UNIVERSITY OF PAVIA – IUSS SCHOOL FOR ADVANCED STUDIES PAVIA

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Preserved and Impaired Semantic Processing Across Abstract Concept Dimensions in Right Temporal Variant Frontotemporal Dementia

Supervisors:

Prof. Eleonora Catricalà

Dott. Alessandro Cocuzza

Thesis written by

Najma Leena Jamilah Jaufeerally

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Abstract

Right temporal variant frontotemporal dementia (rtvFTD) is characterised by a progressive degeneration of the right anterior temporal lobe and causes prominent impairments in socioemotional semantic processing. While explicit semantic deficits are well documented in this syndrome, much less is known about the integrity of implicit semantic activation across different dimensions of abstract concepts. The present study investigated semantic priming and d-prime (d') across six different categories of abstract concepts (social, emotional, moral, interoceptive, theoretical, and quantitative) in patients with rtvFTD and healthy controls. The results showed a largely preserved semantic priming effect across most categories, with the exception of interoceptive concepts. In contrast, d' was significantly reduced for social, quantitative, theoretical, and interoceptive concepts, while accuracy remained relatively preserved. The results suggest that different implicit measures capture distinct aspects of semantic processing, with d-prime (d') revealing impairments that were not evident in task accuracy or semantic priming alone.

Keywords: right temporal variant frontotemporal dementia, abstract concepts, semantic priming, interoception, semantic memory, right anterior temporal lobe

Introduction

1 Semantic Memory and Conceptual Knowledge

1.1 What is Semantic Memory?

From emotions and social relationships to internal bodily states, abstract concepts form a fundamental yet complex component of human semantic knowledge. This knowledge is supported by semantic memory, a widely studied area of cognitive neuroscience, while still not closing all the literary gaps.

Semantic memory constitutes a long-term memory system that supports the retention of general and abstract knowledge, which encompasses factual information and conceptual representations acquired throughout an individual's lifespan (Ozel-Kizil et al., 2024). Abstract conceptual knowledge, such as understanding the concepts like "justice" or "pain", is not stored in a unitary representation, but rather depends on the integration of multiple experiential dimensions, which include affective, social and linguistic components (Acosta et al., 2025; Borghesani et al., 2021).

While defining the multidimensionality of semantic memory is important, it is also fundamental to have a clear understanding of the differences between episodic and semantic memory, as they are both independent systems within long-term memory. While the definition of semantic memory entails the generic, theoretical, and factual knowledge about the world, which also includes facts and conceptual associations (Ozel-Kizil et al., 2024), episodic memory, on the other hand, involves recalling specific personal experiences linked to a specific, temporal, spatial, and emotional context (Ozel-Kizil et al., 2024). For instance, knowing the capital of a particular country pertains to semantic memory, whereas recalling a trip to a specific place relies on episodic memory. Besides their definitions, the difference between the two extends to their phenomenological properties. Episodic memory enables the

re-experiencing of past events through “mental time travel” and is correlated with autonoetic consciousness, where autonoetic awareness is defined as the ability to consciously re-experience events from one’s personal experience (Ozel-Kizil et al., 2024). Semantic memory, on the other hand, involves noetic awareness without re-experiencing (Ozel-Kizil et al., 2024). On the neurobiological level, episodic memory is heavily dependent on the medial temporal lobe and the hippocampus, while semantic memory is more broadly distributed in the neocortical regions, which include temporal, parietal, and frontal areas of the brain (Ozel-Kizil et al., 2024). Moreover, while these two types of memory are different from each other, a lot of studies have concluded that they interact dynamically, where certain episodic memories contribute to the formation of certain semantic knowledge and structures, which in turn provide a scaffold for encoding and retrieving episodic events (De Brigard et al., 2022). This interplay highlights the complexity of memory systems and is particularly relevant for understanding how conceptual knowledge is represented and affected in neurological conditions.

1.2 Organisation of Semantic Memory

The organisation of the semantic memory can be depicted as a complex, multi-layered structure that integrates modality-specific information with abstract representations. According to Reilly et al (2016), this specific system is oftentimes described as a hybrid hub-and-spoke model, whereby the sensorimotor regions, known as “spokes”, encode certain features, such as visual form or action, while central hub regions, more specifically the anterior temporal lobes, integrate this information into amodal abstract representations. A simple example of this is the knowledge of a tool, which requires visual features processed in occipitotemporal regions, action properties in parietal and motor areas, all integrated into a synthesised concept within the anterior temporal lobes (ATLs) (Reilly et al., 2016). In

addition, this organisation is structured hierarchically, with lower-order hubs, such as the angular gyrus, which support the integration of multimodal features, and higher-order hubs that enable more abstract and symbolic processing (Reilly et al., 2016). It is also important to note that semantic representations are dynamic reconstructions rather than static ones, in which abstract representations may reactivate relevant sensorimotor features depending on task demands (Reilly et al., 2016). This organisation is considered flexible due to the fact that it is heavily shaped by connectivity and experience, thus leading to specialisation across brain regions and environmental structures, where they all contribute to how concepts are categorised and distinguished (Chen et al., 2017). Furthermore, semantic memory organisation is shaped by the interplay of two distinct features: concreteness (the degree of perceptibility) and specificity (the degree of category inclusiveness) (Villaini et al., 2024). Together, these features establish a hierarchy - often described as 'levels of abstraction' - that ranges from general categories to highly complex, specific taxonomic relationships (Villani et al., 2024).

2 Abstract Concepts and their Dimensions

2.1 What are abstract concepts?

Building on the multi-layered organisation of semantic memory, two distinct categories make up the latter: abstract and concrete concepts, which differ in their degree of sensory grounding and specificity (Villaini et al., 2024). On one hand, 'concrete concept' refers to units that can be directly experienced through the senses, for example, "animal", whereas 'abstract concept' designates non-perceptible phenomena, including emotions, social norms, or constructs and mental states such as concepts of freedom or justice (Villaini et al., 2024). A widely recognised finding in the field, known as the concreteness effect, posits that concrete concepts are predominantly acquired earlier and processed more easily and

accurately than abstract concepts (Villaini et al., 2024). However, this advantage can be contradicted or reversed in environments where contextual and task-related factors are controlled (Villaini et al., 2024). On the other hand, the concept of "abstraction" is an essential mechanism to represent and learn meaning in memory, where the consensus definition is aggregating features across experiences to create a "central" average, such as the concept of a "bird" (Jones, 2018). Moreover, abstraction is not reduced to a single dimension, but rather to the interaction between concreteness and specificity, which contributes to the construction of a semantic space where concepts can be organised into four broad types: generic-concrete, specific-concrete, generic-abstract, and specific-abstract (Villaini et al., 2024). These four types can subsequently be arranged in what can be called "ladders of abstraction", which can be defined as a hierarchical framework where the concepts are categorised from highly general, inclusive categories at the top to more specific and detailed ones at the bottom (Schendan, 2012). The ladders of abstraction vary greatly across conceptual categories, as not all of them will have the same length (Villaini et al., 2024). Some semantic categories have longer taxonomic ladders as they require higher levels of specification through multiple 'rungs', such as the concept of "animal" (Villaini et al., 2024). Whereas certain concepts have rather shorter taxonomic ladders, such as "essence", because it is difficult to identify other subtypes or generic categories linked to them (Villaini et al., 2024). This organisation holds certain biological underpinnings reflected in the brain, where some studies suggest that it is also organised hierarchically in this context (Martin & Chao, 2001). In that sense, semantic processing is organised along a posterior-to-anterior gradient in the temporal lobe, with increasing levels of information integration as processing moves anteriorly (Martin & Chao, 2001). More anterior temporal regions are therefore thought to play a critical role in supporting fine-grained, subordinate-level semantic distinctions, which are required for differentiating between closely related concepts (Martin & Chao, 2001).

2.2 Multidimensional Nature of Abstract Concepts

To reiterate the point above, abstract concepts are discerned by their lack of a bounded, identifiable, and clearly perceivable physical referent (Borghi et al., 2017). Abstract concepts are multidimensional due to several factors. Unlike concrete concepts, which are mostly grounded in sensorimotor systems, abstract concepts have a heavy reliance on multiple cognitive functions known as high-dimensional semantic space, which is simply defined by varied dimensions including sensation, emotion, thought, social interaction, morality, executive function, quantity, time, and space (Borghi et al., 2017). Hence, abstract concepts hold more situational and introspective properties due to the fact that they rely mostly on internal states, social situations, and institutional aspects such as beliefs, complex relations, and communication (Borghi et al., 2017). It also means that they are quite dynamic as they are less stable over time and hold great significance through life experiences, culture, and other situational factors, which is a contrasting feature with respect to concrete concepts that are overall more stable (Borghi et al., 2017). Moreover, the linguistic grounding of abstract concepts is a primordial scaffold as it provides a root when physical referents are absent, hence making language a compensatory element for a reduced perceptual experience (Borghi et al., 2017).

There are specific classes of abstract concepts that comprise social, quantity, emotional, interoceptive, theoretical, and moral (Catricalà et al., 2021). The social concept refers to concepts that indicate social relations and interactions among individuals and groups, such as charm, talent, sociability, friendship, alliance, and so on (Catricalà et al, 2019). The neural underpinnings of the social concepts are associated with the right superior anterior temporal lobe (sATL) and the right intraparietal sulcus (IPS) (Catricalà et al., 2021). Quantity-related concepts are defined in relation to size, amount, or scope and are part of a broader domain known as magnitude, which includes concepts such as immensity, thickness,

reduction, shortage, abundance, decrease, and more (Catricalà et al., 2021). The quantity-related concepts involve regions of the brain like the IPS, which are traditionally linked to numerical representations (Catricalà et al., 2021). Moreover, the emotion concept refers to the internal affective states, where its definition also partly overlaps with the interoceptive abstract concept (Catricalà et al., 2019; Catricalà et al., 2021). The emotion category comprises emotions like joy, anger, fear, disgust, grief, panic, and so on, and is generally associated with the anterior cingulate cortex, which some research suggests may be selectively preserved in certain neurodegenerative diseases while other abstract concepts are impaired (Catricalà et al., 2019).

2.3 Abstract Concepts in Neurodegenerative Diseases

Research on neurodegenerative diseases has provided critical insight into how the brain organises abstract conceptual knowledge. In healthy individuals, concrete words are typically processed faster than abstract words, and in neurological populations, this concreteness advantage is usually greater (Jefferies et al., 2009). However, while in most brain-injured patients concrete concepts are easier to grasp than abstract ones, patients with ATL atrophy may show the opposite effect - known as the reverse imageability effect - which subsequently challenges the idea that the anterior temporal lobes are only responsible for processing sensory-based, concrete information (Jefferies et al., 2009). Yet, there are some cases of semantic dementia patients demonstrating a higher success rate for more imageable words, which highlights that the ATLs underpin semantic knowledge for both concrete and abstract concepts, and perhaps that imageable items are stronger in the face of semantic decline (Jefferies et al., 2009).

Abstract concepts are not homogeneous, and different categories draw on different, distinct neural substrates (Catricalà et al., 2021). Oftentimes, there are double dissociations,

especially in cases of patients affected by semantic variant primary progressive aphasia (svPPA) and patients with corticobasal syndrome (CBS): while the former showed abolished priming for social concepts but preserved quantity concepts, the latter displayed the opposite pattern of impairment (Catricalà et al., 2021). This ultimately suggests that the ATLs support social-semantic representations while the parietal cortices support quantity-related concepts (Catricalà et al., 2021). The role of the right ATL in socioemotional semantics is further supported by the case of patients affected by right temporal variant frontotemporal dementia (rtvFTD), where focal right ATL degeneration disrupts non-verbal semantic knowledge for concepts of socioemotional relevance (Younes et al., 2022).

More recent evidence refines this model further. Social and non-social-semantic deficits were severe and highly correlated in FTD, loading onto a single semantic memory component uniquely associated with bilateral ATL grey matter (Rouse et al., 2024). This supports the view that social-semantic knowledge is part of a broader conceptual system underpinned by a bilaterally implemented semantic hub (Rouse et al., 2024). The right ATL is selectively critical for the affective, non-verbal dimensions of socioemotional concepts, but unilateral damage produces a more circumscribed deficit than bilateral damage because the intact left ATL can support linguistic and quantitative domains (Catricalà et al., 2019). Semantic priming paradigms are particularly valuable in this context because they provide an automatic, implicit measure that can detect preservation or degradation of conceptual knowledge not captured by explicit tasks, and this dissociation has diagnostic value in differentiating rtvFTD from behavioural variant FTD (Ulugut et al., 2021; Rossi et al., 2022).

