Gamma Motor Neurons:
The Silent Orchestrators of Embodied Attention

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Abstract

This article proposes a novel paradigm for understanding the role of gamma motor neurons (γMNs) in attention. Traditionally viewed as mere regulators of proprioceptive sensitivity during movement (α–γ coactivation), we suggest that γMNs are, in reality, active orchestrators of a brain-controlled sensory preamplification mechanism. This top-down gamma modulation enables precise and targeted attentional focus in all its forms: from internal attention (such as body awareness and interoception) to multimodal external attention (visual, auditory, tactile, chemical). The classical model of proprioception fails to explain how attention can refine perception in the absence of macroscopic movement. The hypothesis outlined here addresses this gap by showing how γMNs can enhance the salience of subtle signals stemming from basal muscle tone, intrinsic body micro-oscillations, or simple motor intention. Through this modulation, muscle spindles become hypersensitive, amplifying proprioceptive feedback and providing a fundamental bodily anchor for the direction and quality of attention. My approach aligns with theories of predictive control and embodied cognition, while distinguishing itself from—and integrating critiques of—the premotor theory of attention. While the latter emphasizes the preparation of macroscopic movements (e.g., saccades) for spatial attention, the γMN hypothesis proposes a more microscopic, peripheral mechanism that supports attention at a deep level, rendering the body an active instrument for sensory exploration. This article offers a concrete neurophysiological mechanism for a unified theory of attention as an intrinsically embodied process, suggesting new directions for future research.

Keywords: Gamma Motor Neurons (γMNs), Embodied Attention, Proprioception, Sensory Modulation, Top-Down Attention, Embodied Cognition, Predictive Control, Muscle Spindles, Alpha-Gamma Coactivation, Motor Intention.

Introduction: A Novel Paradigm for Perception and Awareness

Motor control has long been primarily associated with α motor neurons (αMNs), the nerve cells that directly innervate the extrafusal muscle fibers responsible for generating movement (Sherrington, 1906). In addition, γ motor neurons (γMNs), which innervate the intrafusal fibers within muscle spindles, have been traditionally considered auxiliary regulators, crucial for maintaining proprioceptive sensitivity during muscle shortening (α–γ coactivation) and for providing accurate feedback on muscle length and velocity (Matthews, 1974).

However, an emerging and more audacious perspective suggests that the role of γMNs extends far beyond mere sensory regulation, positioning them as critical mediators of attentional focus in all its forms—both internal and external—and across multiple sensory modalities. This functional hypothesis proposes that γMNs act as a brain-controlled sensory preamplifier, facilitating an attentional engagement and disengagement mechanism that integrates perception and action at a deep, embodied level. This role extends to all forms of attention, both internal (e.g., body awareness, interoception) and multimodal external (visual, auditory, tactile, olfactory, gustatory), providing a fundamental bodily anchor for directing and modulating attention.

This article explores this innovative view, analyzing its neurophysiological plausibility and providing concrete examples of how γMNs can serve as key mediators in orchestrating not only somatosensory and motor attention but also other forms of attention. In doing so, it provides a unifying substrate for attention across different sensory modalities, even in the absence of overt, macroscopic movements.

The Classical Model of Proprioception and Its Limitations in Attention

The muscle spindle is the primary proprioceptive organ that provides the central nervous system (CNS) with vital information about muscle dynamics via primary (Ia) and secondary (II) afferent fibers. Within the spindle, there are two types of intrafusal fibers: nuclear bag fibers (dynamic and static) and nuclear chain fibers. Ia afferents (annulospiral endings) encircle both bag and chain fibers and are sensitive to both the speed of stretch and muscle length. II afferents (flower-spray endings) predominantly innervate nuclear chain fibers and are more sensitive to static muscle length. Importantly, these sensory afferents (Ia and II) have a well-defined receptive field, corresponding to the specific portion of the muscle they innervate. Any variation in length or tension within this muscle receptive field will result in activation of the spindle afferents.

α−γ coactivation is a fundamental mechanism in which αMNs and γMNs are activated simultaneously. This ensures that the spindle remains sensitive even during extrafusal muscle contraction, preventing it from becoming slack and maintaining the spindle's effectiveness in monitoring muscle length throughout all phases of movement (Matthews, 1974). Additionally, dynamic γMNs primarily influence Ia afferents, making them more sensitive to rapid changes in length (stretch velocity), while static γMNs influence both Ia and II afferents, modulating their sensitivity to static muscle length.

