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and provides cues to our mind for space, time, location, and self

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ORIGINAL ARTICLE

Functional representation of vision within the mind: A visual consciousness model based in 3D default space



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Abstract The human eyes and brain, which have finite boundaries, create a “virtual” space within our central nervous system that interprets and perceives a space that appears boundless and infinite. Using insights from studies on the visual system, we propose a novel fast processing mechanism involving the eyes, visual pathways, and cortex where external vision is imperceptibly processed in our brain in real time creating an internal representation of external space that appears as an external view. We introduce the existence of a three-dimension default space consisting of intrapersonal body space that serves as the framework where visual and non-visual sensory information is sensed and experienced. We propose that the thalamus integrates processed information from corticothalamic feedback loops and fills-in the neural component of 3D default space with an internal visual representation of external space, leading to the experience of visual consciousness. This visual space inherently evades perception so we have introduced three easy clinical tests that can assist in experiencing this visual space. We also review visual neuroanatomical pathways, binocular vision, neurological disorders, and visual phenomenon to elucidate how the representation of external visible space is recreated within the mind.

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Introduction

The visual system is a heavily studied area of neuroscience yet very little is known about how visual consciousness arises. In this paper, we discuss insights from studies on the visual system, various neurological disorders and visual phenomenon, and we discuss a few simple tests that can be done to examine what we refer to as the visual sensory memory space within the mind. The eyes and visual system give insights into the inner workings of visuospatial consciousness, which accounts for a large portion of conscious experience. For example, 80% of external input processed by the brain is processed by the visual pathway [1]. If proven correct, our hypothesis will be an essential step in understanding visual consciousness and how the brain functions as the mind. It may also have implications in treating neurological disorders, neurologically-based visual dysfunction, and even impairments in memory and cognition.

Visual consciousness insights from binocular vision and neural correlates

Flat inverted images formed on each retina combine to form a seamless three dimension (3D) visual space within the mind. Each eye has a slightly different two dimensional viewpoint, allowing for depth perception and the subsequent creation of a single seamless 3D visual space. 3D glasses are a great example for explaining how the brain creates one 3D image from two retinal images because these glasses work by recreating the way humans normally see. A 3D movie shows the same scene from two different viewpoints in two different colors and the color filters of the 3D glasses then separate the two different images so that each eye only sees one viewpoint. The brain then combines these separate images and “sees” a single 3D image. However, depth perception, though improved with binocular vision, is still possible with monocular vision [2]. For example, in addition to binocular depth cues, such as stereopsis and binocular disparity, there are also monocular depth cues such as size, texture gradients, and perspective [2]. When discussing visual processing one must also discuss the area of the eye involved in sharp clear vision, the fovea.

The fovea accounts for only 1% of the retina but 50% of the visual cortex is devoted to processing foveal information [3]. Similarly, an animal study found that 27% of the striate cortex is allotted to the central 4° of vision but is only supplied by 12% of retinal ganglion cells, suggesting that more of the visual cortex is allotted per ganglion for processing of information from the macula than from the rest of the retina [4]. This would account for why only a small portion of vision, which is seen by the fovea, is focused and high resolution while the surrounding vision is low resolution. Saccadic eye movements allow for the fovea to quickly and imperceptibly scan the visual field and create a visual map [5]. It has been proposed that presaccadic suppression, postsaccadic enhancement, and time compression may allow for visual images to be clear rather than blurred in the presence of constant saccadic eye movements [5].

The functional processing pathway of visual information that results in visual consciousness consists of synchronized electrical oscillations between visual pathways that include the retina, lateral geniculate body, striate cortex, prestriate cortex, inferotemporal cortex or posterior parietal cortex,

and prefrontal cortex [6]. Visual consciousness may arise from synchronized neural oscillations that integrate and consolidate visual information, resulting in conscious awareness. In addition, much of the content of visual consciousness stems from processing in the ventral stream; however, the dorsal stream contributes essential information to this content, such as spatial locations [7]. Although the parietal lobe is more commonly associated with spatial mapping, areas in the frontal lobe have also been shown to be involved in spatial orienting in working memory [8]. These cortical areas and the thalamus contribute not only to the visual consciousness but to other sensory information that is integrated into consciousness awareness.