3 Neural Basis of Semantic Memory

3.1 Brain Regions Involved

The biological underpinnings of semantic memory were first conceptualised through case studies of patients suffering from brain injuries or diseases; however, recent neuroimaging studies have pinpointed several areas of the brain accountable for semantic memory. Semantic memory is supported by a distributed network of cortical regions that parallel the organisation of sensory, motor, and linguistic systems (Schendan, 2012). Instead of being localised in a single area, conceptual knowledge arises due to the interaction between specialised regions of the brain that process information and control systems that conduct retrieval and selection processes (Martin & Chao, 2001). In other words, it can be understood as a network of neuronal units, where knowledge is acquired and strengthened through experience-dependent mechanisms (Martin & Chao, 2001).

A fundamental part of this system is the anterior temporal lobe (ATL), which lies adjacent to the limbic system and is an amodal semantic hub that integrates information across sensory and motor modalities to form coherent representations (Schendan, 2012). As mentioned previously, the ATLs display a "Hub-And-Spoke" architecture whereby a central integration site is the primary "hub" according to the distributed-plus-hub theory, which posits that concepts are integrated from different sensory and motor systems rather than being stored in modality-specific areas (Zhao et al., 2016). Then there is the mediator layer, which acts as an intermediary that establishes connections between the inputs from the sensory regions, such as the visual cortex, and other semantic areas to coordinate retrieval (Farahibozorg et al., 2021). This integration is thought to perform nonlinear transformations that take away the modality-specific details to form abstract, amodal representations, which enable more detailed differentiation between similar concepts, for example, distinguishing a

Dalmatian from other dogs (Zhao et al., 2016; Catricalà et al., 2021). To support this, neurophysiological evidence further demonstrates that the left ATL is the first cortical region that is modulated by word meaning, with activity beginning as early as ~100 ms post-stimulus, according to EEG and MEG studies (Farahibozorg et al., 2021). Furthermore, the dynamic causal modelling identifies the ATLs as the initial network hub during early retrieval (0-250 ms), with sustained involvement through the N400 window (Farahibozorg et al., 2021). In terms of function, the ATL is lateralised, meaning that the left side of the brain supports verbal semantics, while the right side supports non-verbal and social processing, such as faces, empathy, and theory of mind (Farahibozorg et al., 2021; Tee & Gorno-Tempini, 2019). The ATLs also have a graded-specialisation functional organisation, where the superior regions are linked to abstract concepts, as they are closely associated with auditory-verbal information networks, the ventromedial regions are linked to concrete concepts because of their strong connectivity to visual processing areas, and finally, the dorsal polar regions to social concepts and affective processing through their connections to the limbic system (Catricalà et al., 2019). In the clinical context, more precisely in the case of svPPA, ATLs degeneration causes hypometabolism and focal atrophy, usually starting in the left hemisphere, leading to pronounced naming and comprehension deficits (Teen & Gorno-Tempini, 2019; Gorno-Tempini, 2011). In terms of connectivity and network topology, the ATLs are supported by extensive connectivity through white matter tracts, including the inferior longitudinal fasciculus (ILF) and the uncinate fasciculus, with the level of connectedness predicting semantic performance (Zhao et al., 2016; Teen & Gorno-Tempini, 2019). Together, these findings show that the ATLs are not only an early and sustained processor of semantic information but, more broadly, a specialised integrative hub that transforms and unifies distributed inputs into coherent, abstract concepts, hence highlighting the essential role of the ATLs in semantic memory.

On the other hand, the medial temporal lobe (MTL), including the hippocampus, helps by supporting the gradual formation of conceptual knowledge across experiences and represents concepts independent of their sensory form (Schendan, 2012). In addition to this, the frontal regions are mainly involved in the controlled retrieval and manipulation of semantic knowledge, more specifically, the parts of the frontal lobe relevant to semantic memory include the lateral and medial prefrontal regions and anterior cingulate regions (Martin & Chao, 2001; Nyberg et al, 2002). Moreover, the role of the prefrontal cortex (PFC) in semantic memory and processing can be identified through the activation of a common network of four specific regions: the left frontopolar cortex, the left mid-ventrolateral PFC, the left mid-dorsolateral PFC, and the dorsal anterior cingulate cortex, all mostly used for tasks including fact retrieval, synonym generation, and classification (Nymberg et al., 2002). However, the aforementioned regions also have other specific functions of their own, for instance, the left frontopolar cortex is associated with the higher-order control of goals and the processes used to achieve them (Nymberg et al., 2002). The left Mid-Ventrolateral PFC is linked to the active encoding and retrieval of information, which, in semantic memory, may assist the maintenance and updating of the contents of the working memory needed to process semantic information (Nymberg et al., 2002). The left Mid-Dorsolateral PFC is associated with the active selection, monitoring, and evaluation of information, whereby, in semantic tasks, it acts upon material retrieved from memory and evaluates external information that is attended to (Nymberg et al., 2002). Finally, the Dorsal Anterior Cingulate Cortex is responsible for effortful task completion and general cognitive control during semantic memory challenges, and its activation correlates with task difficulty (Nymberg et al., 2002).

Within this context, posterior cortical regions, including temporal, parietal, and occipital lobes, play a valuable role in the storage and integration of modality-specific semantic information, supporting the sensory and motor features that define conceptual

knowledge (Martin & Chao, 2001). For instance, the left posterior middle temporal gyrus supports the depiction of action-related knowledge, such as identifying tools or generating action words (Martin & Chao, 2001), while the ventral occipitotemporal cortex, also known as fusiform gyrus, processes object form, showing category-specific activation for inanimate and animate objects (Martin & Chao, 2001). A hierarchical system can be recognised in this functional organisation where the posterior regions process basic perceptual features, and the more anterior regions integrate them into higher-order, more abstract representations, contributing to enabling certain abilities like object recognition across various contexts (De Zubicaray et al., 2010). Moreover, the angular gyrus of the parietal lobe contributes to the incorporation of information from different sources to support understanding, while the occipital regions provide visual information that can be reactivated during semantic processing (Schendan, 2012). All these regions are interconnected through white matter pathways such as the inferior fronto-occipital fasciculus, which in turn facilitates communication across the semantic network (De Zubicaray et al., 2010). Altogether, this highlights how semantic memory relies on both specialised and integrated processing that supports both complex and multidimensional concepts.

3.2 Distributed vs. Hub Models

For a more holistic view of what semantic memory is, it is important to delve deeper into the different theories of semantic memory, which debate whether semantic memory should be depicted as a distributed-only model or a hub-based model. Theories supporting the distributed-only model suggest that concepts are represented solely by modality-specific sensory-motor systems distributed across the brain, whereas distributed-plus-hub models suggest that there is an extension in the form of heteromodal hubs that integrate the

information into coherent concepts, and the disruption of a hub leads to a semantic decline across all modalities (Zhao et al., 2016; Catricalà et al., 2019). Despite the ATLs being identified as a primary hub, other studies put forth an alternative theory of convergence zones, arguing that multiple regions, including the angular gyrus (AG), middle temporal gyrus, and inferior frontal gyrus, act as equally important hubs in coordinating the semantic network (Farahibozorg et al., 2021). Considering evidence related to temporal patterns of activity of these regions, the ATL is the initial hub during semantic retrieval (0-250 ms) where it initiates activity in the cortico-cortical connections, whereas the AG engages later at ~450 ms to integrate semantic information with broader cognitive systems (Farahibozorg et al., 2021). Additional regions contribute specialised roles, such as the anterior cingulate cortex (ACC), where the nodes have a high number of connections and support executive control over context-appropriate semantic retrieval (Zhao et al., 2016). Moreover, certain categories of abstract domains rely on distinct neural substrates found outside the temporal lobe, such as the IPS, which is critical for magnitude-related concepts, for example, time, quantity, and space (Catricalà et al., 2019). In addition to this, some clinical evidence supports this distributed yet specialised architecture, where degeneration of the ATLs in svPPA leads to multimodal semantic deficits, whereas IPS damage in CBS selectively impairs concepts of quantity (Catricalà et al., 2019; Catricalà et al., 2021). Further analyses on networks show that reduced connectivity - also known as reduced nodal degree - in key hubs, more precisely in the ATL and ACC, predicts the degree of semantic impairment, which could cause widespread network dysfunction (Zhao et al., 2016; Teen & Gorno-Tempini, 2019).

3.3 Category-Specific Processing

The organisation of conceptual knowledge within the semantic system is not uniform across categories, as suggested by neuroimaging and neuropsychological studies that

converge on a more graded and lateralised architecture (Montembeault et al., 2026). Within the hub-and-spoke framework, while the ATLs function as transmodal hubs integrating modality-specific information, the two hemispheres do not contribute equally to all conceptual domains (Montembeault et al., 2026). The left ATL is particularly specialised for integrating verbal and tool-related knowledge, whereas the right ATL is preferentially engaged by nonverbal, socioemotional information including facial expressions, affective prosody, and emotion concepts (Montembeault et al., 2026). For concrete concepts, models within the embodied cognition framework emphasise the differential contribution of sensory and motor systems, with distinct brain regions supporting different kinds of conceptual content (Borsa et al., 2025). According to this view, conceptual representations are not stored in a unitary format but are instead shaped by the neural systems that support the corresponding perceptual, motor and affective experiences (Borsa et al., 2025). Category-specific semantic disorders following a localised brain damage have provided direct support for the above claim, positing that conceptual knowledge relied on distinct neural substrates that provide underlying support for the processing of category-relevant features (Catricalà et al., 2021).

In the abstract domain, behavioural, neuroimaging, and neurophysiological studies indicate that abstract concepts are organised along multiple experiential dimensions, including sensory and motor features, but also introspective, affective, social and magnitudinal aspects (Borsa et al., 2025). This multidimensional organisation suggests that different subtypes of abstract concepts may be grounded in distinct neural systems, for example, social concepts have been linked to the superior anterior temporal lobe, whereas quantity-related concepts have been primarily associated with the IPS (Borsa et al., 2025).

This organisation becomes relevant in neurodegenerative diseases, where ATL atrophy in svPPA has been associated with impaired social conceptual knowledge, whereas

parietal involvement in corticobasal syndrome (CBS) has been linked to deficits in quantity-related concepts (Catricalà et al., 2021). Moreover, the ATL on both sides of the brain work together to store our general knowledge but they specialise in the type of information they process, for example, the left side as a hub for language-based concepts by activating speech and grammar centres, while right side focuses on visual and non-verbal information (Montembeault et al., 2026).

4 Semantic Impairment in Neurodegenerative Disorders

4.1 Frontotemporal Dementia

Importantly, the models mentioned above are widely supported by evidence from certain neurodegenerative disorders such as frontotemporal dementia (FTD), where damage to key hub regions would lead to certain deficits. The core definition of FTD is characterised by a heterogeneous neurodegenerative syndrome that affects various aspects such as behaviour, executive and language deficits, and has a high prevalence rate in people under the age of 65, after Alzheimer's disease (Khalil et al., 2024; Bustamante-Barrientos et al., 2023; Gao et al., 2023). On a clinical level, FTD can often be mistaken for other neurodegenerative or psychiatric disorders, as the symptoms often occur well after the pathology is established and manifests itself through psychiatric like symptoms, for example, executive dysfunction and language impairment, hence, making early recognition and stratification challenging (Chouliaras et al., 2023; Khalil et al., 2024; Bustamante-Barrientos et al., 2023).

On the biological level, FTD is considered a proteinopathy: neurodegeneration is caused by misfolded proteins that accumulate in neurons and adjacent brain cells, where the deposits lead to the development of the disease (Khalil et al., 2024; Gao et al., 2023). The major proteins involved in this neuropathology are known as tau and TDP-43, each

accounting for about half of the cases, and the FUS (Fused in Sarcoma) protein, which represents much rarer occurrence (Khalil et al., 2024; Gao et al., 2023). Tau proteinopathy is one of the most prominent biological factors in the disease, as it is involved in microtubule stability and, when abnormal, exacerbates neuronal dysfunction and degeneration (Khalil et al., 2024). However,, TDP-43 holds important nuclear functions as well, such as regulating RNA, but in the context of the disease, it misfolds and leaves the nucleus and accumulates in the cytoplasm, where it gains toxic effects (Gao et al., 2023). Furthermore, in the rare cases where FUS is involved in FTD, it adopts a similar mechanism when it abnormally aggregates in the cytoplasm, causing toxicity to the cell (Neumann et al., 2009). Hence, it is conspicuous that FTD is biologically heterogeneous, meaning that two patients can both have FTD, but the underlying molecular brain pathology can differ (Khalil et al., 2024; Gorno-Tempini et al., 2011).