Despite its importance, this traditional model fails to fully explain the subtle modulation of perception and attention we experience daily. How can we "feel" a specific part of our body without actively moving it macroscopically? How do we maintain a smooth visual focus on a moving object, or isolate a single voice in a noisy environment? These phenomena suggest a mechanism of "selective amplification" of sensory information that goes beyond its simple transmission, indicating an active role of the body in directing attention, even in the absence of overt movements. The need to explain attentional modulation leads us to consider a deeper role for γMNs, one that can also operate at the level of subtle motor activity, muscle tone, or pure intention, not only during gross movements.

The γMN-Mediated Attentional Focusing Hypothesis

The central hypothesis is that γMNs are not merely passive regulators of proprioceptive feedback, but rather active mechanisms for 'pre-tuning' the sensory system in accordance with our attentional intention. This pre-tuning becomes evident across multiple domains:

Internal Attention: Body Awareness and Interoception

The capacity to direct one' attention toward internal sensations—such as limb position, heartbeat, or visceral signals—is fundamental for body awareness and interoception (Craig, 2002).

Proposed mechanism: This process is guided by a top-down flow from the central nervous system (CNS). Higher cortical areas, such as the posterior parietal cortex (involved in the body schema and spatial attention) and the somatosensory cortices (Corbetta & Shulman, 2002), would generate an intentional signal. This signal would descend along neural pathways and be directed specifically to the γMNs of the body region or muscle of interest.

The activation of γMNs (potentially both dynamic and static, depending on whether attention is on changes or on the maintenance of a subtle posture) would selectively increase the tension of the intrafusal fibers in the local muscle spindles. This would render the Ia and II sensory neurons, which originate from those spindles, hypersensitive. This "targeted amplification" of proprioceptive input operates in overlap with general α–γ coactivation and relies on the γMNs' ability to make signals derived from basal muscle tone, physiological intrinsic micro-oscillations of the body, or simple motor intention (even in the absence of overt movement) salient, thus constituting the neural foundation of conscious and focused body perception. It is as if the brain, through γMNs, were to switch on a "sensory spotlight" on a specific area, making its sensations intrinsically more salient and perceptible, even in the absence of macroscopic movement.

It is crucial to clarify that γMNs, as efferent neurons, do not possess a receptive field in the traditional sense (i.e., a sensory area from which they receive input). Rather, their action consists in modulating the receptive field of the muscle spindle. Their activation defines a specific proprioceptive field of influence, corresponding to the muscle area whose spindles will have their sensitivity finely regulated to direct attention.

Specificity of γMNs: Dynamic versus Static and Their Role in Attention

Dynamic γMNs (γ-D) primarily innervate dynamic nuclear bag fibers and predominantly modulate the sensitivity of Ia afferents, making them extremely responsive to rapid changes in muscle length (i.e., stretch velocity). They are crucial when attention is focused on rapid or anticipated changes in the body or environment, amplifying the perception of subtle dynamics. Static γMNs (γ-S), on the other hand, innervate static nuclear bag fibers and nuclear chain fibers, influencing both Ia and II afferents, and are crucial for sensitivity to static muscle length and for maintaining tone. Their activation is predominant when attention is focused on maintaining a posture, on basal muscle tone, or on static and sustained sensations. This specificity allows the brain to "tune" the muscle spindle for the type of proprioceptive information most relevant to the attentional goal.

The following examples illustrate the potential role of γMNs in pre-amplifying sensory signals.