Afferent external visual input enters both eyes separately but processing by cortical feedback loops and the thalamus, including the lateral geniculate bodies, produces one seamless image. The interactive connections between the cortex and retina allow for the processing of two monocular images, as perceived by the contralateral hemispheres, into a single binocular image (Fig. 1).

Previously proposed mechanisms of visual consciousness and perception

Hermann von Helmholtz and Richard Gregory propose that external visual information cannot be directly perceived because of the relatively poor quality of sensory information detected by the retina [9]. Therefore retinal images are interpreted based on already acquired and stored knowledge. Helmholtz proposed that the visual system draws “unconscious inferences” or “inductive conclusions” by drawing conclusions from individual experiences [9]. However, following this logic, if sensory information from the retina is of such poor quality then previously acquired visual information, that inferences are drawn from, would also be of poor quality and would therefore not provide much information from which to draw inferences. Therefore, this hypothesis does not seem to be a viable mechanism underlying the processing that results in the high quality visual information that is perceived. Gregory proposes a similar top-down processing hypothesis in which visual perception is based on a collection of learned information and hypotheses [10]. These proposed visual consciousness mechanisms via indirect perception may help to explain visual illusions, such as the hollow mask illusion in which a concave mask appears to be convex [11]. Gregory posits that the bias to see the hollow mask as a normal convex face is evidence of top-down processing in vision [11]. It has been shown that direct perception hypotheses may lack adequate explanation of such visual phenomenon. For example, James Gibson proposes a bottom-up processing hypothesis in which he proposes that we gain direct awareness of the external world from stimulus information and there is no need for processing or interpretation of this information [12]. Our hypothesis combines these previously proposed hypotheses that lie on opposite ends of the spectrum. We emphasize the processing of retinotopic information as well as the creation of an internal representation of the external visual world within the mind that draws directly from both processed retinal information and from inferences from visual memory. Our model also combines elements from the two most currently accepted theories of consciousness: the Global Workspace Theory and the Integrated Information Theory.