Moreover, there are certain genes in FTD that often point towards the underlying pathology of the disease (Khalil et al., 2024; Gao et al., 2023). For instance, the genes C9orf72 and GRN are strongly associated with the TDP-43 pathology (Khalil et al., 2024; Gao et al., 2023). The C9orf72 gene is the most common genetic cause of FTD and ALS (Amyotrophic Lateral Sclerosis), and its mechanism in the pathogenesis includes loss of normal gene function, RNA foci, and toxic repeat-driven proteins (Gao et al., 2023). Furthermore, the GRN gene mutations cause a decline in the progranulin protein, which is a vital growth factor for regulating inflammation and neurodevelopment, among others (Townley et al., 2017). Hence, this deficiency is associated with inflammatory microglial changes and TDP-43 aggregation (Gao et al., 2023).

Furthermore, the biomarker landscape of FTD should not be ignored due to its pertinence in the disease. The neurofilament light chain (NfL) found in the CSF and blood is one of the most viable and currently available biomarkers for FTD, especially when

distinguishing between behavioural fronto-temporal dementia (bvFTD) and other psychiatric disorders (Khalil et al., 2024). In that sense, the elevated concentration of NfL in the CSF and blood, as compared to primary psychiatric disorders, makes it a useful tool for challenging differential diagnoses of the behavioural-variant FTD as compared to other conditions that resemble it (Khalil et al., 2024). The genetic and biomarker level of this condition works hand in hand as NfL levels can differ quite meaningfully in people with certain genetic subtypes; NfL is the highest in people with the GRN mutation, intermediate in C9orf72 mutation, and the lowest in MAPT mutation carriers (Khalil et al., 2024). In addition to this, depending on the genetic mutation, define the timing of the NfL presymptomatic rise, with approximately 30 years before symptom onset in C9orf72, 15 years in GRN, and around the time of symptom onset for MAPT mutation carriers (Khalil et al., 2024). These markers bring about important prognostic value in FTD, as higher baseline NfL levels are strongly linked to an increased risk of developing symptomatic disease, while a greater yearly increase in NfL predict and even higher likelihood of clinical conversion (presymptomatic to symptomatic) in mutation carriers (Khalil et al., 2024). As a result, NfL has been suggested as a way to both be a criterion for selecting high-risk participants in clinical trials and as a biological marker for monitoring the disease progression (Khalil et al., 2024). Nonetheless, an important drawback remains the lack of a validated PET tracer for the TDP-43 pathology, which accounts for about half of FTD cases, hence restricting the ability to confirm the pathology during life (Chouliaras et al., 2023). However, amyloid and tau PET imaging can aid in differentiating FTD from Alzheimer's disease, especially in the prodromal stages, but they mostly serve as markers reflecting alternative pathologies rather than FTD itself (Chouliaras et al., 2023). On the other hand, PET imaging has demonstrated microglial activation in frontotemporal regions, which underlines a neuroinflammatory component that may lead to a biomarker or therapeutic target (Gao et al., 2023).

NfL is particularly relevant in neuroinflammation, as it reflects neuronal injury and degeneration but does not identify the underlying biological mechanism causing this damage (Gao et al., 2023). One prominent upstream mechanism is neuroinflammation, particularly microglial inflammation, which has emerged as a key feature of FTD (Gao et al., 2023). PET imaging and post-mortem studies have subsequently shown increased microglial activation in the frontal and temporal regions mostly affected by the disease, and this inflammation can be detected even before symptom onset in people with the aforementioned genetic mutation (Gao et al., 2023). The genetic architecture of FTD provides additional evidence for this inflammatory component, whereby mutations in genes involved in immune signaling, such as TBK1, which produces kinase enzymes responsible for controlling the body's innate immune system, and TREM2, a microglial receptor, are associated with an increased risk of the disease (Gao et al., 2023). TREM2 is important in FTD because it helps microglia recognise and clear pathological TDP-43; when TREM2 is deficient or non-functional, microglia fail to activate properly, leading to reduced TDP-43 clearance and increased neuronal injury (Gao et al., 2023). Furthermore, mutations in TBK1 disrupt normal regulation of the innate immune system, leading to abnormal inflammatory responses in the brain that contribute to the development of FTD (Gao et al., 2023). In addition to this, the strongest link between genetics, inflammation, and biomarkers is found in people carrying the GRN mutation (Gao et al., 2023). The reduced progranulin levels due to this mutation lead to dysfunctional microglial activity, which in turn exacerbates TDP-43 aggregation, lysosomal dysfunction, synaptic loss, and myelin debris accumulation (Gao et al., 2023). Because progranulin deficiency directly reflects this pathological process, its concentration is being investigated as a potential blood biomarker (Gao et al., 2023). Overall, no single biomarker is sufficient for FTD, so research is increasingly focused on integrating fluid, imaging, genetic, and inflammatory measures to capture its biological heterogeneity (Gao et al., 2023).

4.2 Right Temporal Variant FTD

Right temporal variant frontotemporal dementia (rtvFTD), also known as right temporal variant of semantic dementia (rSD) or semantic behavioural variant frontotemporal dementia (sbvFTD), is a less common clinical phenotype within the realm of the frontotemporal lobar degeneration spectrum (Rossi et al., 2022; Acosta et al., 2025). It was initially conceptualised as a mirror-image counterpart to the more common left-predominant semantic variant of primary progressive aphasia (svPPA); rtvFTD is characterised by a pattern of asymmetric neurodegeneration which predominantly affects the right anterior temporal lobe (Rossi et al., 2022; Acosta et al., 2025). Unlike other forms of frontotemporal dementia that may show primary executive dysfunction or linguistic decline, rtvFTD is characterised by its early impairment of non-verbal and socioemotional semantics, including impairments in recognising familiar faces, navigating known environments and interpreting social cues (Ulugut et al., 2025; Acosta et al., 2025). The diagnostic framework is operationalised through three main domains of impairment: multimodal knowledge of non-verbal information, socioemotional behaviour and the prioritisation of specific interests and hedonic valuation (Acosta et al., 2025). Moreover, there is an ongoing nosological debate regarding the classification of rtvFTD due to its separate clinicopathology instead of a straightforward mirror-image phenotype of the left-sided semantic disorders (Acosta et al., 2025).

The core clinical presentation of rtvFTD presents itself as early socioemotional and behavioural alterations, such as the progressive loss of empathy, along with social disinhibition and overall personality changes (Rossi et al., 2022). In addition to this, prosopagnosia, which is a deficit in recognising familiar faces, is a hallmark cognitive impairment in rtvFTD affecting 60-70% of patients (Acosta et al., 2025). Topographic agnosia is also frequently present causing patients to be unable to recognise familiar

landmarks or navigate known routes due to a deficit in their spatial semantic memory (Acosta et al., 2025). While the syndrome may eventually involve semantic language impairment such as agnosia and word-finding difficulties, these typically follow the initial behavioural and social cognitive decline (Acosta et al., 2025). Episodic memory may also show early impairment, manifesting as repetitive questioning and the misplacement of belongings (Acosta et al., 2025).

The defining neural signature of rtvFTD is focal atrophy and hypometabolism concentrated in the rATL, which often extends to adjacent cortical structures such as anterior temporal cortex, where atrophy is seen through neuroimaging studies in the temporal pole, hippocampal formation, and the parahippocampal gyrus (Acosta et al., 2025). Furthermore, in the socioemotional processing networks, the involvement of the amygdala has a direct link with loss of empathy and deficits in emotion processing (Acosta et al., 2025). Atrophy in the fusiform gyrus and ventral occipitotemporal cortex is associated with the presence of prosopagnosia (Acosta et al., 2025). Beyond the cortical regions, atrophy can also be observed in subcortical regions including the thalamus and putamen, alongside some white matter loss in the inferior fronto-occipital and uncinate fasciculi (Kleinerova et al., 2024).

The study of rtvFTD is highly relevant in the functional lateralisation of semantic memory, providing crucial support for the hub-and-spoke model. While the left anterior temporal lobe is traditionally viewed as the primary hub for verbal and linguistic semantic knowledge, the right ATL (rATL) serves as a crucial hub for socioemotional and non-verbal semantics (Acosta et al., 2025). The semantic disorders in rtvFTD are multimodal, impacting the recognition of people, objects, environmental cues and potentially the semantic representation of internal bodily states (Acosta et al., 2025; Younes et al., 2022; Ulugut et al., 2024). Specifically, the rATL is responsible for integrating visceral and non-verbal information to attribute value to social behaviours and to construct complex concepts of

people and places (Acosta et al., 2025). Furthermore, emerging evidence further suggest that the right ATL contributes to the integration of interoceptive and visceral bodily signals into semantic and socioemotional representations, which implies that degeneration of this region may also disrupt the processing of concepts grounded in internal bodily states (Younes et al., 2022; Ulugut et al., 2024). The degradation of the right temporal semantic hub in rtvFTD shows that semantic memory is not only a linguistic system but also an important framework for social cognition and the interpretation of the non-verbal world (Acosta et al., 2025).

4.3 Semantic Variant Primary Progressive Aphasia (svPPA)

Semantic variant primary progressive aphasia (svPPA) and right temporal variant frontotemporal dementia (rtvFTD) are both rare clinical phenotypes within the FTD spectrum that in most cases share a common underlying neuropathology but differ in their clinical onset, neuroanatomical and cognitive profile (Rossi et al., 2022). In svPPA, the impairments are characterised as a progressive loss of verbal semantic knowledge, manifesting as anomia, impaired single-word comprehension, and surface dyslexia, with atrophy centred on the left ATL (Rossi et al., 2022; Lead Tee et al., 2019). In contrast, rtvFTD was initially thought to be a mere right-sided mirror of svPPA, but is now recognised as a distinct clinical entity (Rossi et al., 2022; Acosta et al., 2025). The two syndromes dissociate in the type of semantic knowledge they disrupt: the left ATL structures damaged in svPPA are important for verbal and linguistic semantic processing, whereas the right ATL structures affected in rtvFTD are important for non-verbal, socioemotional, and person-specific knowledge, including face recognition and emotion processing (Acosta et al., 2025; Ulugut et al., 2025).

On the pathological level, svPPA is strongly and fairly homogeneously associated with the TDP-43 type C proteinopathy, whereas rtvFTD shows considerable pathological heterogeneity with TDP-43 Types A and B as well as tau-MAPT pathology alongside Type C,

and motor neuron involvement has been found in up to 28% of rtvFTD cases but is rare in svPPA (Rossi et al., 2022). Importantly, as atrophy in rtvFTD spreads from the right to the left temporal lobe, patients increasingly develop language-based semantic deficits resembling svPPA, illustrating that the two phenotypes represent different initial entries into a bilateral degenerative process of the ATL network (Ulugut et al., 2021).

5 Semantic Priming as a Clinical Tool

5.1 What is Semantic Priming?

Semantic priming refers to the facilitation of processing a target word or concept when it is preceded by a semantically related prime, as compared to an unrelated prime (Catricalà et al., 2021). This effect is most commonly measured in lexical decision tasks, where the participants respond faster and often more accurately to a target when the priming word is semantically related (Catricalà et al., 2021). This occurrence is said to reflect the organisation of the semantic memory whereby related concepts are stored in proximity within a distributed semantic network, and the activation one node subsequently and automatically spread to the neighbouring nodes, which lowers their activation threshold (Catricalà et al., 2021; Woollams et al., 2016). Critically speaking, semantic priming tasks enable a direct measure of the integrity of semantic memory, relying less on conscious retrieval strategies and more on an automatic processing (Catricalà et al., 2021). The distinction between automatic and controlled processing makes semantic priming a particularly valuable tool when it comes to investigating the organisation of conceptual knowledge in both healthy and clinical populations.

At the cognitive level, semantic priming can be explained through the framework of the spreading activation model, where the activation of one concept automatically propagates along associative links to related concepts, pre-activating them and thus speeding subsequent

recognition (Catricalà et al., 2021). Some connectionist models posit that semantic processing contributes more strongly to words with irregular spelling-to-sound rules, as it relies on semantic knowledge to read them carefully, hence highlighting the interaction between semantic and phonological pathways during lexical processing (Woollams et al., 2016). The ATLs, in particular the left ATL, play a pivotal role in this process and are conceptualised through the framework of the hub-and-spoke model as pan-modal semantic hub which integrates modality specific information into coherent conceptual representations (Catricalà et al., 2019). Neuroimaging and transcranial magnetic stimulation studies provide support for the involvement of the ATLs in semantic processing, including category-specific semantic representations such as social concepts, by disrupting the semantic priming effect (Catricalà et al., 2019). Importantly, there is a distinction between automatic and controlled semantic processing whereby implicit semantic priming tasks primarily reflect automatic spreading activation, while explicit semantic tasks require more strategic retrieval and are more susceptible to executive and attentional impairments (Catricalà et al., 2021). This distinction is relevant in neurodegenerative disorders, where preserved automatic priming may coexist with impaired explicit semantic performance (Catricalà et al., 2021).

