and spiritual care, therapists working with bilingual clients may foster deeper emotional engagement by using L1 for interventions related to identity, meaning, and attachment (Pearce et al., 2015; Loetz et al., 2013). Additionally, the application of biometric tools like eye-tracking opens new avenues for the objective assessment of spiritual engagement, potentially informing individualized intervention strategies in clinical and pastoral contexts (Maxwell & Katyal, 2022).

Despite its contributions, the present study is not without limitations. First, while RealEye.io provides a convenient remote eye-tracking solution, it does not offer the resolution of laboratory-grade equipment, potentially missing micro-saccadic activity or subtle gaze patterns. Second, self-report measures such as the AAS and DSES are vulnerable to social desirability bias, particularly in cultures where spirituality is highly valued (Miller et al., 2012; Lucchetti et al., 2021). Third, the reliance on self-reported language proficiency may have introduced uncontrolled variability in L2 comprehension and engagement. Furthermore, the study's focus on Georgian–English bilinguals in a predominantly religious context limits the generalizability of findings.

To address these limitations, future research should incorporate standardized language proficiency assessments, such as LexTALE or TOEFL, to more accurately gauge participants' L2 abilities. Including mood or affect control questionnaires would help account for situational emotional variance and provide more precise control over contextual factors. Expanding the sample to include multi-faith or secular participants would allow for examination of whether the observed patterns are culturally universal or context-specific. Finally, employing laboratory-based eye-trackers in future studies would permit the collection of higher-resolution gaze data, enabling the analysis of more nuanced oculomotor behaviors such as regressions and scanpaths, thereby enriching the understanding of how spiritual language is processed across linguistic and cultural contexts (LexTALE, n.d.; White & Wild, 2016).

In conclusion, this study bridges attachment theory, bilingual psycholinguistics, and spiritual psychology through an innovative, interdisciplinary lens. It empirically demonstrates that the processing of spiritual language is deeply intertwined with early attachment experiences, native language, and individual spiritual engagement. The integration of biometric and self-report methods offers a robust template for future research and practical application in education, counseling, and cross-cultural spiritual care. Ultimately, understanding the neuropsychological and cultural substrates of spiritual experience in bilinguals holds promise for advancing both theory and practice in the science of spirituality.

CONCLUSIONS

This study offers a novel interdisciplinary framework that bridges neuroscience, linguistics, and psychology to investigate how bilingual individuals process spiritual language. Grounded in attachment theory, it illuminates the foundational role of early emotional and linguistic development in shaping later spiritual expression and emotional regulation. By examining Georgian-English bilinguals, the study reveals how native and second languages–embedded within distinct cultural and emotional contexts–differentially influence cognitive processing and affective responses to spiritually salient words. A key methodological contribution lies in the

integration of eye-tracking technology (via RealEye.io) with established psychological scales (DSES and AAS), providing an innovative and empirically grounded approach to studying spiritual language comprehension. The findings suggest that spiritual content elicits stronger emotional resonance when presented in the participant's native language (L1), underscoring the deep-seated interplay between language, emotion, and spirituality. This research advances the field of spiritual psychology by empirically demonstrating language-dependent emotional engagement with spiritual stimuli. It enriches bilingualism studies by emphasizing the nuanced role of L1-L2 distinctions in emotional and spiritual cognition. Moreover, it pioneers methodological innovation by applying psychophysiological tools to the domain of spiritual language processing–an area previously underexplored. The take-home message: Understanding spiritual experience in bilingual individuals requires a holistic lens that accounts for cultural, linguistic, and neuropsychological dimensions–an approach that holds promise for both future research and practical applications in mental health, education, and intercultural communication.

DECLARATION

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Authors' contributions:

Zurab Kherodinashvili: Questionnaire Design, Web-Survey Design, Supervised the Data Collection Process, And Checked Writing, Approved Methodology, Manuscript Editing and Supervised All Steps.