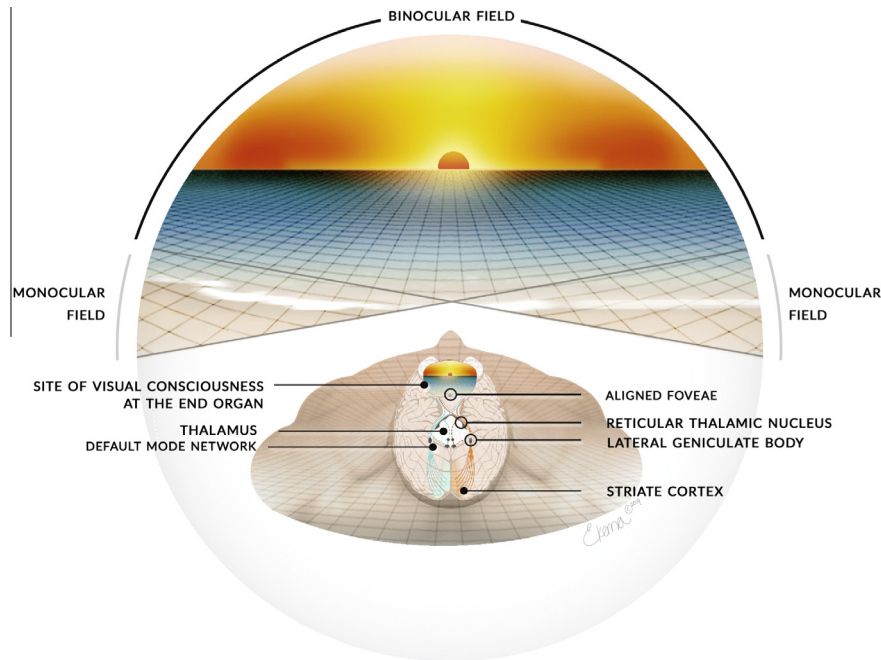


Fig. 1 Intrinsic spatial mapping of visual and non-visual stimuli within the 3D default space. This figure illustrates our proposed mechanism of how two separate images of a visual scene from each retina are imperceptibly and instantaneously combined into a single seamless image within the mind. The simplified visual pathway illustrates how light from the scene projects onto each retina, including the aligned foveae, and is processed via the visual pathways. Corticothalamic feedback loops including the striate cortex and other cortices are involved in processing of visual information while the thalamus integrates the information from these feedback loops. Although the retinas are intrinsically wired for distance, the parietal lobes create a spatial map of the visual scene as well as a spatial map of the body and other sensory information. When this processed visual and other sensory information, including the spatial mapping, is integrated by the thalamus it is filled into the 3D default space. We propose that the final processed image that arises to conscious awareness is perceived by the thalamus and corticothalamic feedback loops but is experienced at the eyes.

Proponents of the Global Workspace (GW) Theory propose that processing hubs throughout the cortex coordinate and compete via a “winner-take-all” mechanism in which multiple processing streams settle on one stream to broadcast. It is that single stream that then rises to conscious awareness [13]. The Integrated Information Theory addresses more of what consciousness is and proposes that consciousness is integrated information [14]. Before making this definitive statement Tononi states that consciousness “corresponds to the capacity to integrate information,” which is more in line with our model. Tononi’s model also involves a multidimensional ‘qualia’ space in which informational relationships form shapes that are unique to a specific experience. Our model does not equate consciousness with integrated information, though conscious experience obviously involves the integration of information. Koch has used the Integrated Information model to support panpsychism in which integrated information in inanimate objects, such as a thermostat, constitutes consciousness [15]. Our model and these widely accepted consciousness models, emphasize the important role of corticothalamic feedback loops and the integration of information in consciousness. They also all designate a multidimensional “space” within which this experience of consciousness occurs. Another important but less well-known model, is the Retinoid Model proposed by Arnold Trehub. Trehub proposes a retinoid system in which separate 2D foveal images project onto retinoid arrays resulting in a single 3D world scene. This is an

important model in examining how separate 2D images on the retinas can become a seamless 3D scene within the mind; but it does not address extensive corticothalamic processing that occurs or any neural correlates of consciousness.

3D default space: the infrastructure of visual consciousness

Using insights from vision studies and various disorders we propose that visual information is processed by corticothalamic feedback loops and integrated by the thalamus, resulting in a recreation of external visual space within the mind (Fig. 2).

Our bodies, bounded by skin, form the matrix for this 3D default space. We propose that thalamocortical feedback loops process visual and non-visual sensory information that is integrated by the thalamus within this 3D default space [16]. Visual information and perceived visual information constitutes a portion of this consciousness “space.” The 3D default space is the intrapersonal space that is formed by all cells of the body, which are all interconnected, electrically charged, and developed from a single cell. Together they form a space that makes up a pre-conscious state in which consciousness arises. Visual information and other sensory information such as peripheral signals from the arms, legs, and viscera are transmitted to the thalamus where they are relayed throughout the brain. Fast thalamocortical oscillations create the vast consciousness experience perceived within 3D default or