5.2 Semantic Priming in Semantic Disorders

In rtvFTD, the progressive degeneration of the ATL leads to a primary disruption of non-verbal and socioemotional semantic representations, which can be detected through alterations in semantic priming (Rossi et al., 2022; Acosta et al., 2025). While hyperpriming for certain category-coordinated concrete objects may occur as conceptual boundaries become less distinct, similar to svPPA, however, the most typical feature of rtvFTD is highlighted by a loss of priming for social and person-specific concepts (Catricalà et al., 2021; Acosta et al., 2025). This altogether reflects a breakdown in the automatic activation of social knowledge and visceral information, which integrated in the right hemisphere, and

serves as an implicit marker for the early loss of empathy and presence of prosopagnosia (Acosta et al., 2025; Catricalà et al., 2019). One key diagnostic feature of rtvFTD is the dissociation between impaired explicit socioemotional processing and a potentially preserved implicit automatic priming for linguistic or quantitative-related domains, showing the uneven degradation of multimodal semantic systems (Catricalà et al., 2021). Neuroimaging evidence suggests that as the right ATL atrophy advances, the brain may attempt to compensate by over-engaging left-hemisphere language regions and posterior perceptual networks, although this reorganisation is often not enough for apparent behavioural and personality changes (Borghesani et al., 2021). Overall, while the core socioemotional concepts are degraded, residual activation in less affected semantic hubs can still support some forms of automatic priming, even when the ability to explicitly integrate social cues into appropriate behaviour is greatly impaired (Borghesani et al., 2021; Catricalà et al., 2021).

5.3 Semantic Priming and Abstract Concepts

Semantic priming is useful for studying abstract concepts as it provides an automatic measure of semantic memory with faster responses when a target follows a semantically related prime, and it suppresses the influence of deliberate and strategic retrieval processes that can complicate explicit naming or association tasks (Catricalà et al., 2021). The existing literature suggests that abstract concepts are not represented as a single homogeneous class, but rather draw on multiple dimensions such as affective, social, contextual, and linguistic information, with categories like emotions, social relations, cognitive states, and traits showing partly different representations (Della Rosa, 2024; Catricalà et al., 2019). Hence, this paradigm has shown to be particularly informative in characterising the representation of abstract concepts and differs from concrete concepts not only in their lack of physical referents but also in the multiple experiential dimensions that support their neural organisation (Della Rosa, 2014). Affective and social concepts resulted as particularly

relevant dimensions for specific classes of abstract concepts: for instance, affective information seems to play a continuous and graded role across abstract words, while social concepts like friendship are grounded in neural systems that support social cognition (Catricalà et al., 2019; Della Rosa, 2014). A state-dependent TMS-priming study in healthy participants showed that the right superior anterior temporal lobe selectively processes social concepts, with TMS abolishing the priming effect specifically for this category, while the right intraparietal sulcus contributes to quantity-related concepts (Catricalà et al., 2019). In the context of rtvFTD, where degeneration targets the right ATL, the disruption of these socioemotional semantic networks may underlie the early loss of empathy and altered social behaviour that characterise the syndrome, reflecting a specific breakdown of the non-verbal, affective dimensions of conceptual knowledge (Acosta et al., 2025; Ulugut et al., 2021).

5.4 Clinical and Research Relevance

Semantic priming paradigms offer a sensitive and complementary measure of the semantic network along with the standard neuropsychological tests. Because priming provides an automatic, implicit measure of semantic memory, it can detect preservation or degradation of conceptual knowledge that may not be caught by explicit tasks (Catricalà et al., 2021). This dissociation has diagnostic value in rtvFTD, where abolished priming for social-related abstract concepts (e.g., "glory" or "charm") serves as a cognitive marker for right superior anterior temporal lobe damage, potentially helping to differentiate rtvFTD from the behavioural variant of FTD (bvFTD), which is often a clinical confound (Catricalà et al., 2021; Rossi et al., 2022). Moreover, inter-individual variability in semantic priming effects further indicates differences in the reliance on semantic processing during reading, with priming magnitude for social concepts correlating with the right ATL, a region essential for integrating non-verbal and visceral information into social behaviours (Acosta et al., 2025). Recent longitudinal and neuroimaging approaches further indicate that while degeneration

starts in the right temporal lobe, the eventual spread of atrophy to the left hemisphere leads to a convergence of clinical symptoms into a multimodal semantic disorder (Ulugut et al., 2021). Altogether, these findings support the use of implicit priming paradigms, especially when combined with electrophysiological measures, as potential tools for early detection and differential diagnosis of rtvFTD, relative to other disorders such as Alzheimer's disease and behavioural variant FTD (Borghesani et al., 2021).

6. Aims of the Present Study

The present study aimed to investigate implicit semantic processing in patients with right temporal variant frontotemporal dementia (rtvFTD) using a semantic priming paradigm. In particular, semantic priming effects were examined across six categories of abstract concepts: social, emotional, moral, interoceptive, theoretical, and quantitative concepts.

By comparing the performance of patients with rtvFTD and healthy older adults, the study aimed to determine whether semantic priming effects differ between groups and whether patterns of semantic activation vary according to different abstract concept categories. Furthermore, the study aimed to explore the relationship between implicit semantic processing, as measured by semantic priming, and explicit semantic performance assessed through standard neuropsychological measures.

Based on previous clinical and neuropsychological evidence in right temporal variant frontotemporal dementia, we hypothesised that expected impairments in semantic processing for emotional, social, and interoceptive concepts (Ulugut et al., 2024; Younes et al., 2022) in patients relative to healthy controls, reflecting the known alterations of socioemotional and bodily conceptual representations in rtvFTD.

Methodology

7 Study Design

In this experimental study, a lexical decision task will be employed in a priming paradigm to investigate implicit semantic processing through the assessment of the priming effect and related measures. The design is cross-sectional with both a clinical group and a control group.

8 Participants

8.1 Sample Characteristics

The study involved two different groups of participants: a control group and an experimental group, whereby the participants were diagnosed with right temporal variant frontotemporal dementia (rtvFTD). The inclusion criteria for the study were patients with a diagnosis of rtvFTD for the experimental group based on established clinical for right temporal variant FTD (Ulugut et al., 2020; Ulugut et al., 2024; Younes et al., 2022), and the controls were recruited on a voluntary basis. Participants were excluded if they had any neurological, psychiatric, or other medical conditions that could compromise their performance on the test administered.

The control group initially included 27 healthy participants who completed both the neuropsychological assessment and the semantic priming task b,ut for analytical purposes, only 16 participants over the age of 60 were retained to ensure the results would be comparable to those of the experimental group ($M_{age} = 67.3,\ SD_{age} = 6.9;\ M_{education} = 11.8,\ SD_{education} = 3.9$). Lastly, the

experimental group consisted of 6 patients diagnosed with rvFTD, all males ($M_{age} = 76.33,\ SD_{age} = 5.54;\ M_{education} = 12.33,\ SD_{education} = 3.83$)

8.2 Neuropsychological assessment

Before the experiment, the participants underwent a neuropsychological battery to assess and characterise their cognitive and semantic abilities.

The following neuropsychological tests were used to assess the semantic cognition impairment level: naming of colored photographs from CaGi battery (CaGi - Denomination; Catricalà et al., 2012b), word-picture matching test from CaGi battery (CaGi - Comprehension; Catricalà et al., 2012b), naming of items from SAND battery (SAND - Denomination; Catricalà et al., 2017), and congruency to the target word from DeCAbs battery (DeCAbs - Association Task; Della Rosa et al., 2014). The Mini-Mental State Examination (MMSE; Folstein et al., 1975; Italian normative data by Measso et al., 1993) was used to assess the patient's global cognitive level.

CaGi - Denomination looks at the lexical access and naming ability, such as the retrieval of word forms from semantic memory and object and concept naming. The CaGi explicitly evaluates expressive semantic abilities and helps determine whether semantic deficits are present (Conca et al., 2025). For this assessment, the participants were asked to name coloured photographs without any time constraint. This allows for comparison between the explicit naming performance and implicit semantic processing, also known as the priming task (Conca et al., 2025).

CaGi - Comprehension assesses verbal semantic comprehension and evaluates cognitive domains including understanding of a word, semantic association and

categorisation, and language comprehension independent of speech production (Catricalà et al., 2012b). The subtest was a word-picture matching task in which the participant was presented with a spoken word and had to select the corresponding picture among four alternatives (the target, a semantic distractor, a visual distractor, and an unrelated item) (Catricalà et al., 2012b). In the current study, the purpose of the CaGi is to ensure that the reduced priming effect is not due to severe comprehension deficits (Catricalà et al., 2012b).

SAND (Screening for Aphasia and NeuroDegeneration) assesses semantic access in naming with a focus on neurodegenerative conditions, specifically to capture the core language features required for the diagnosis and classification of PPA (Catricalà et al., 2017). This subscale contains 14 hand-drawn black and white items divided into living (V) and non-living (LV), where participants had to name the stimulus in 6 seconds, whereby if they were unable to, a phonological cue was provided (Catricalà et al., 2017). The domains it evaluates include accuracy in naming and semantic errors as compared to phonological errors (Catricalà et al., 2017). This particular assessment is used in the study as it is sensitive to semantic degradation in dementia, and is a good complementary test to the CaGi as it provides more details and is useful to identify the different PPA variants.

DeCabs association task contains 40 items and 8 stimuli from five abstract categories that include human actions, cognition, traits, emotions, and social (Della Rosa et al., 2014). A target word is shown to the participant along with three different options, and they are asked to select the option that is more congruent with the target word (Della Rosa et al., 2014). This test allows for the assessment of conceptual reasoning in abstract concepts as well as semantic integration, which is relevant in the study as it allows for comparison between explicit semantic association and a more implicit priming.

MMSE determines the global cognitive functioning of the participant, which extends across various cognitive domains such as orientation, attention and concentration, immediate and delayed memory, language, and basic visual constructions (Arevalo-Rodriguez et al., 2015). The Italian normative study by Measso et al. (1993) provided age- and education-adjusted cutoff scores for the Italian population, and a corrected score of 24 or lower was considered indicative of cognitive impairment, consistent with the exclusion criteria adopted in the standardization samples of the other tests administered. The purpose of the MMSE in the present study is to provide a general overview of the participants' cognitive status, i.e., to characterise the cognitive impairment, but also to ensure they can understand the task instructions adequately.

9 Stimuli

The stimuli used in the semantic priming task consisted of two types of prime-target pairs: word-word pairs and word-pseudoword pairs. Word-word pairs were used to assess semantic priming effects, while pseudo-word pairs ensured the validity of the lexical decision task by requiring participants to discriminate between real words and pseudowords. The generation and selection procedures for both pair types are described in the following sections.

9.1 Word-word pairs

A database, developed by Borsa et al (2025), was used to select the stimuli, which consisted of nouns (n=206), belonging to the following semantic categories of interest: social, emotional, quantitative, theoretical, interoceptive, and moral. A total of 109 nouns were then selected manually from the database. This subset was selected to ensure balanced representation across semantic categories and to exclude items with incomplete or unreliable

ratings, while maintaining control over key psycholinguistic variables, for example, familiarity, concreteness, and age of acquisition, required for the experimental design.

A rating for the missing dimension was performed, where the participants saw each word one at a time and were asked to rate it across several dimensions i.e., Concreteness (CNC), Imaginability (IMG), Familiarity (FAM), Age of Acquisition (AoA), Emotional valence, Arousal, Social, Moral, Theoretical, Quantitative, Interoceptive, and Emotional dimensions. Each word from this task was rated by a minimum of 7 participants and a maximum of 13 participants ($M = 10.25, SD = 1.36$). Thereafter, 26 participants of which 11 males, ($M_{age} = 25.72, SD_{age} = 1.90$) were asked to rate the semantic similarity of 320 paired words created from the set of 109 stimuli based on a nine point likert scale, where 9 is highly similar and 1 is not similar. Each pair was evaluated by at least 7 participants and at most 10 participants ($M = 9, SD = 1.73$).

9.2 Generation of words pairs

Semantically related pairs

Careful considerations had to be made when generating the word pairs, either semantically related or unrelated. This was to ensure that each word had a clear demarcation to which category it belongs and had no overlap across word categories, hence avoiding confounds.