Illustrative examples:

- The guitarist who "feels" the correct fret: An expert guitarist performing a complex solo does not look at their own fingers; they feel the exact position on the guitar neck. This is not merely passive feedback. Focused attention on finger position and pressure on the frets could activate γMNs (potentially both dynamic and static for finesse and posture maintenance) in the intrinsic muscles of the hand and forearm. While maintaining α–γ coactivation for movement control, this would increase the sensitivity of the muscle spindles (in particular the Ia and II afferents), allowing the guitarist to perceive with exceptional subtlety every minimal variation in position and muscle tension, facilitating millimeter-level precision even without visual aid. This gamma modulation can refine perception even during micro-adjustments or isometric pressure of the fingers, not only during the execution of a dynamic solo.
- Concentration on a postural anomaly: A person performing a Pilates exercise who focuses on the "sensation" of spinal alignment or the activation of a deep muscle (e.g., the transverse abdominis) without making a large movement. In this case, the intention to focus attention on that specific interoceptive and proprioceptive sensation could induce a top-down modulation of γMNs in the target muscles. Even in the absence of a large contraction (and thus with minimal α activity, or only tone), this gamma activation would make the proprioceptive signals

originating from the spindles of those muscles (via Ia and II afferents) more salient and accessible to awareness, allowing the perception of a deep muscle without macroscopic movement.

- Meditation and awareness of breath/heartbeat: During meditation, a person can focus attention on their breath or heartbeat. Although the diaphragm and intercostal muscles move, attention is not on the external movement but on the internal sensation. Here, the top-down intention could selectively activate γMNs in the respiratory muscles (or muscles adjacent to the heart), making the afferents from the spindles more salient and contributing to the conscious perception of internal processes that would otherwise remain subliminal. It is not the act of breathing itself, but the ability to actively perceive and monitor these internal sensations, which could be facilitated by gamma modulation.

External Attention: Multimodal Attentional Anchoring

External attention involves focusing on environmental stimuli, whether visual, auditory, tactile, or chemical. My hypothesis on γMNs suggests that, here as well, proprioception mediated by γMNs may serve as a bodily anchoring mechanism for attention.

Proposed mechanism: External attentional focusing is a dynamic process that integrates bottom-up influences (originating from the stimulus) and top-down influences (arising from attentional intentions). The hypothesis suggests that γMNs contribute to maintaining attention on the stimulus not by directly modulating primary sensory receptors (e.g., retinal, cochlear), but by finely modulating proprioceptive feedback from the body as it interacts—or prepares to interact—with the environment, irrespective of the sensory modality.

When you track a moving object (e.g., a bird in flight), your eyes and head move. This requires extremely precise feedback regarding the position and movement of the neck and eye muscles. The CNS, through top-down control (e.g., from the dorsolateral prefrontal cortex, which is involved in sustained attention; Miller & Cohen, 2001), can modulate the activity of γMNs in the muscles engaged in these tracking movements or in the body's preparation to interact with the environmental stimulus. This modulation, superimposed on normal α–γ coactivation, increases the sensitivity of muscle spindles, providing the brain with more detailed and refined proprioceptive information about the position and dynamics of the head and body in space, in relation to the attentional stimulus (whether visual, auditory, tactile, etc.). This gives rise to a modulated "Proprioceptive Attentional Field": although γMNs do not possess receptive fields in the traditional sensory sense, their modulatory action generates a sort of "window of heightened proprioceptive sensitivity." Rather than projecting attention outward, they refine the internal perception of the body in relation to the external object, rendering proprioceptive signals from the body parts actively involved in the interaction—or even merely preparing for action—more salient.

Illustrative examples:

- The sniper who "feels" their breath: A sniper aiming at a distant target focuses on their visual objective, but their accuracy also depends on impeccable bodily control. During the crucial moment of the shot, they "feel" the stability of their posture, the rhythm of their breath, and the slight tremor in their muscles. The γMNs could modulate the muscle spindles in the muscles of the torso and arms. This modulation, which overlays normal α–γ coactivation for postural control, amplifies proprioceptive feedback on these micromovements and on basal muscle tension (even in the absence of significant macroscopic movement). The detailed information from the spindles (via Ia and II afferents) allows the sniper to take the shot at the moment of maximum bodily stillness, supporting visual attention with an extremely fine and "tuned" bodily awareness.
- The palpating doctor: A doctor performing an abdominal palpation to identify an anomaly not only touches but also focuses intensely on sensations of resistance or consistency. The doctor's tactile attention is supported by γ modulation in the muscles of the fingers and wrist, which increases the sensitivity of the muscle spindles in those regions. This proprioceptive refinement (which occurs alongside α–γ coactivation for maintaining hand tone and posture) makes the tactile receptors more responsive to subtle changes in pressure and texture, facilitating the discrimination of otherwise imperceptible anomalies.
- The watchmaker with tweezers: A watchmaker working on a tiny mechanism with tweezers requires an extremely high degree of visual and motor attention. While their eyes are on the detail, their movements are guided by exquisitely fine proprioception in the fingers. The γMNs in the hands and fingers could be activated to increase sensitivity to the slightest inputs of pressure and movement, allowing for ultra-precise motor control that supports visual focus on such a small object. This mechanism operates in synergy with α–γ coactivation, further refining proprioceptive feedback.
- The sound engineer "mixing": A sound engineer in the studio, while carefully listening to a vocal track for mixing, might make subtle head movements, slightly vary the tension of facial muscles, or even clench their jaw. These micro-postural adjustments, mediated by γMNs, do not directly alter auditory reception. Instead, they refine the proprioception of the "listening body," increasing the sensitivity of the muscle spindles in the neck, jaw, and facial muscles.