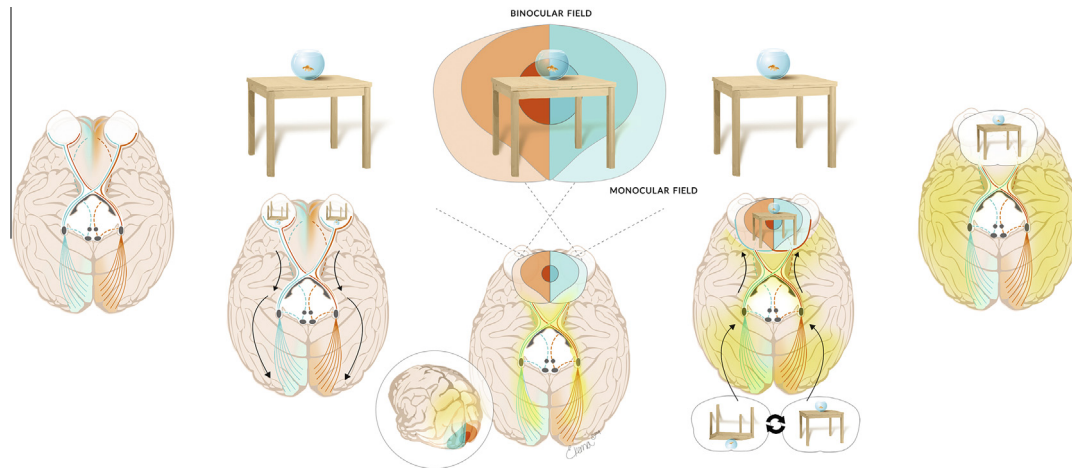


Fig. 2 Visual processing pathway and formation of visual consciousness. The outer light red and light blue portions of the visual field represent the monocular fields while the inner dark red and blue areas represent the binocular fields. The circle in the center of the visual field represents the area seen by the fovea, where vision is detailed and in focus. The inverted image, seen by the brain, is projected on the retina of both eyes. This information is then sent via the optic nerve to the thalamus, including the lateral geniculate bodies, and to the rest of the brain via corticothalamic feedback loops. The information from the left visual field is processed in the right hemisphere of the brain while information from the right visual field is processed in the left hemisphere. The yellow coloring depicts the visual information moving through the brain as it is processed. The middle image depicts where the visual information reaches the striate cortex. This is likely the area of the brain where the inverted image from the retina becomes upright, as depicted in the fourth brain. This is also likely the area where the separate images from each eye begin to integrate and merge. We propose that visual stimuli are detected by the eyes but integrated and perceived by the thalamus via corticothalamic feedback processes. Although processing and perception of vision occurs within the brain, the experience of vision occurs at the end-organ (i.e., the eyes).

intrapersonal space. We have termed this 3D “default” space because it is an intrinsic space and the neural sensory memory space aspect may be associated with default mode network activity, though more research is needed to establish such a relationship. It is estimated that 90% of the brain’s energy is used by intrinsic or default mode network activity [17]. We propose that much of this energy that is used for intrinsic neural activity, such as default mode activity, is used to create and maintain the neural framework of the 3D default space in which consciousness arises. Similarly, one study found that the brain displays around 80% of normal patterned neural activity in complete darkness [18]. This suggests that neural activity evoked by sensory stimuli modulates and triggers already occurring activity within the brain and that the intrinsic neural activity that occurs at rest may be creating the neural representation of the outside world within the brain [18]. In addition, during eyes open, “exteroceptive” networks such as the attentional system, ocular motor system, and arousal systems are more active than during eyes closed when “interoceptive” networks such as the visual system (lingual gyrus, fusiform gyrus and cuneus), auditory system, somatosensory system, and parts of the default mode network showed higher activity, suggesting that more resources are allocated to the visual system during eyes open in comparison to other sensory systems [19]. These studies support the existence of a neural space, such as the neural component of 3D default space that may arise from intrinsic activity and is filled in by processed sensory information. This differs from other consciousness theories because the 3D default space consists of the entire brain and body whereas in other theories, such as the GW Theory, the workspace exists solely within the brain. Our

consciousness model emphasizes the equally vital role of the active sensory memory space in the brain and the input from throughout the body. Both the mind and body form conscious experience.

Our model also differs from many other consciousness models in that we emphasize the role of the thalamus as a central hub. The thalamus has long been considered a simple relay station for sensory information but studies on corticothalamic feedback loops have shown that the thalamus is an important part of visual and other sensory processing [20,21]. The role of the thalamus in relaying and processing sensory information via corticothalamic feedback loops make it a prime candidate for the center of consciousness [22] and the visual reimagining of external space. Although most processing occurs within corticothalamic feedback loops, the vital integration of this processed information is likely done by the thalamus [22–24]. We propose that in order to rise to conscious awareness the thalamus fills in visual information within the sensory memory space of 3D default space to create a neural representation, whereas the GW Theory proposes that consciousness arises from hubs throughout the cortex.