Seventy-two semantically related pairs were created, with 12 pairs for each of the six categories. The first word is the prime, and the second word is the target, where both words belong to the same category; for example, in the social category, the prime word would be ‘friend’ and the target ‘trust’.

To ensure that each word fit its designated category without any overlaps, they were rated based on the six categories separately. The primes and the targets would belong to a category in which they were rated higher by at least 0.5 using a paired sample t-test ($p < .001$), therefore, avoiding category mixing.

However, there have been some exceptions. For instance, the word 'formula' could belong to both the quantitative and the theoretical categories, which explains why the rating difference was considerably slimmer, with a difference of 0.23 instead of the usual 0.5, which was in favour of the theoretical category. Furthermore, exceptions were also made for emotional words as they tended to score high on both the emotion and interoceptive categories, but were ruled to be emotion words despite not enforcing the 0.5 rule. The overlap between emotional and interoceptive categories is an important nuance as they reflect real human cognition: while emotional words may overlap with interoceptive ones, they are distinguishable.

Semantically unrelated pairs

The control condition is made up of seventy-two semantically unrelated word pairs as well, with 12 pairs in each of the six categories. The unrelated pairs are formed by combining targets and primes from different categories, for example, 'pain' (interoceptive) and 'justice' (moral).

The formation of such pairs is carefully chosen by having the target preceded by primes from all five other categories. For instance, the social targets are preceded by 3 emotional primes, 3 theoretical primes, 2 moral primes, 2 quantitative primes, and 2 interoceptive primes. This method ensures that there are no biases and makes the unrelated pairs fair and balanced.

Moreover, the word pairs have to be balanced with each other, which is why the primes and the targets are matched for frequency, number of letters, number of syllables, bigram frequency (letter patterns), and familiarity (FAM) using a paired sample t-test ($p > .09$). This measure ensures that the one word in a pair is not longer or rarer than the other. This would help control for the eventuality that if someone is slower, it would not be due to the word itself but rather the meaning, hence controlling the primes and targets within a category. In addition to this, the six categories were balanced with respect to semantic similarity such that no categories were more closely related to another than the rest. The categories were also matched separately for primes and targets based on frequency, number of letters and syllables, bigram frequency, and FAM using a one-way ANOVA ($p > .16$). Hence, the categories are equally dissimilar from each other and equally easy at the word level, which means that no category has an advantage or disadvantage.

9.3 Generation of word - pseudoword Pairs

The word-pseudoword pair is half of the trials ($n = 144$), which forces the participant to make real lexical decisions. They consist of a prime, which is a real word, and the target, which is a made-up word selected from the Borsa et al. (2025) database. This ensures that the participant makes an active decision on whether the word is real or not. The pseudowords are created to emulate real target words that can be pronounced so that they look realistic, but inherently have no meaning. A total of 217 pseudowords were created by taking real target words and replacing a letter after a syllable. Pseudowords with a Levenstein distance of 1 or 2 were excluded from the pool ($n = 88$). The Levenstein distance is a string metric for measuring the amount of difference between two sequences (Greenhill, 2011).

Additionally, the length of the words in terms of syllables and letters was checked across four stimulus groups: primes in word-pseudoword pairs, targets in word-pseudoword pairs, primes in word-word pairs, and targets in word-word pairs. This ensures that the pseudowords are pronounceable but still distinct from real words; hence, the differences in performance of the participants can be attributed to the semantic processing, and not to word length, difficulty, or familiarity.

10. Task and Procedure

10.1 Task Description

The participants performed the lexical decision task in conjunction with a semantic priming paradigm. In each trial, the priming stimulus was presented first at 200 ms, and then it was followed by a blank screen at 50 ms, and then the target stimulus was shown, which remained on the screen until the participant gave a response, either a real word or a pseudoword. The stimulus presentation was such that the participants were seated 50 cm away from the monitor, and the letters were presented in white capital letters on a black background.

The participants responded to the target word by pressing one of two buttons with their right hand, B or N, as quickly and accurately as they could.

10.2 Experimental design and condition

A total of 288 trials were conducted, which were divided into two blocks of 144 trials each. Each block consisted of 72 word-word pairs and 72 word-pseudoword pairs which were presented in pseudorandomised order. The constraint was that no more than three word-word

or word-pseudoword pairs were shown consecutively. Two pseudorandomisation trials were created, lists A and B, and they were presented in a counterbalanced order across participants. The two trial blocks were also presented to all participants in the same sessions in a counterbalanced order as well.

10.3 Practice Session

Before the experimental trials were administered, the participants underwent a practice session, which lasted approximately 1 minute. The objective of the practice session was to have the participants familiarise themselves with the task and also confirm their understanding of the instructions and response mapping.

10.4 Variables

The study included three independent variables: pair type, semantic category, and matching condition.

The first independent variable was pair type, which comprised word-word pairs and word-pseudoword pairs. Word-word pairs were used to assess semantic priming effects through the presentation of semantically related and unrelated prime-target combinations. Word-pseudoword pairs were included to maintain the lexical decision component of the task by requiring participants to distinguish between real words and pseudowords.

The second independent variable was semantic category. The stimuli were divided into six categories of abstract concepts: emotional, quantitative, social, moral, theoretical, and interoceptive. Emotional stimuli represented affective states and were characterised by high ratings of emotional valence and arousal. Although some emotional words also received

relatively high interoceptive ratings, they were assigned to the emotional category because this dimension received the highest ratings. Quantitative stimuli consisted of concepts related to numbers, measurements, and mathematical reasoning. Some words, such as formula, showed overlap between the quantitative and theoretical dimensions but were classified according to their dominant semantic rating. Social stimuli comprised abstract concepts related to interpersonal relationships, social interactions, and societal structures. These words were selected because they received significantly higher ratings on the social dimension than on any other semantic dimension. Moral stimuli included concepts associated with ethics, values, and the distinction between right and wrong and were selected based on their predominance within the moral dimension. Theoretical stimuli referred to concepts associated with ideas, academic constructs, principles, and hypotheses. Finally, interoceptive stimuli represented internal bodily sensations and physiological states, reflecting concepts grounded in bodily awareness.

The third independent variable was the matching condition, which consisted of matched and unmatched trials. In the matched condition, the prime and target belonged to the same semantic category and were semantically related, whereas in the unmatched condition, the prime and target belonged to different semantic categories and were semantically unrelated.

The dependent variables included priming effect, accuracy, and d-prime (d'). The priming effect, calculated as the difference in reaction times between matched and unmatched conditions (Giffard et al., 2025). A larger difference between conditions was interpreted as a stronger semantic priming effect. Accuracy was calculated as the percentage of correct responses provided during the lexical decision task. Furthermore, d′ was computed according to Signal Detection Theory (Green & Swets, 1966) and provided a measure of participants' ability to discriminate between words and pseudowords while accounting for response bias.

Specifically, d′ was calculated as the difference between the z-transformed hit rate and false alarm rate (d′ = Z(Hits) − Z(False Alarms), where higher values indicate greater sensitivity in distinguishing words from pseudowords) (Green & Swets, 1966).

11 Data collection

The control group comprised 16 participants upon application of the exclusion criteria.($f = 8$, $M_{age} = 67.3$, $SD_{age} = 6.9$; $M_{education} = 11.8$, $SD_{education} = 3.9$).

Data was also collected from the experimental group, which consisted of patients diagnosed with right temporal variant frontotemporal dementia (rtvFTD). The experimental group included 6 males ($M_{age} = 76.33$, $SD_{age} = 5.54$; $M_{education} = 12.33$, $SD_{education} = 3.83$).

In the control group, the target word was displayed for only three seconds, as compared to the experimental group, which had ten seconds. This discrepancy is intentional to account for the cognitive impairment of the experimental group, hence why the response window has been adapted while maintaining the task structure.

12 Data Analysis

A pilot study was conducted before the main experiment to verify that the semantic priming paradigm elicited measurable priming effects across the semantic categories included in the task. The pilot sample consisted of nine healthy young adults (4 females; $M_{age} = 27.25$, $SD_{age} = 1.16$; $M_{education} = 15.5\ years$, $SD_{education} = 3.12$). The findings from the pilot study were used to confirm the suitability of the experimental design

before proceeding with the main analyses. The results of the pilot study are presented separately in the Results section.

Before the statistical analysis, the dataset was screened to ensure no entry errors were made and was subsequently cleaned to include only participants above the age of 60 years. Descriptive statistics were performed for all demographic and clinical variables in order to characterise the sample. Measures of central tendency and dispersion (means, standard deviations, and medians where appropriate) were reported for continuous variables, while frequencies and percentages were calculated for categorical variables, including sex distribution. Assumptions of normality were assessed using the Shapiro–Wilk test, and homogeneity of variance was examined using Levene's test. Based on these assumption checks, either parametric or non-parametric tests were applied for group comparisons.

The same strategy was applied for the group differences pertaining to the dependent variables of this study, where the assumption of normality was checked, and the independent samples t-test was applied accordingly. The Mann-Whitney test was applied if an assumption of normality was violated. A chi-square test was used for the categorical variables such as sex distribution. The level of statistical significance was set at $p < .05$. Effect sizes were calculated to complement significance testing, using Cohen's d for t-tests.

All statistical analyses were performed with Jamovi (Version 2.2). The graphs for the dependent variables were computed using R software.

Given the exploratory nature of the study and the novelty of the hypotheses tested across semantic categories, no correction for multiple comparisons was applied. Therefore, results should be interpreted with caution, as the probability of Type I error is increased across multiple tests.

Results

13 Participant Characteristics

The study included two groups of participants: a healthy control group (HC; n = 16) and a clinical group (rtvFTD; n = 6). Participants were compared on demographic and neuropsychological measures relevant to semantic and global cognitive functioning. All available data were included in the analyses, with no missing values across the variables of interest.

13.1 Pilot Study

A preliminary pilot study was conducted to confirm that the semantic priming task elicited measurable priming effects across the semantic categories included in the experiment. The pilot sample consisted of nine healthy young adults ($4\ females;\ M_{age} = 27.25,\ SD_{age} = 1.16;\ M_{education} = 15.5\ years,\ SD_{education} = 3.12$)

A priming effect was observed for all semantic categories, ranging from 0.35% for the theoretical category to 5.39% for the interoceptive category. These findings supported the use of the task in the main study.

13.2 Age and Education

Normality of the dependent variables was assessed using the Shapiro-Wilk test. For age, the assumption of normality was not violated $W = .918,\ p = .069$. However, for education, the distribution significantly deviated from normality $W = .883,\ p = .014$, indicating a violation of normality for this variable.

Given the mixed results of assumption checking, both parametric (independent samples *t*-tests) and non-parametric (Mann-Whitney U tests) results are reported..

There was a statistically significant difference in age between the two groups. Patients with rtvFTD ($M = 76.30$, $SD = 5.54$, $n = 6$) (see Table 1) were significantly older than the HC ($M = 67.30$, $SD = 6.90$, $n = 16$), $t(20) = -2.88$, $p = .009$, $Cohen's\ d = -1.38$. This indicates a large effect size. The non-parametric Mann-Whitney U test confirmed this result ($U = 14.00$, $p = .013$, $rank - biserial\ correlation = .71$).

There was no statistically significant difference in years of education between the two groups. HC ($M = 11.80$, $SD = 3.89$, $n = 16$) and rtvFTD ($M = 12.30$, $SD = 3.83$, $n = 6$) did not differ significantly ($t(20) = -0.31$, $p = .756$, $Cohen's\ d = -0.15$). The Mann-Whitney U test similarly indicated no significant difference

($U = 41.00$, $p = .617$, $rank - biserial\ correlation = .15$) *(See Table 2).*

Table 1

Group Descriptives for Age and Education

	Group	N	Mean	Median	SD	SE
age	1	16	67.3	65.5	6.90	1.726
	2	6	76.3	76.5	5.54	2.26
education	1	16	11.8	12.0	3.89	0.973
	2	6	12.3	13.0	3.83	1.56

Note. *N* = sample size; *M* = mean; *SD* = standard deviation; *SE* = standard error.

Table 2

Independent Samples T-Test for Age and Education

		Statistic	df	p		Effect Size
age	Student's t	-2.880	20.0	0.009	Cohen's d	-1.379
	Mann-Whitney U	14.0		0.013	Rank biserial correlation	0.708
education	Student's t	-0.314	20.0	0.756	Cohen's d	-0.151

Mann-Whitney U	41.0	0.617	Rank biserial correlation	0.146	

Note. *df* = degrees of freedom; *p* = probability value; *t* = Student's *t* statistic; *d* = Cohen's *d* effect size; *U* = Mann–Whitney *U* statistic.