This richer proprioceptive feedback, supported by α–γ coactivation for the maintenance of posture, could contribute to a more discriminating auditory perception, almost as if the body were tuning itself in resonance with auditory attention to capture subtle acoustic nuances and artifacts.

- The sommelier and the aroma: Similarly, when a sommelier focuses on the aroma of a wine, subtle, though often imperceptible, movements of the head or of the respiratory musculature might be accompanied by γ modulation that refines the proprioception of the "smelling body," enhancing the sommelier's olfactory discriminatory ability through more detailed bodily feedback.

Perception and Movement: An Indissoluble Relationship

It is essential to clarify that my hypothesis does not propose the possibility of conscious, focused perception in the absolute absence of motor activity. Rather, it maintains that attention—particularly internal attention or that requiring fine discrimination—is always supported by some form of motor or pre-motor activity, albeit at a microscopic level or in residual muscle tone.

When referring to the "absence of macroscopic movement," this denotes the absence of large, overtly visible, or easily measurable movements with conventional instruments. However, the human body is intrinsically dynamic, characterized by basal muscle tone and physiological micro-oscillations (e.g., postural tremors, slight balance adjustments). These signals, normally subliminal, become salient and accessible to awareness when γMNs selectively "preamplify" the sensitivity of muscle spindles.

Furthermore, even the simple intention to move or to "feel" a part of the body, without any actual movement occurring, can generate a descending discharge to the γMNs. This intention can be interpreted as a form of pre-motor activity or "preparation for action" at the neural level, which actively modulates the proprioceptive system, contributing to defining the direction of attention. This principle aligns with established observations in other sensory systems, such as vision. For example, experiments show that by preventing microscopic ocular movements (microsaccades), the image tends to "fade" (Ditchburn & Ginsborg, 1952). This emphasizes that even at the ocular level, continuous (albeit minimal) motor activity is fundamental for maintaining perception. Likewise, my hypothesis extends this concept to the general proprioceptive system: the body, through its intrinsic dynamicity and the active modulation of γMNs, is an inescapable actor in the perceptual and attentional process.

Attention and Perception: An Integrated and Top-Down Process

My γMN hypothesis does not imply that attention is a completely separate and temporally antecedent system to perception in a linear sense. Rather, it suggests a bidirectional, recursive, and deeply integrated interplay between attention and perception, with a crucial role for top-down mechanisms.

When we talk about "top-down intention," we refer to the ability of our higher-order intentions, expectations, goals, or cognitive plans to actively influence and "pre-tune" the sensory system before a stimulus is fully processed at the perceptual level. This is consistent with models of predictive control (Wolpert & Ghahramani, 2000), where the brain generates internal models and anticipations to optimize sensory processing and action.

In this context, the proposed sequence is as follows: (1) An intention or cognitive goal (top-down) generates a signal aimed at focusing attention on a specific sensory or bodily area. (2) This signal descends and activates the γMNs, which modulate the sensitivity of the peripheral muscle spindles. (3) The spindles, now "pre-tuned," send amplified and detailed proprioceptive signals (bottom-up) to the CNS. (4) This amplified proprioceptive information, along with specific inputs from the sensory modality (visual, auditory, tactile, etc.), contributes to the formation of a clearer, more salient, and focused perception.