The visual processing of afferent sensory information from the eyes integrates with cortical projections including the occipital striate cortex, parietal cortex for spatial orientation, frontal and prefrontal executive cortices. This information is processed by dynamic corticothalamic feedback loops and integrated by the thalamus. We propose that the thalamus, including the lateral geniculate bodies and reticular thalamic nuclei, process optical afferent information, relay this information to widespread cortical projections, integrate this processed information, and fills-in a neural representation of visual space

within the 3D default space [16]. The visual image projected on the retina is magnified within the brain and processed within milliseconds thereby generating a real-time illusion that visual information that is reimaged inside the mind is perceived as external. The retina sees images as external rather than internal because the eye and brain work as one unit to instantaneously visualize and constantly refocus the image on the retina in real time. The internal visual representation of external space is perceived within the active visual space but is actually experienced at the eyes. The experience of sensory information at the end organs likely allows us to interact with our environment more efficiently and faster than if the experience of these sensations occurred within the sensory memory space, where it is actually perceived and rises to conscious awareness. The visual information from the retina triggers the thalamus and the Edinger–Westphal nucleus to adjust the pupillary diameter and lens focal length [25] while the corticothalamic feedback loops between the visual, parietal, and frontal cortices allow for almost immediate perception. The illusion is that the image within the mind, from the processed retinal information, replaces the actual external visual space. In addition, the 3D default space within the mind, which also integrates sensory information from throughout the body, fills in external and internal visual and non-visual space (Fig. 3).

This is because the actual visual and non-visual spaces are processed and recreated within the mind, resulting in inconsistencies between external reality and conscious perception. This internal visual representation allows for integration of learned visual memory information as well, which may help to explain

illusions, such as our misperception of a hollow mask as a convex face even in the presence of depth cues. The end product of the visual processing that occurs throughout the cortex and thalamus results in the retinal images forming a merged and dynamic internal visual space that forms the basis of visuospatial consciousness that is experienced in the eyes (Fig 4).

The 3D default space consists of the entire brain and body because signals from the entire body are integrated in the mind, forming this space that is filled-in by the thalamus with processed sensory information that rises to conscious awareness. Fig. 4 illustrates how our skin forms the boundary of the human body between internal and external space and afferent information from the dermis, muscles, visceral structures, and sensory organs are processed by their respective areas in the brain and, when merged, help to create our body schema within the mind.

This space is innervated by various sensory motor neurons that feed into the corticothalamic feedback loops. For example, the parietal lobe is associated with spatial processing and orientation [26–28] and the lateral intraparietal area provides spatial awareness of the body and visual and other sensory information by spatially locating stimuli via retinally mapped coordinates [27,28]. In addition to spatial processing in the parietal lobe, visual information retains visuospatial information throughout processing. In particular, the near and far neurons that are hard-wired for distance in the striate cortex (for example from 1 foot, 10 feet, 1000 ft, or infinity) are actively connected to the visual component of 3D default space. Binocular neurons are found in the striate cortex, where