The HC group contained 8 male participants and 8 female participants as shown on Table 3, whereas the rtvFTD group contained 6 male participants and no females. These deviations from the expected frequencies suggested that sex was not evenly distributed across the two groups. The chi-square test of independence was conducted to examine the association between group membership and sex distribution. The results indicated a statistically significant association between group and sex, $\chi^2(1, N = 22) = 4.71, p = .030$ *(see Table 4).*

Table 3

Contingency Table for Sex Distribution

		Group		
sex		**1**	**2**	**Total**
0	Observed	8	6	14
	Expected	10.18	3.82	14.00
1	Observed	8	0	8
	Expected	5.82	2.18	8.00
Total	Observed	16	6	22
	Expected	16.00	6.00	22.00

Note. *Group 1* = controls; *Group 2* = rtvFTD. Sex was coded as 0 = male and 1 = female. Observed frequencies represent the actual counts in each cell, whereas expected frequencies are based on the assumption of independence between variables. The analysis was conducted using a chi-square test of independence (χ^2).

Table 4

χ^2 Tests

	Value	df	p
χ^2	4.71	1	0.030
N	22		

Note. χ^2 = chi-square test statistic; *df* = degrees of freedom; *p* = probability value; *N* = total sample size.

13.3 Neuropsychological Performance

Descriptive statistics for neuropsychological performance in controls and rtvFTD patients are presented in Table 5. Overall, controls showed higher mean scores than rtvFTD patients across most measures. For Abstract Decision Accuracy, performance was similar between controls ($M = 37.4$, $SD = 2.17$) and rtvFTD patients ($M = 36.0$, $SD = 2.29$), with no deviations from normality in either group ($controls$: $W = 0.923$, $p = .190$; $rtvFTD$: $W = 0.986$, $p = .978$). For Category Identification – Naming, controls ($M = 46.8$, $SD = 1.24$) scored higher than rtvFTD patients ($M = 43.6$, $SD = 3.63$), with a violation of normality in the control group ($W = 0.836$, $p = .008$) and no violation in the rtvFTD group ($W = 0.958$, $p = .802$). For Category Identification – Comprehension, controls ($M = 48.0$, $SD = 0.00$) showed slightly higher scores than rtvFTD patients ($M = 47.7$, $SD = 0.82$), with a significant deviation from normality in the rtvFTD group (0.503, $p < .001$). For the Mini-Mental State Examination (MMSE), controls ($M = 28.9$, $SD = 1.15$) obtained higher scores than rtvFTD patients ($M = 25.0$, $SD = 5.72$), with deviations from normality observed in both

groups ($controls$: $W = 0.881$, $p = .041$; $rtvFTD$: $W = 0.787$, $p = .045$). For SAND – Total Naming Score, controls ($M = 13.5$, $SD = 0.712$) performed higher than rtvFTD patients ($M = 11.6$, $SD = 2.31$), with non-normal distribution in the control group ($W = 0.705$, $p < .001$) and no deviation in the patient group ($W = 0.928$, $p = .568$). Finally, for SAND – Living Items Naming Score, controls ($M = 6.71$, $SD = 0.458$) scored higher than rtvFTD patients ($M = 5.30$, $SD = 1.90$), with a violation of normality in the control group ($W = 0.652$, $p < .001$)and no significant deviation in the rtvFTD group ($W = 0.891$, $p = .326$).

Table 5

Descriptive statistics for neuropsychological performance in controls and rtvFTD patients

Measure	Group	N	Mean	Median	SD	W	p
Abstract Decision Accuracy (%)	Controls	16	37.4	37.5	2.17	0.923	.190
	rtvFTD	6	36.0	36.2	2.29	0.986	.978
Category Identification – Naming (%)	Controls	16	46.8	47.0	1.24	0.836	.008
	rtvFTD	6	43.6	43.8	3.63	0.958	.802
Category Identification – Comprehension (%)	Controls	16	48.0	48.0	0.00	—	—
	rtvFTD	6	47.7	48.0	0.823	0.503	< .001
Mini-Mental State Examination (MMSE)	Controls	16	28.9	29.0	1.15	0.881	.041
	rtvFTD	6	25.0	26.4	5.72	0.787	.045
SAND – Total Naming Score	Controls	16	13.5	14.0	0.712	0.705	< .001
	rtvFTD	6	11.6	11.8	2.31	0.928	.568
SAND – Living Items Naming Score	Controls	16	6.71	7.00	0.458	0.652	< .001
	rtvFTD	6	5.30	5.72	1.90	0.891	.326

Note. N = sample size; SD = standard deviation; W = Shapiro–Wilk test statistic; p = probability value. MMSE = Mini-Mental State Examination; SAND = Screening for Aphasia in NeuroDegeneration; rtvFTD = right temporal variant frontotemporal dementia.

To determine whether patients and healthy controls differed in semantic priming performances, a series of Mann-Whitney U tests were done for each semantic category for both healthy controls and the patient group presented in Table 6. The three main outcomes that were analysed were the priming effect magnitude, overall accuracy, and d'.

14 Analysis of Dependent Variables

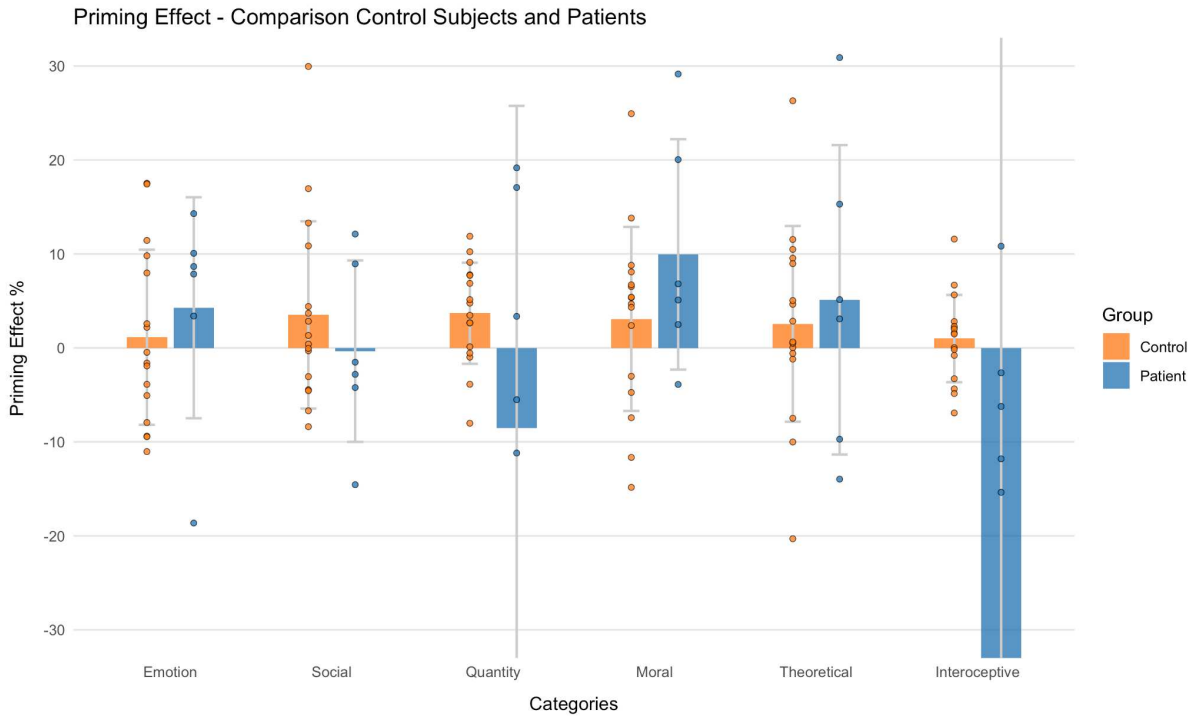
14.1 Priming Effects

The comparisons of the priming effects revealed a relatively preserved semantic priming across most semantic abstract categories. There were no significant group differences noted for the emotional ($U = 35.00, p = .367$), social ($U = 39.00, p = .541$), quantitative ($U = 40.00, p = .590$), moral ($U = 35.00, p = 367$), or theoretical ($U = 42.00, p = .693$) categories, as shown in Figure 1. Moreover, the effect sizes for the above four categories ranged from small to negligible with rank-biserial correlations between .13 and .27, which ultimately suggests that the magnitude of facilitation produced by the congruent stimuli was largely equivalent between the patient group and healthy controls.

On the other hand, a significant group difference could be observed for the interoceptive category ($U = 20.00, p = .040$), with a moderate-to-large effect size ($r = .58$). This finding indicates that the two groups had differences in the extent to which congruent interoceptive information facilitated their performance. Unlike the other semantic categories, interoceptive processing was found to be associated with altered priming effects in the patient group.

Figure 1

Priming Effects Between Control and Patients with rtvFTD



Note. Bars represent the group mean semantic priming effect (%) across the six abstract semantic categories. Individual dots represent participant values, and error bars indicate ±1 standard deviation. Positive values indicate faster responses for semantically related than unrelated prime-target pairs.

14.2 Accuracy

The comparison of the overall task accuracy across the semantic categories showed no statistically significant differences between the rtvFTD patients and the healthy controls. The non-significant values were as follows: emotional ($U = 46.00$, $p = .893$), social ($U = 29.50$, $p = .090$), quantitative ($U = 35.50$, $p = .284$), moral

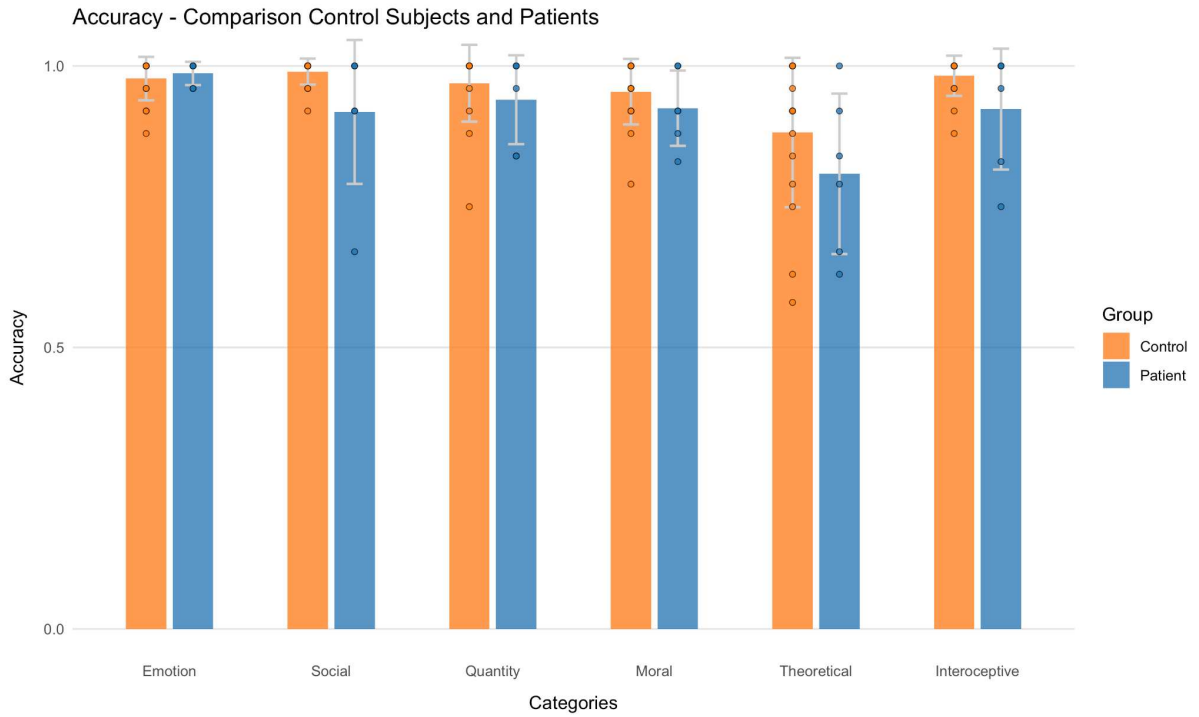
($U = 34.40$, $p = .316$), theoretical ($U = 33.00$, $p = .277$), and interoceptive ($U = 33.00$, $p = .195$).

The respective effect sizes were also generally small, which indicates a limited difference in overall performance accuracy between the two groups. Moreover, the social category approached statistical significance and showed a somewhat larger effect size ($r = .39$) compared to the remaining categories, but still did not reach the threshold for statistical significance.

These findings overall indicate that patients were able to perform the task with levels of accuracy similar to those of healthy controls across all semantic categories *(see Figure 2)*.