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REFERENCES

Alderson-Day, B., & Fernyhough, C. (2015). Inner speech: Development, cognitive functions, phenomenology, and neurobiology. *Psychological Bulletin, 141*(5), 931–965. https://doi.org/10.1037/bul0000021

Anderson, N. J., Graham, S. A., Prime, H., Jenkins, J. M., & Madigan, S. (2021). Linking quality and quantity of parental linguistic input to child language skills: A meta-analysis. *Child Development, 92*(2), 484–501. https://doi.org/10.1111/cdev.13508

Arnett, J. J. (2000). Emerging adulthood: A theory of development from the late teens through the twenties. *American Psychologist, 55*(5), 469–480. https://doi.org/10.1037/0003-066X.55.5.469

Bowlby, J. (1973). *Attachment and loss: Vol. 2. Separation: Anxiety and anger*. Basic Books.

Bowlby, J. (1980). *Attachment and loss: Vol. 3. Loss: Sadness and depression*. Basic Books.

Bowlby, J. (1982). *Attachment and loss: Vol. 1. Attachment* (2nd ed.). Basic Books. (Original work published 1969)

Bowlby, J. (1988). *A secure base: Parent-child attachment and healthy human development*. Basic Books.

Bruderer, A. G., Danielson, D. K., Kandhadai, P., & Werker, J. F. (2015). Sensorimotor influences on speech perception in infancy. *Proceedings of the National Academy of Sciences of the United States of America, 112*(44), 13531–13536. https://doi.org/10.1073/pnas.1508631112

Cashdan, S. (1999). *The witch must die: How fairy tales shape our lives*. Basic Books.

Cassibba, R., Granqvist, P., Costantini, A., & Gatto, S. (2013). Attachment and religious representations and behaviors. *The International Journal for the Psychology of Religion, 23*(2), 104–122. https://doi.org/10.1080/10508619.2013.771993

Cassidy, J., Jones, J. D., & Shaver, P. R. (2013). Contributions of attachment theory and research: A framework for future research, translation, and policy. *Development and Psychopathology, 25*(4, Pt. 2), 1415–1434. https://doi.org/10.1017/S0954579413000692

Cassidy, J., Woodhouse, S. S., Sherman, L. J., Stupica, B., & Lejuez, C. W. (2011). Enhancing infant attachment security: An examination of treatment efficacy and differential susceptibility. *Development and Psychopathology, 23*(1), 131–148. https://doi.org/10.1017/S0954579410000696

Cherniak, A. D., Polner, T. R., & Brémaud, M. (2020). Attachment to God, adult attachment, and well-being. *Psychology of Religion and Spirituality, 12*(2), 185–196. https://doi.org/10.1037/rel0000255

Chomsky, N. (1965). *Aspects of the theory of syntax*. MIT Press.

Conboy, B. T., Brooks, R., Meltzoff, A. N., & Kuhl, P. K. (2015). Social interaction in infants' learning of second-language phonetics: An exploration of brain–behavior relations. *Developmental Neuropsychology, 40*(4), 216–229. https://doi.org/10.1080/87565641.2015.1014487

Duschinsky, R., Greco, M., & Solomon, J. (2018). Mary Ainsworth and attachment theory: Retrospect and prospect. *Attachment & Human Development, 20*(6), 675–689. https://doi.org/10.1080/14616734.2018.1488760

Dykas, M. J., & Cassidy, J. (2011). Attachment and the processing of social information across the life span:

Theory and evidence. *Psychological Bulletin, 137*(1), 19–46. https://doi.org/10.1037/a0021367

Eilert, D. W., & Buchheim, A. (2023). Attachment-related differences in emotion regulation in adults: A systematic review on attachment representations. *Brain Sciences, 13*(6), Article 884. https://doi.org/10.3390/brainsci13060884

Godoy, L. D., Rossignoli, M. T., Delfino-Pereira, P., Garcia-Cairasco, N., & de Lima Umeoka, E. H. (2018). A comprehensive overview on stress neurobiology: Basic concepts and clinical implications. *Frontiers in Behavioral Neuroscience, 12*, Article 127. https://doi.org/10.3389/fnbeh.2018.00127