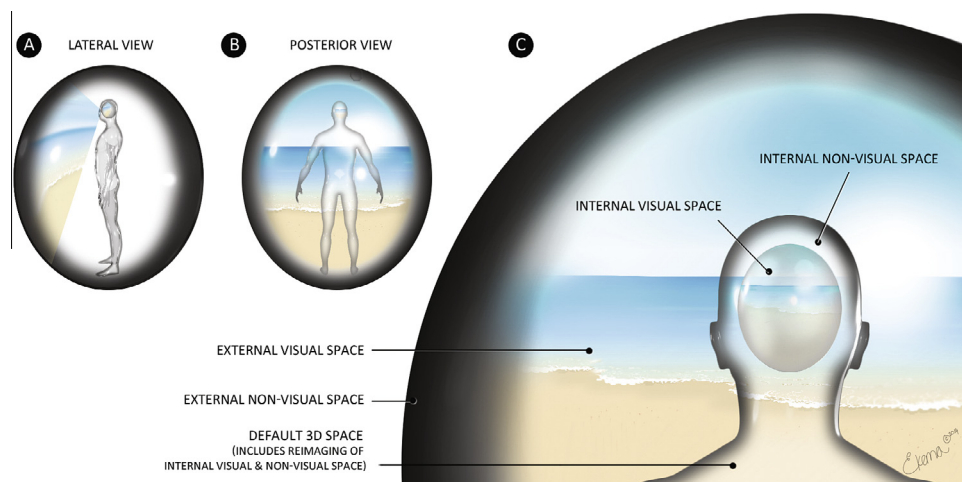


Fig. 3 Correlation of external and internal space. An important aspect of consciousness is the processing of sensory information. This figure aims to show the processing of visual sensory information and the default 3D space created in the mind. The area surrounding the figure represents the external visual space and the black surrounding area represents external non-visual space. The global visual field is surrounded by dark shading to illustrate where the figure's visual field ends. This external visual space is seen by the eyes, processed by the brain, and an internal visual representation of external visual space is imaged within the mind, along with non-visual space. We refer to this reproduction of visual and non-visual space as the 3D default space. Note that this representation of the internal representation of external visual space illustrates this phenomenon and is not meant to indicate any anatomical landmarks in the brain. The outline of the figure is also surrounded by dark shading to show where internal space ends and reflects how the external non-visible space is mirrored functionally within the internal non-visible space. The brain is constantly receiving internal information from throughout the body and external information via the sensory systems that contribute to the formation of consciousness, a sense of self, and a 3D default space consisting of integrated and reprojected internal and external space. The external visual and non-visual world appears separate from our internal world due to the high speed processing of corticothalamic information. This illusion allows the brain to function as the mind in a seemingly seamless reality. Figure and description reprinted with permission from the copyright holder.

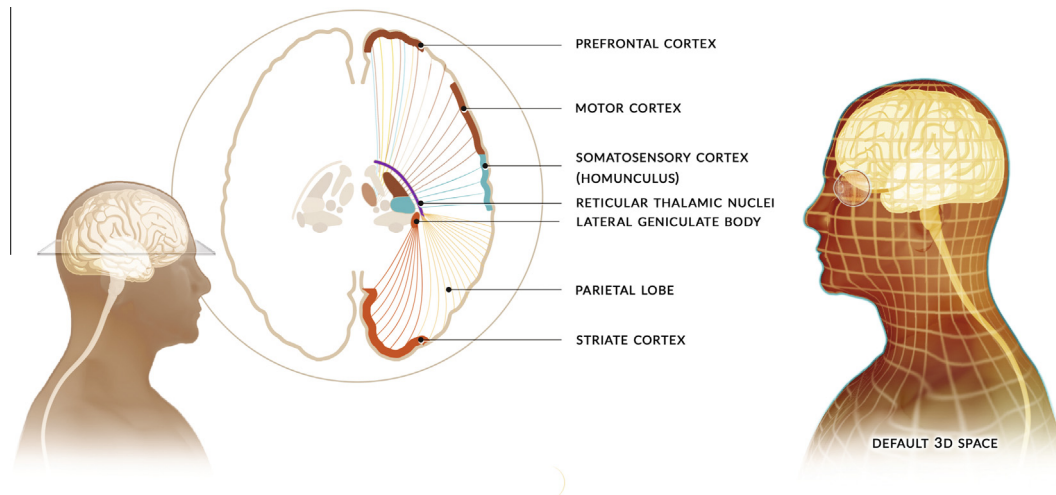


Fig. 4 Corticothalamic feedback loops and the creation of visual consciousness within the 3D default space. The corresponding color of the retina and striate cortex illustrate the extensive processing of retinal information that occurs in the striate cortex and occipital lobe. The corresponding color of the retinal grid, body grid, and parietal lobe illustrate how the parietal lobe spatially locates and maps visual and non-visual sensory information. The corresponding colors of the sensory cortex and skin and the motor cortex and body respectively, illustrate the processing of skin sensations by the sensory cortex and processing and signaling of the muscles by the motor cortex. Processed visual information forms the visual consciousness aspect of 3D default space while processed non-visual sensory information forms the larger non-visual aspects of 3D default space. The retinal information is processed in the thalamus and lateral geniculate body and then sent to the visual and parietal cortices, and frontal lobe. This information is processed in parallel via corticothalamic feedback loops within 150 ms. The figure also depicts the map of 3D default space within the body in which visual and non-visual information is spatially mapped in the parietal lobe and then integrated and perceived by the thalamus and corticothalamic feedback loops to reach consciousness. The conscious sensations that make up our body schema and visual and non-visual consciousness are processed and perceived in the brain but experienced at the sensory organs such as the eyes, ears, and skin.

binocular convergence is thought to begin in the visual processing system [29]. The far binocular cells are stimulated by disparities further than the plane of fixation, where the eyes are focused, while near cells are stimulated by disparities closer than the plane of fixation and zero cells are stimulated by disparities on the plane of fixation [30]. This leads to depth perception [30] and contributes to preservation of spatial aspects of visual information. It has been shown that early visual areas are involved in maintaining spatial specificity of visual working memory [31]. The formation of this dynamic visual space forms the basis of the visual component of the larger 3D default mind-body space.