Figure 2

Accuracy between Controls and Patients with rtvFTD



Note. Bars represent the mean lexical decision accuracy for healthy controls and patients with rtvFTD across the six abstract semantic categories. Individual dots represent participant values, and error bars represent ±1 standard deviation.

14.3 d-prime (d')

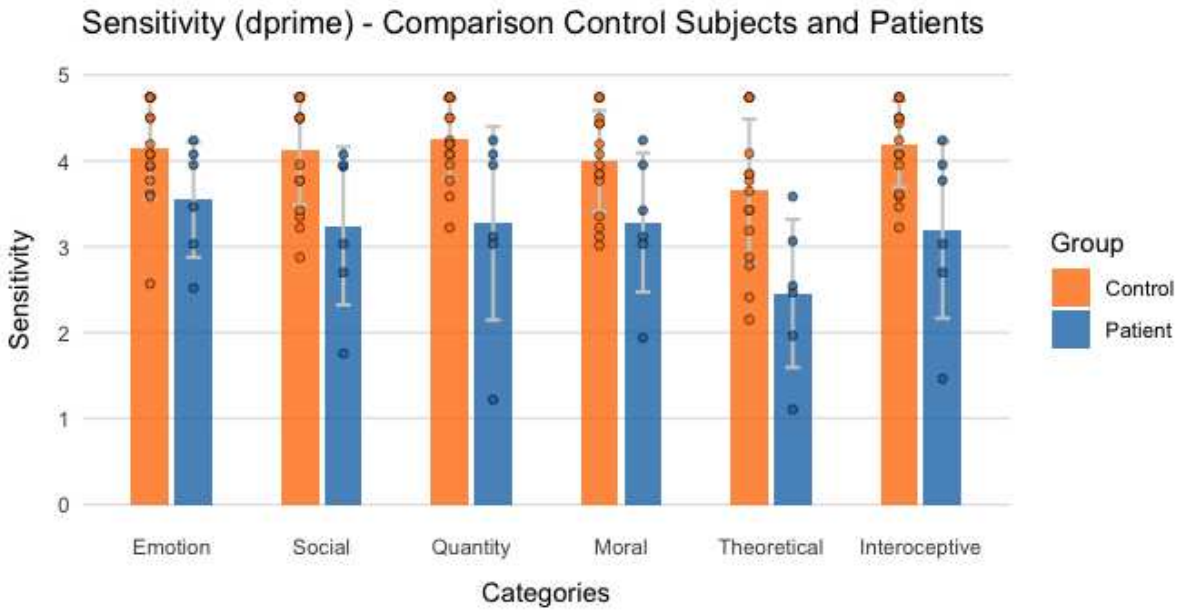
In terms of the d' analysis, a different pattern emerged, which is illustrated in Figure 3. Significant group differences were identified in multiple semantic categories, which suggests that patients experienced difficulties discriminating target stimuli despite their relatively preserved accuracy.

A significant difference was observed in the social category ($U = 21.00,\ p = .049$), with a moderate-to-large effect size ($r = .56$). Similarly, significant group differences were also observed in the quantitative ($U = 17.00,\ p = .0.23,\ r = .65$), theoretical ($U = 15.00,\ p = .016,\ r = .69$), and interoceptive ($U = 16.00,\ p = .020,\ r = .67$) categories. In addition to this, the effect sizes associated with these comparisons were also consistently large, which indicates a substantial difference in the ability to discriminate relevant stimuli between groups.

Although the emotional and moral categories did not reach statistical significance, both showed moderate effect sizes and results approaching significance. For the emotion category, the comparison was not statistically significant ($U = 23.50,\ p = .075$), although a moderate effect size was observed ($r = .51$). Similarly, the moral category did not reach statistical significance ($U = 24.00,\ p = .082$), but was associated with a moderate effect size ($r = .50$),

Figure 3

d-prime (*d'*) *between Controls and Patients with rtvFTD*



Note. Bars represent the mean d-prime (*d'*) scores for healthy controls and patients with rtvFTD across the six abstract semantic categories. Individual dots represent participant values, and error bars represent ±1 standard deviation. Higher d′ values indicate greater sensitivity in discriminating words from pseudowords.

Table 6

Group comparisons between healthy controls and patients with rtvFTD across semantic categories

Semantic Category	Measure	U	p	Rank-biserial r	Significant?
Emotional	Priming Effect	35.0	.367	.27	No
	Accuracy	46.0	.893	.04	No
	d′	23.5	.075	.51	Trend
Social	Priming Effect	39.0	.541	.19	No
	Accuracy	29.5	.090	.39	Trend
	d′	21.0	.049	.56	**Yes**
Quantitative	Priming Effect	40.0	.590	.17	No
	Accuracy	35.5	.284	.26	No
	d′	17.0	.023	.65	**Yes**
Moral	Priming Effect	35.0	.367	.27	No
	Accuracy	34.5	.316	.28	No
	d′	24.0	.082	.50	Trend
Theoretical	Priming Effect	42.0	.693	.13	No
	Accuracy	33.0	.277	.31	No
	d′	15.0	.016	.69	**Yes**
Interoceptive	Priming Effect	20.0	.040	.58	**Yes**
	Accuracy	33.0	.195	.31	No

d′	16.0	.020	.67	**Yes**

Note. Mann–Whitney U tests were conducted to compare healthy controls and patients. Rank-biserial correlation (r) is reported as the measure of effect size. Significant results ($p < .05$) are shown in bold. "Trend" refers to comparisons approaching significance ($p < .10$).

Discussion

15 Brief Overview of Findings

The present study investigated semantic priming across six different categories of abstract concepts in patients with rtvFTD and healthy controls. Specifically, the study aimed to explore whether implicit semantic processing differs between groups and whether distinct categories of abstract concepts show differential vulnerability to right temporal lobe degeneration. The neuropsychological tests conducted revealed significant group differences on measures of semantic functioning, whereby patients with rtvFTD performed significantly worse than the healthy controls on the CaGi Comprehension task and the SAND Denomination Total score. In addition to this, a trend towards significance was also observed for CaGi Denomination. On the other hand, no significant differences were found on measures of global cognitive functioning, including the MMSE and DeCAbs which suggests a relatively preserved general cognition within the patient group.

In the context of the experimental task, group differences varied depending on the outcome measure. Performance accuracy did not differ significantly between healthy controls and patients with rtvFTD across the six semantic categories, indicating that both groups were able to perform the lexical decision task successfully.

Similarly, semantic priming effects were largely preserved in patients with rtvFTD, with no significant differences emerging for the social, emotional, moral, theoretical, or quantitative categories. However, a significant group difference emerged only for interoceptive concepts which suggests that there is a selective alteration in the processing of this category. Importantly, this finding is in line with with previous literature showing that rtvFTD is associated with impaired conceptual processing of bodily and interoceptive information, likely reflecting disruption of socio-emotional and self-referential semantic

systems (Marshall et al., 2017; Migeot et al., 2022; Connell et al., 2018). This result ultimately aligns with our initial hypothesis which predicted a selective vulnerability of interoceptive semantic processing in rtvFTD.

Concerning d-prime (d'), there were significant group differences across several categories. Patients with rtvFTD showed reduced d' for social, quantitative, theoretical, and interoceptive concepts, while emotional and moral showed trends towards significance but did not reach the threshold for statistical significance. The impairment observed for interoceptive concepts is again consistent with the hypothesis of the present study and is also seen in prior research that highlight altered bodily and socio-emotional semantic representations in rtvFTD (Marshall et al., 2017; Mancano & Papagno, 2025; Younes et al., 2022). Moreover, significant reductions in d' for quantitative and theoretical concepts were not fully anticipated based on the initial hypotheses. While semantic impairments in rtvFTD have been most consistently reported for social and interoceptive domains, broader involvement of abstract conceptual knowledge systems has been proposed in models of semantic cognition (Borghi et al., 2017; Hoffman et al., 2018; Rogers et al., 2004), which may extend to more abstract, knowledge-based categories such as quantitative and and theoretical concepts. However, empirical evidence specifically linking rtvFTD to quantitative or theoretical semantic deficits remains limited and less consistent as compared to social and interoceptive concepts. Hence, these findings may suggest a more widespread disruption of abstract semantic representations in rtvFTD than originally expected. Thus, these findings may suggest that although patients were generally able to perform the task accurately and showed preserved semantic priming effects across most categories, more subtle impairments in discriminating between words and pseudowords were present, as indicated by the d'.

Overall, the results support a pattern of selective semantic vulnerability rather than a global semantic deficit in rtvFTD. The presence of category-specific effects, particularly

interoceptive concepts, is critical as it indicates that impairments are not driven by a uniform breakdown of semantic processing. Instead, selectively strengthens the interpretation that rtvFTD is characterised by targeted degradation of specific conceptual domains, which directly supports the aims of the present study.

16 Neuropsychological Findings

As mentioned aboveforth, the neuropsychological assessments conducted revealed that patients with rtvFTD had a relatively preserved global cognitive functioning as seen in the lack of significant difference between the control and patient group for MMSE and DeCAbs battery. However, there were genuine semantic deficits revealed by the significant group differences in the CaGi comprehension task and the SAND denomination, with a trend towards significance in the CaGi denomination task. This dissociation between impaired semantic measures and preserved global cognition is quite clinically meaningful, as it suggests that the present findings of this experimental study are unlikely to be attributed to a generalised cognitive decline but rather that the deficits seem to be more selective. This is consistent with the characterisation of rtvFTD as the disorder is driven by the degenerative progression of the ATLs, which play a role in semantic representation (Younes et al., 2022; Ulugut et al., 2020). The findings are consistent with the existing literature where the predominant right anterior lobe degeneration is marked by the early loss of empathy and person-specific semantic impairment, which is supposed to be driven by a progressive decline in semantic memory of concepts for socioemotional relevance rather than a decline in global cognition (Younes et al., 2020). Similarly, clinical radiological frameworks have identified that word-finding difficulties, episodic memory deficits and behavioural changes are prominent features of rtvFTD while establishing a difference from the behavioural variant

FTD and Alzheimer's Disease based on its distinct neuropsychological features (Ulugut et al., 2020). Hence, these findings altogether support the interpretation that the neuropsychological profile seen in this sample reflects a genuine and selective disruption of category-specific semantic processing consistent with the known clinicopathological characteristics of rtvFTD.

Moreover, it is also important to note that the MMSE is widely used as a brief cognitive screening tool and has known limitations in discerning domain-specific deficits in frontotemporal dementia spectrum disorders. The MMSE mostly focuses on orientation, attention, and memory, which are all aspects that remain relatively preserved in early rtvFTD, and has been shown to be less sensitive than more specific brief cognitive instruments like the Mini-Addenbrooke's Cognitive Examination (M-ACE) in frontotemporal dementia populations (Hsieh et al., 2014). In addition to this, other existing literature on the MMSE reported that it tends to overestimate cognitive preservation in primary progressive aphasia patients, since it tends to focus on memory and misses other subtle and specialised deficits in other areas like language and executive control (Osher et al., 2007).

17 Semantic Priming Findings

17.1 Preserved Semantic Priming Across Most Categories

The semantic priming results revealed no significant group differences in most categories between healthy controls and patients for emotional, social, moral, theoretical, or quantitative concepts, suggesting broadly similar levels of automatic semantic activation across groups. This pattern should not be interpreted as evidence of preserved semantic memory in rtvFTD, but rather as indicating that residual semantic network dynamics may still support implicit processing despite impaired explicit conceptual functioning.

This dissociation is consistent with models of semantic cognition distinguishing between automatic spreading activation and controlled semantic retrieval processes (Davey et al., 2015; Hoffman et al., 2018). Lexical decision tasks primarily engage automatic activation mechanisms, which are less dependent on higher-order control systems implicated in explicit semantic access. Neurocognitive accounts further suggest that priming reflects early, automatic activation within distributed semantic networks, whereas explicit semantic judgments require additional integrative and control processes supported by temporoparietal and frontal regions (Gold et al., 2006; Davey et al., 2015).

Within the hub-and-spoke framework, the anterior temporal lobe supports the integration of modality-specific information into coherent conceptual representations (Catricalà et al., 2019). In rtvFTD, degeneration of right anterior temporal regions may differentially affect representational richness and precision while leaving some automatic activation processes relatively intact (Younes et al., 2022; Davey et al., 2015). However, this interpretation must be considered alongside the reduced d' observed across several categories, including social, quantitative, theoretical, and interoceptive concepts.

Overall, the combined pattern suggests that automatic semantic activation may remain partially preserved in rtvFTD, whereas the distinction of specific conceptual representations may be compromised. Rather than reflecting a global semantic deficit, the findings are more consistent with selective degradation of representational specificity across particular semantic domains (Rogers et al., 2004; Hoffman et al., 2018).