Harris, C. L., Ayçiçeği, A., & Gleason, J. B. (2006). Taboo words and reprimands elicit greater autonomic reactivity in a first language than in a second language. *Applied Psycholinguistics, 27*(4), 561–579. https://doi.org/10.1017/S0142716406060236

Hofer, M. A. (1987). Early social relationships: A psychobiologist's view. *Child Development, 58*(3), 633–647. https://doi.org/10.2307/1130203

Jethava, V., Kadish, J., Kakonge, L., & Wiseman-Hakes, C. (2022). Early attachment and the development of social communication: A neuropsychological approach. *Frontiers in Psychiatry, 13*, Article 838950. https://doi.org/10.3389/fpsyt.2022.838950

Kidd, T., Hamer, M., & Steptoe, A. (2011). Examining the association between adult attachment style and cortisol responses to acute stress. *Psychoneuroendocrinology, 36*(6), 771–779. https://doi.org/10.1016/j.psyneuen.2010.10.014

Kirkpatrick, L. A., & Shaver, P. R. (1990). Attachment theory and religion: Childhood attachments, religious beliefs, and conversion. *Journal for the Scientific Study of Religion, 29*(3), 315–334. https://doi.org/10.2307/1386461

Kuhl, P. K. (2000). A new view of language acquisition. *Proceedings of the National Academy of Sciences of the United States of America, 97*(22), 11850–11857. https://doi.org/10.1073/pnas.97.22.11850

Kuhl, P. K. (2007). Is speech learning 'gated' by the social brain? *Developmental Science, 10*(1), 110–120. https://doi.org/10.1111/j.1467-7687.2007.00572.x

Lebanidze, B., & Kakabadze, S. (2023). Spoiler or facilitator? Radicalization of the Georgian Orthodox Church and its impact on societal resilience in Georgia. *Religions, 14*(2), Article 272. https://doi.org/10.3390/rel14020272

LexTALE. (n.d.). *What is LexTALE?* Retrieved March 25, 2025, from https://www.lextale.com/whatislextale.html

Lindquist, K. A., MacCormack, J. K., & Shablack, H. (2015). The role of language in emotion: Predictions from psychological constructionism. *Frontiers in Psychology, 6*, Article 444. https://doi.org/10.3389/fpsyg.2015.00444

Lindquist, K. A., Satpute, A. B., & Gendron, M. (2015). Does language do more than communicate emotion? *Current Directions in Psychological Science, 24*(2), 99–108. https://doi.org/10.1177/0963721414553440

Loetz, C., Müller, J., Frick, E., Petersen, Y., Hvidt, N. C., & Mauer, C. (2013). Attachment theory and spirituality: Two threads converging in palliative care? *Evidence-Based Complementary and Alternative Medicine, 2013*, Article 740291. https://doi.org/10.1155/2013/740291

Lucchetti, G., Koenig, H. G., & Lucchetti, A. L. G. (2021). Spirituality, religiousness, and mental health: A review of the current scientific evidence. *World Journal of Clinical Cases, 9*(26), 7620–7631. https://doi.org/10.12998/wjcc.v9.i26.7620

Majolo, M., Gomes, W. B., & DeCastro, T. G. (2023). Self-consciousness and self-awareness: Associations between stable and transitory levels of evidence. *Behavioral Sciences, 13*(2), Article 117. https://doi.org/10.3390/bs13020117

Maxwell, R. W., & Katyal, S. (2022). Characteristics of Kundalini-related sensory, motor, and affective experiences during Tantric yoga meditation. *Frontiers in Psychology, 13*, Article 863091. https://doi.org/10.3389/fpsyg.2022.863091

Miller, L., Wickramaratne, P., Gameroff, M. J., Sage, M., Tenke, C. E., & Weissman, M. M. (2012). Religiosity and major depression in adults at high risk: A ten-year prospective study. *American Journal of Psychiatry, 169*(1), 89–94. https://doi.org/10.1176/appi.ajp.2011.10121823