In this model, attention (understood as the act of focusing or "pre-tuning") is an active process that shapes and directs perception, making certain stimuli more relevant than others. Attention and perception are therefore not two disjointed systems but rather two interconnected aspects of a single integrated sensorimotor and cognitive process. Attention, through γ modulation, acts as a "filter" or an "amplifier" that prepares the system to receive and give meaning to sensory information, decisively influencing the content and quality of perception. It is a strong affirmation of the idea of an embodied mind, where the distinction between action and perception is fluid and interdependent.

Connections with Existing Neuroscience Research

My γMN hypothesis is in line with several established research areas, offering a specific neurophysiological mechanism for phenomena already observed:

(i) Predictive control of movement and perception: The brain operates in a predictive manner, anticipating events and preparing responses (Wolpert & Ghahramani, 2000). The activity of γMNs is under significant cortical control and is believed to play a crucial role in "pre-tuning" the sensitivity of muscle spindles based on movement expectations and, by extension, sensory expectations. This "anticipatory tuning" of the sensory system, mediated by γMNs, provides a concrete efferent mechanism for sensory prediction and for directing attention, even in the absence of an overt motor action, but only with an intention or a motor image. It is an example of how the brain, through efferent motor neurons, can actively influence the elaboration of sensory information from specific receptive fields of muscle spindles, refining perception.

(ii) Interaction with other attentional systems: The γMN hypothesis does not propose an isolated attentional system, but rather a peripheral efferent mechanism that operates in synergy with broader cortical and subcortical attentional networks. The top-down focusing mediated by γMNs is the final result of complex processing involving various brain areas (posterior parietal and prefrontal cortices). It is from these higher-order areas that attentional intention originates, which is then translated into descending signals that directly or indirectly modulate the activity of γMNs. According to my hypothesis, γMNs therefore act as a key effector of an attentional sensorimotor feedback loop. Cognitive intentions (top-down) modulate the γMNs, which in turn pre-tune the proprioceptive afferents (bottom-up). This amplified information returns to the brain, informing and reinforcing perception and attention in a recursive cycle. In this way, the body becomes an active and dynamic participant in the attentional process, not just a passive receiver of sensory information.

Comparison with the Premotor Theory of Attention

The emerging hypothesis that sees γMNs as the silent orchestrators of attention positions itself in a relationship of continuity and, at the same time, specificity with the well-known Premotor Theory of Attention (Rizzolatti et al., 1987; Rizzolatti & Craighero, 2004). However, it is crucial to recognize that, despite its influence, this theory has been the subject of debate and significant criticism, as highlighted in recent reviews (e.g., Smith & Schenk, 2012). Both perspectives offer an embodied approach to cognition, but they differ in the primary mechanism, the scale of action, and their empirical robustness.

Points of Convergence

- Attention as an embodied motor process: Both the premotor and γMN hypotheses converge on the idea that attention is not an abstract entity but an intrinsic process deeply rooted in the motor organization of the brain and body. Attention is conceived as a direct manifestation of motor preparation or intention, rather than a mere selection of sensory information.

- Action-oriented perception: In both theories, perception is not a passive process of reconstructing reality but is actively influenced and shaped by our intentions and preparations for action. Space and objects are encoded according to motor demands and potential interactions (Barsalou, 2008).
- Dependence of attention on motor programming: Selective spatial attention is regarded as a consequence of the activation of neurons involved in programming spatially directed movements. This motor preparation, even when the movement is not overtly carried out, directly influences perception, facilitating the processing of stimuli within the attended area.

Points of Difference

- Primary mechanism and scale of action:
  - The Premotor Theory of Attention (Rizzolatti et al., 1987) focuses on the preparation of macroscopic, overt, or covert movements, particularly eye movements (saccades), as the basis for spatial attention. Spatial attention is considered a direct consequence of the activation of neurons in spatial pragmatic maps (cortical areas that program motor actions). The main supporting evidence concerns the deviation of vertical saccade trajectories based on the direction of attention, demonstrating the involvement of the oculomotor system even in the absence of overt movements. The theory emphasizes the "facilitation of neurons" in these maps as a consequence of movement preparation. However, as noted by Smith and Schenk (2012), the interpretation of these data is problematic. For example, in the Frontal Eye Field (FEF), it has been observed that the neuronal populations involved in saccadic control are often separate from those involved in visual selection, suggesting a functional dissociation rather than an equivalence (Thompson et al., 1997). Studies employing microstimulation and TMS, which activate large neuronal populations, thus cannot provide unequivocal support for the idea that attention is specifically driven by motor signals.
  - The Gamma Motor Neuron Hypothesis proposes a mechanism at a more microscopic and subtle level, focusing on the active modulation of proprioceptive sensitivity through γMNs. The γMNs do not directly generate macroscopic movement but rather "pre-amplify" the sensory signals originating from the muscle spindles. This allows for highly refined attentional focus even in the absence of significant overt movements, based on basal muscle