17.2 Interoceptive Concepts as a Unique Category

In our sample, interoceptive concepts were the only category to show statistically significant reduction of the semantic priming effect. The selective alteration in semantic

priming for interoceptive concepts, in contrast to the relative preservation observed in other abstract categories, suggests that these concepts constitute a unique and highly vulnerable semantic domain. Within the framework of embodied cognition, interoceptive concepts such as “hunger”, “thirst” or “fatigue”, are uniquely grounded in internal bodily representations which are more fundamental in how we construct meaning, as our understanding of abstract ideas is built upon physical sensations rather than just logical definitions, which ultimately play a more substantial role in grounding abstract knowledge than traditional exteroceptive senses (Connell et al., 2018). The disruption of this category in rtvFTD may be attributed to the progressive degeneration of the anterior insula and the associated networks, which are important for the integration of interoceptive signals with emotional and self-referential information (Migeot et al., 2022).

Importantly, this interpretation is supported by clinical and neurocognitive findings in FTD showing alterations in bodily awareness and interoceptive processing. Patients with rtvFTD have been reported to show abnormal reactions to internal bodily states and altered perception of physiological signals, consistent with disrupted interoceptive monitoring and self-referential processing (Migeot et al., 2022; Marshall et al., 2017). In addition, recent evidence highlights specific impairment in the semantic processing of bodily and interoceptive concepts in semantic and behavioural variants of FTD, further supporting the notion that this domain is selectively vulnerable in neurodegenerative disease affecting anterior temporal and insular networks (Younes et al., 2022; Marcano & Papagno, 2025).

Another interpretation is that neuroanatomical findings have has shown that interoceptive accuracy and the processing of socioemotional abstract concepts converge in the right anterior insula, a region that serves as a primary hub for representing homeostatic signals and constructing a coherent sense of the bodily self and self-related information, they may be susceptible to the “allostatic-interoceptive overload” characteristic of frontotemporal

degeneration, where the brain's ability to model and predict internal states is compromised (Migeot et al., 2022). However, given the small sample size of the present study, which is often the case in the study of rare neurodegenerative variants, the finding of selective priming must be considered preliminary.

18 d-prime (d') findings

One of the most significant findings of the present study is the dissociation between preserved lexical decision accuracy and reduced d' across multiple categories in patients with rtvFTD. Both groups performed the task with good levels of accuracy, patients with rtvFTD showed lower d' for social, quantitative, theoretical, and interoceptive, with trends towards significance for emotional and moral concepts. These results indicate a substantial difference in the ability to discriminate real words from pseudo-words across the abstract concepts. The pattern suggests that d' captures a subtle, gradual impairment in semantic processing that accuracy measures alone may overlook, consistent with signal detection accounts, which propose that d' reflects the strength of the internal evidence on which lexical decisions are based (Rhodes et al., 1993). This interpretation is supported by evidence that lexical decision performance in semantic dementia is shaped by the integrity of semantic representations, with d' providing a more graded index of discrimination ability than binary accuracy scores (Patterson et al., 2006). The preservation of accuracy alongside reduced d' implies that residual knowledge and semantic knowledge may still support coarse lexical decisions, while finer discrimination between semantically overlapping items becomes compromised (Jefferies et al., 2009). This aligns with the profile of gradual semantic degradation in semantic dementia, in which conceptual boundaries become less distinct and items sharing overlapping features become harder to differentiate from one another (Jefferies et al., 2009).

The category-specific pattern of reduced d' further shows the differential alterations of abstract concepts in rtvFTD (Borghi et al., 2017). Concepts relying on social, interoceptive, and theoretical dimensions showed the most apparent reductions in d', which is consistent with the idea that these dimensions depend on distributed networks that include the right anterior temporal regions that are affected in this syndrome (Borghi et al., 2017). On the other hand, emotional and moral concepts showed only trends towards impairment, possibly reflecting partial preservation of affective processing networks or greater reliance on left-hemisphere language systems that remain relatively spared in early rtvFTD (Younes et al., 2022). This selective pattern suggests that d' may be particularly sensitive to the breakdown of non-verbal and socioemotional semantic representations that characterise right temporal degeneration (Younes et al., 2022).

Connectionist models of semantic deterioration provide an account of this accuracy dissociation by positing that as semantic representations degrade in a distributed network, the system progressively loses the ability to generate distinctive features for individual items, while still retaining broad categorical information (Rogers et al., 2004). In this framework, words and pictures continue to generate meanings even when knowledge is severely degraded, but the meanings derived for semantically related items grow increasingly indistinguishable from one another (Rogers et al., 2004). In the current task, this means that patients with rtvFTD can still recognise a target word as a real word, because the degraded representations still carry sufficient information to differentiate it from a pseudo-word. However, the precision of that representation is still diminished, resulting in weaker signal strength and thus lower d' (Rhodes et al., 1993). The graded nature of this deterioration may also explain why moral and emotional concepts showed only trends towards significance, as they rely on regions or networks that are partially but not yet fully compromised (Ralph et al., 2006).

19 Implicit and Explicit Semantic Processing

The present findings suggest different patterns of performance across explicit and implicit measures of semantic processing in patients with rtvFTD. While patients showed impaired performance on explicit neuropsychological assessments of semantic knowledge, semantic priming effects were largely preserved across most abstract concept categories, with the exception of the interoceptive concepts. However, significant impairments in d' across several semantic categories indicate that not all aspects of implicit semantic processing were preserved. Together, these findings suggest that different components of semantic processing may be differently affected in rtvFTD.

This may be explained by the fact that explicit semantic tasks require controlled retrieval, selection, and integration of conceptual information, which places higher demands on semantic control systems and frontotemporal-parietal networks than automatic priming processes (Davey et al., 2015; Hoffman et al., 2018; Gold et al., 2006). This distinction is relevant in rtvFTD, where the right ATL is thought to play a critical role in integrating non-verbal and socioemotional semantic representations (Younes et al., 2022). This interpretation is further supported by evidence that the right ATL is specialised for processing socioemotional and person-specific semantic knowledge, domains that may rely more heavily on controlled retrieval mechanisms (Younes et al., 2022; Catricalà et al., 2019). More generally, explicit semantic judgments require flexible access to context-appropriate conceptual representations, which is particularly vulnerable when anterior temporal and connected networks are compromised (Rogers et al., 2004; Hoffman et al., 2018; Tee & Gorno-Tempini, 2019).

In contrast, automatic spreading activation within the semantic network may depend less on the integrity of this region and can therefore remain relatively preserved even when

right temporal atrophy is present (Gold et al., 2006; Davey et al., 2015; De Zubicaray et al., 2010). This reflects the fact that priming is primarily driven by fast, automatic co-activation of distributed semantic representations and is less dependent on controlled retrieval or executive semantic demands (Davey et al., 2015; Gold et al., 2006). Nevertheless, the impaired d' observed across several semantic categories should not be interpreted as evidence of globally impaired implicit semantic processing. Rather, the findings indicate that while automatic semantic activation may remain relatively resilient, other aspects of lexical-semantic processing, such as discriminating between words and pseudowords, are already compromised in rtvFTD. The selective vulnerability of explicit semantic retrieval in rtvFTD, together with reduced lexical discrimination, may therefore reflect the disruption of right-lateralised networks that support the strategic access and integration of socioemotional conceptual knowledge, rather than a general breakdown of semantic representations (Younes et al., 2022).

20 Implications for Theories of Abstract Concepts

The category-specific pattern of results in the present study has some implications for multidimensional theories of abstract concepts. These theories propose that abstract concepts are not a homogeneous class but instead draw on multiple experiential dimensions, including affective, social, interoceptive, and magnitude-related information (Borghi et al., 2017), which is supported by the findings that not all abstract concepts showed equivalent priming or d' profiles. In particular, the interoceptive concept showed to be selectively impaired with both reduced priming effect and significantly lower d' in patients with rtvFTD, while they resulted in more preserved in the processing of other categories. These results suggest that

different categories of abstract concepts may rely on partially distinct brain regions that are differentially vulnerable to right ATL degeneration (Borghi et al., 2017).

These findings can also be interpreted within graded hub-and-spoke models of semantic memory, which propose that the anterior temporal lobes function as transmodal hubs that integrate information from modality-specific spokes (Rogers et al., 2004). According to these models, the right anterior temporal lobe is particularly specialised for integrating non-verbal and socioemotional information (Younes et al., 2022). The selective impairment of interoceptive concepts observed here may therefore reflect the disruption of right-lateralised interoceptive spokes and their integration within the right ATL hub, while emotional and social concepts may benefit from additional or overlapping bilateral connections that remain relatively preserved in early rtvFTD (Hoffman et al., 2018).

Taken together, these results support the view that abstract concepts are organised along multiple, partially dissociable dimensions, and that theoretical models must account for the differential neural grounding of specific categories (Borghi et al., 2017). The selective alterations of interoceptive concepts, in contrast to the relative preservation of other types of concepts, suggests that right temporal regions may play a particularly important role in supporting interoceptive dimensions of abstract meaning (Mancano & Papagno, 2025). This has broader implications for understanding how different types of abstract concepts are represented and how they may be differentially affected by focal neurodegeneration.

21 Limitations

Several limitations of the present study should be acknowledged. First, the sample size of patients with rtvFTD was relatively small, which limits the generalisability of the findings and may have reduced statistical power to detect more subtle group differences and could have also given rise to type II errors. Furthermore, the study was cross-sectional in

nature, precluding any conclusions regarding the progression of semantic impairment over time or the potential utility of semantic priming as a longitudinal marker. In addition to this, although efforts were made to match groups on demographic variables, the influence of potential confounding factors such as medication use, disease severity, and individual differences in cognitive reserve cannot be fully excluded. Importantly, there were group differences in age and education, as well as sex distribution, which may have influenced performance on some of the semantic measures and therefore limit the interpretation of results. However, the observation that group differences were not uniform across all semantic measures, but instead emerged selectively for specific categories, suggests that these effects may not be entirely explained by demographic differences alone. Rather, the pattern of results may reflect underlying neurobiological differences between patients with rtvFTD and healthy controls, which contribute to category-specific impairments beyond what is expected from age, education, or sex alone. Moreover, the findings are preliminary and require replication in larger, independent cohorts before firm conclusions can be drawn regarding the clinical utility of implicit semantic measures in rtvFTD. In addition to this, a limitation of the present study is that multiple statistical comparisons were conducted across semantic categories and outcome measures without applying corrections for multiple testing. Although this approach was justified by the exploratory nature of the study, it increases the risk of Type I error and means that some significant findings may be due to chance; hence, future studies with larger samples should apply appropriate corrections for multiple comparisons to confirm the strength of these effects. Finally, another limitation is that no MRI data were acquired for this study; therefore, linking specific cognitive impairments to certain brain regions or network alterations was not possible.

22 Future Directions

Several directions can be implemented to ensure the strengthening of the present findings, as well as means to extend them. Replication in larger and multicentre cohorts would increase the statistical power and improve the generalisability of the framework of rtvFTD. Moreover, longitudinal studies would provide insights about the progression of the disease in terms of semantic priming and d' could potentially serve as early biomarkers, in addition to already existing approaches in the research and diagnosis of diseases in the frontotemporal dementia spectrum. In addition to this, correlating the behavioural performance with structural and functional imaging would help establish a direct link to the neural substrates of category-specific semantic deficits, in particular the contribution of the right ATL and insula. This triangulation method would help in strengthening the data. Moreover, extending the paradigm to concrete concepts as well would also be valuable, as it would allow a direct comparison between abstract and concrete concept semantic processing as seen in studies of semantic dementia (Jefferies et al., 2009). Finally, another comparison worth exploring is a direct comparison between svPPA and rtvFTD, which would help establish the specificity of the observed patterns and their potential diagnostic utility.

Conclusion

In conclusion, the present study provides support for the selective alterations of implicit semantic processing of different types of abstract concepts in patients with rtvFTD, when compared to healthy controls. While semantic priming effects were largely maintained across most abstract concept categories, patients demonstrated alterations in d' for social, quantitative, theoretical, and interoceptive concepts, suggesting that their semantic representation is compromised. The selective vulnerability of interoceptive concepts shows the importance of considering multiple dimensions in theories of abstract concept representations and points to a particular role for the right ATL regions in supporting interoceptive semantic knowledge. These findings suggest that implicit measures can thus contribute to a more nuanced understanding of semantic impairment in rtvFTD. All in all, the results support the value of including both implicit and category-specific measures when investigating semantic cognition in neurodegenerative diseases.

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