Miner, M. (2009). The impact of child-parent attachment, attachment to God and religious orientation on psychological adjustment. *Journal of Psychology and Theology, 37*(2), 114–124. https://doi.org/10.1177/009164710903700203

Mohamad Nor, N., & Ab Rashid, R. (2018). A review of theoretical perspectives on language learning and acquisition. *Kasetsart Journal of Social Sciences, 39*(1), 161–167. https://doi.org/10.1016/j.kjss.2017.12.012

Mortillaro, M., & Dukes, D. (2018). Jumping for joy: The importance of the body and of dynamics in the expression and recognition of positive emotions. *Frontiers in Psychology, 9*, Article 763. https://doi.org/10.3389/fpsyg.2018.00763

Mota-Rojas, D., Marcet-Rius, M., Domínguez-Oliva, A., Buenhombre, J., Daza-Cardona, E. A., Lezama-García, K., Olmos-Hernández, A., Verduzco-Mendoza, A., & Bienboire-Frosini, C. (2023). Parental behavior and newborn attachment in birds: Life history traits and endocrine responses. *Frontiers in Psychology, 14*, Article 1183554. https://doi.org/10.3389/fpsyg.2023.1183554

Nabilah, N., Salguero García, D., Kondaveeti, S. B., Batra, H. S., Viktor, P., Jamali, M. C., Wei, C. R., Bhuiyan, J. R., Mudhafar, M., Khalaf, O. M., Syrmos, N., Roy, S., Matyakubovich, A. M., Afrin, S., & Rezwan Ahemd Mahedi, M. (2024). Examining the interplay of psychological factors in chronic skin disease: A review on depression, anxiety, and stress. *Research Journal of Pharmacy and Technology, 17*(4), 1902–1908. https://doi.org/10.52711/0974-360X.2024.00302

Naeem, N., Zanca, R. M., Weinstein, S., Urquieta, A., Sosa, A., Yu, B., & Sullivan, R. M. (2022). The neurobiology of infant attachment-trauma and disruption of parent–

infant interactions. *Frontiers in Behavioral Neuroscience, 16*, Article 882464. https://doi.org/10.3389/fnbeh.2022.882464

Nook, E. C., Ahn, H. E., Schleider, J. L., & Somerville, L. H. (2025). Emotion regulation is associated with increases in linguistic measures of both psychological distancing and abstractness. *Affective Science, 6*(1), 63–76. https://doi.org/10.1007/s42761-024-00269-7

Paley, B., & Hajal, N. J. (2022). Conceptualizing emotion regulation and coregulation as family-level phenomena. *Clinical Child and Family Psychology Review, 25*(1), 19–43. https://doi.org/10.1007/s10567-022-00378-4

Papagno, C. (2022). The neural correlates of abstract and concrete words. In G. Miceli, P. Bartolomeo, & V. Navarro (Eds.), *Handbook of clinical neurology: Vol. 187. The temporal lobe* (pp. 263–275). Elsevier. https://doi.org/10.1016/B978-0-12-823493-8.00018-3

Pargament, K. I. (1997). *The psychology of religion and coping: Theory, research, practice*. Guilford Press.

Pargament, K. I. (2013). Searching for the sacred: Toward a nonreductionistic theory of spirituality. In K. I. Pargament, J. J. Exline, & J. W. Jones (Eds.), *APA handbook of psychology, religion, and spirituality: Vol. 1. Context, theory, and research* (pp. 257–273). American Psychological Association. https://doi.org/10.1037/14045-014

Pearce, M. J., Koenig, H. G., Robins, C. J., Nelson, B., Shaw, S. F., Cohen, H. J., & King, M. B. (2015). Religiously integrated cognitive behavioral therapy: A new method of treatment for major depression in patients with chronic medical illness. *Psychotherapy, 52*(1), 56–66. https://doi.org/10.1037/a0036448

Pew Research Center. (2017, May 10). *Religious belief and national belonging in Central and Eastern Europe*. https://www.pewresearch.org/religion/2017/05/10/religious-belief-and-national-belonging-in-central-and-eastern-europe/