tone, intrinsic body micro-oscillations, or simple motor intent. It is a mechanism that operates at a more peripheral and deeply sensorimotor level.

- Focus of attention (sensory/motor dominance):
  - Premotor Theory of Attention: While it recognizes the existence of pragmatic maps for different movements (e.g., arms), its main focus is on visual spatial attention and the oculomotor system, especially in primates with foveal vision. It specifically refers to "oculomotor pragmatic maps" that play a central role in directing attention in space. Smith and Schenk (2012) question the generalizability of this privileged role, highlighting conflicting results regarding the ability of other effector systems to orient attention independently, and emphasizing how exogenous attention may have a stronger link to the oculomotor system than endogenous attention.
  - Gamma Motor Neuron Hypothesis: It extends its role to all forms of attention, both internal (body awareness, interoception) and external multimodal (visual, auditory, tactile, chemical). It suggests that external attention is supported by a fine modulation of the proprioceptive feedback of the body as it prepares to interact with the environment, creating a "Proprioceptive Attentional Field." This means that attention, regardless of the sensory modality of the stimulus, is always supported by a "tuning" of the body.

- "Pre-tuning" mechanism:
  - Premotor Theory of Attention: "Pre-tuning" manifests as the preparation of a motor program for a saccade (or other movement) toward the expected position, making that position salient and facilitating faster responses. The increased responsiveness of visual neurons (e.g., in the superior colliculus) is seen as a consequence of this motor preparation. However, Smith and Schenk (2012) discuss how the ability to dissociate attention from the saccadic target, especially for endogenous attention, suggests that motor preparation is not always a necessary and sufficient condition for spatial attention. They also highlight that pre-saccadic shifts of attention might be qualitatively different from endogenous shifts of attention in the absence of movement, potentially mediated by sensory "remapping" mechanisms rather than by a direct dependence on motor preparation.
  - Gamma Motor Neuron Hypothesis: "Pre-tuning" occurs through the top-down control of γMNs that selectively increase the tension of the intrafusal fibers. This makes the sensory afferents (Ia and II) of the muscle spindles hypersensitive, amplifying weaker proprioceptive signals. This "targeted" amplification of proprioceptive input forms the

foundation of conscious and focused perception, acting as a "sensory spotlight" on the body itself.

Critiques of the Premotor Theory of Attention and Functional Dissociations

It is important to note that, while influential, the Premotor Theory of Attention has sparked debate and significant criticism, which calls into question the validity of some of its key predictions (Smith & Schenk, 2012). The review by Smith and Schenk (2012) analyzes four specific predictions of the Premotor Theory of Attention and concludes that empirical evidence is not fully consistent with the idea that spatial attention is functionally equivalent to motor preparation.

The main criticisms include:

- Anatomical and functional dissociations: Contrary to the prediction that attention and motor preparation use the same neural substrates (Rizzolatti et al., 1987), Smith and Schenk (2012) present evidence of functional and anatomical dissociations between endogenous spatial attention and motor preparation. For example, it has been observed that within areas like the Frontal Eye Field (FEF) and the Posterior Parietal Cortex (PPC), there are separate neuronal populations for saccadic control and for visual selection or attention (Thompson et al., 1997). This suggests that not all areas involved in motor preparation are involved in covert attention, and vice versa.
- Necessity and sufficiency of motor preparation: The prediction that motor preparation is both necessary and sufficient for a shift of attention is strongly contested. While there is evidence that motor preparation is sufficient to orient attention (e.g., pre-saccadic attention), research has shown that it is possible to orient attention endogenously to positions different from the target of an impending movement without interruption (Kowler et al., 1995; Montagnini & Castet, 2007). This calls into question the necessity of motor preparation for all types of attention.
- Privileged role for the oculomotor system: Although exogenous attention seems closely linked to the activation of the oculomotor system, the prediction of a privileged role for the oculomotor system in the orientation of visual spatial attention is not supported conclusively. Furthermore, the role of other effector systems (e.g., manual) in orienting attention is unclear and produces conflicting results (e.g., comparison between Jonikaitis & Deubel, 2011 and Khan et al., 2011).
- Qualitatively different mechanism: Smith and Schenk (2012) suggest that pre-saccadic attention shifts might be qualitatively different from endogenous shifts of attention in the

absence of movement. This could be explained by mechanisms such as visual remapping that occurs before eye movements (Duhamel, Colby & Goldberg, 1992), a process that is not engaged during covert attention without movement.

In conclusion, the review by Smith and Schenk (2012) argues that the Premotor Theory of Attention, in its strongest form, should be rejected, suggesting that a more limited version, in which only exogenous attention depends on motor preparation, may still be valid. They propose that activity in the motor system could contribute to a "polarized competition" between different sensory representations, where the winning element becomes the one that receives attention.

In light of these criticisms, the Gamma Motor Neuron Hypothesis offers an alternative and more general mechanism that can explain the breadth and flexibility of attention. While the premotor hypothesis focuses mainly on visual spatial attention and the programming of overt or inhibited movements (e.g., saccades) for spatial selection, my hypothesis delves deeper into this integration, suggesting that attention, in all its forms, is mediated by a fine modulation of bodily proprioception. This mechanism "pre-tunes" the sensory system to detect even the most subtle signals related to intention or muscle tone, making the body itself an active tool for sensory focusing. The two perspectives, therefore, are not necessarily in competition, but the γMN hypothesis proposes a deeper and more pervasive mechanism that extends the concept of embodied attention to a fundamental sensorimotor level, operating even when the predictions of the strongest form of the Premotor Theory of Attention are not supported.

Conclusions and Future Perspectives

The hypothesis that γMNs play an active role in attentional focusing, both internal and external and across different sensory modalities, represents a significant and revolutionary expansion of their traditional function. They would not only be simple regulators of proprioceptive feedback but key actors in a top-down mechanism of sensory "engagement" and "amplification," which allows the brain to "tune in" to its own body and the surrounding environment through a finely modulated proprioceptive filter, even in the absence of macroscopic movement, relying on basal muscle tone, micro-oscillations, or motor intent. This perspective offers a crucial alternative or complement to existing theories, particularly the Premotor Theory of Attention, whose strongest predictions have been questioned by recent evidence indicating functional dissociations between attention and motor preparation (Smith & Schenk, 2012).

This perspective offers a concrete neurophysiological mechanism to explain how our attention can actively modulate perception, making the body an active tool for sensory exploration and focusing. The ability to "make conscious" a part of the body or to "engage" with an external object through a system that selectively amplifies sensory input at the receptor level is an elegant demonstration of the fluid integration between perception and action, and a pillar for a unified theory of attention as a deeply embodied process.

Future research should aim to test this hypothesis, while recognizing the methodological challenges in measuring the activity of individual γMNs in vivo in humans. However, studies that combine advanced neuroimaging techniques (high-resolution fMRI, EEG/MEG) during multimodal attention tasks with indirect measurements of proprioceptive modulation (for example, through attention-modulated somatosensory or auditory discrimination tests, reflex responses, or nerve stimulation with selective blocks) could provide supporting evidence. The use of computational models and studies on animal systems, where more direct experimental control is possible, could also offer valuable insights. A more in-depth investigation into the role of γMNs would not only enrich our understanding of the motor system but also offer new insights into the complex mechanisms of human consciousness and attention, pushing us to consider proprioception not just as an input but as a powerful efferent mechanism for cognitive control and embodied cognition.

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Author declaration on the use of generative AI and AI-assisted technologies in the writing process

The author used Gemini (Google, https://gemini.google.com/) for the revision, editing, and reorganization of the article draft, and for text formatting according to specific instructions. All AI-generated content was carefully reviewed and modified by the author, who assumes full responsibility for the accuracy, consistency, and final content of the published article.