Prochazkova, E., & Kret, M. E. (2017). Connecting minds and sharing emotions through mimicry: A neurocognitive model of emotional contagion. *Neuroscience & Biobehavioral Reviews, 80*, 99–114. https://doi.org/10.1016/j.neubiorev.2017.05.013

Pulvermüller, F. (2013). How neurons make meaning: Brain mechanisms for embodied and abstract-symbolic semantics. *Trends in Cognitive Sciences, 17*(9), 458–470. https://doi.org/10.1016/j.tics.2013.06.004

Romeo, R. R., Leonard, J. A., Robinson, S. T., West, M. R., Mackey, A. P., Rowe, M. L., & Gabrieli, J. D. E. (2018). Beyond the 30-million-word gap: Children's conversational exposure is associated with language-related brain function. *Psychological Science, 29*(5), 700–710. https://doi.org/10.1177/0956797617742725

Roy, S., Banerjee, A., Roy, C., Nag, S., Sanyal, S., Sengupta, R., & Ghosh, D. (2021). Brain response to color stimuli: An EEG study with nonlinear approach. *Cognitive Neurodynamics, 15*(6), 1023–1053. https://doi.org/10.1007/s11571-021-09692-z

Sarem, S. N., & Shirzadi, Y. (2014). A critical review of the interactionist approach to second language acquisition. *Journal of Applied Linguistics and Language Research, 1*(1), 62–74.

Schaffer, H. R. (1986). Child psychology: The future. *Journal of Child Psychology and Psychiatry, 27*(6), 761–779. https://doi.org/10.1111/j.1469-7610.1986.tb00200.x

Smith, K., & Kirby, S. (2008). Cultural evolution: Implications for understanding the human language faculty and its evolution. *Philosophical Transactions of the Royal Society B: Biological Sciences, 363*(1509), 3591–3603. https://doi.org/10.1098/rstb.2008.0145

Stanisławski, K. (2019). The coping circumplex model: An integrative model of the structure of coping with stress. *Frontiers in Psychology, 10*, Article 694. https://doi.org/10.3389/fpsyg.2019.00694

Suomi, S. J. (2008). Attachment in rhesus monkeys. In J. Cassidy & P. R. Shaver (Eds.), *Handbook of attachment: Theory, research, and clinical applications* (2nd ed., pp. 173–191). Guilford Press.

Tang, E., & Ding, H. (2024). Emotion effects in second language processing: Evidence from eye movements in natural sentence reading. *Bilingualism: Language and Cognition, 27*(3), 460–479. https://doi.org/10.1017/S1366728923000718

Vidrine-Isbell, B. (2017). Language attachment theory: The possibilities of cross-language relationships. In P. Portanova, J. M. Rifenburg, & D. Roen (Eds.), *Contemporary perspectives on cognition and writing* (pp. 95–114). The WAC Clearinghouse; University Press of Colorado. https://doi.org/10.37514/PER-B.2017.0032.2.05

Vrtička, P., & Vuilleumier, P. (2012). Neuroscience of human social interactions and adult attachment style. *Frontiers in Human Neuroscience, 6*, Article 212. https://doi.org/10.3389/fnhum.2012.00212

White, R., & Wild, J. (2016). "Why" or "how": The effect of concrete versus abstract processing on intrusive memories following analogue trauma. *Behavior Therapy, 47*(3), 404–415. https://doi.org/10.1016/j.beth.2016.02.004

Wingenbach, T. S. H., Brosnan, M., Pfaltz, M. C., Peyk, P., & Ashwin, C. (2020). Perception of discrete emotions in others: Evidence for distinct facial mimicry patterns. *Scientific Reports, 10*(1), Article 4692. https://doi.org/10.1038/s41598-020-61563-5

Zhang, H., Gross, J., De Dreu, C., & Ma, Y. (2019). Oxytocin promotes coordinated out-group attack during intergroup conflict in humans. *eLife, 8*, Article e40698. https://doi.org/10.7554/eLife.40698

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