Many studies have shown that widespread feedback connections which greatly outnumber feed-forward connections, likely play a modulatory role rather than a driving role in visuospatial processing [32]. Retinal input only accounts for 5–10% of the input to lateral geniculate relay cells but it is the main driver, while feedback from the visual cortex and brainstem modulates the flow of information from the thalamus [33]. We propose that our visual consciousness hypothesis integrates previous visual processing hypothesis and can help to explain many neurological disorders and phenomenon.

Criticisms of a thalamic model of consciousness

Some researchers have proposed that the thalamus cannot be a hub for visual consciousness because vision can persist in the presence of thalamic lesions. We propose that visual areas of the thalamus, such as the LGN, are responsible for filling in

the visual scenes of the 3D default neural space while other thalamic areas fill in non-visual components. Vision can persist after a thalamic infarction if the LGN and other visual thalamic areas remain intact. The extensive processing of visual information that occurs in the cortex, as well as the creation of the 3D sensory memory space by default mode and other resting networks enables vision to persist in patients with non-visual area thalamic lesions because all components necessary for visual consciousness remain intact. However, if thalamic visual areas are damaged then vision can be impaired or even lost. Ninety percent of optic nerve fibers connect to the LGN [34], creating a bottleneck effect in which most visual information passes through the LGN before being relayed to the cortex [35]. For example, vascular lesions of the LGN can lead to various visual field losses and defects such as homonymous hemianopias, in which there is visual field loss to the left or right of the vertical midline, on the same side of both eyes [36]. A case study on a patient with a bilateral LGN infarct, found that the patient had a visual field defect in a bow-tie configuration [37]. These visual defects vary depending on the extent of the thalamic lesions. More extensive thalamic damage, such as bilateral thalamic lesions, can even lead to impaired consciousness or coma [38].

The critical role of the LGN in visual perception is also found in studies on blindsight. Blindsight is the phenomenon in which patients who are blind, due to lesions in the striate cortex, can respond to unconscious visual stimuli [39]. It has been found that the LGN is critical in blindsight and is responsible for the residual “vision” that remains [39]. This may be

due to direct communication between the LGN and extrastriate visual areas [40]. In our model, visual processing throughout the cortex is required in order for visual consciousness to arise via the thalamus; therefore, intact thalamic visual nuclei are not the only prerequisite for normal visual consciousness to arise.

It is inherently difficult to show strict cause and effect relationships involved in conscious perception due to mechanisms involved in sensory processing and consciousness. The nature of feedback properties of corticothalamic processing make it difficult to decipher at what moment information rises to conscious awareness and which specific areas of the brain are involved. In addition, the role of the thalamus in the initial relay of sensory information to the cortex, as well the corticothalamic feedback loops, make it difficult to determine whether consciousness arises from hubs throughout the cortex (as is proposed by the GW Theory) or via the thalamus. Studies on neural disorders can give us insights into the possible mechanisms involved but still leave unanswered questions. For example, the visual deficits that arise from lesions in the LGN likely occur because intact visual information cannot reach the cortex to be processed. In contralateral neglect, intact visual information reaches the right parietal lobe but cannot be spatially located due to parietal damage. We propose that this damaged information is then integrated by the thalamus and is not able to be projected within the sensory memory space [16]. However, we cannot determine with certainty whether the perception deficits of the left visual field arise at the thalamus when the damaged parietal information is integrated or whether these perception deficits arise somewhere within the cortex. To get a better picture of the role of the thalamus in consciousness, without the complications of its role in relaying information to the cortex, we can examine the olfactory system.

The olfactory system is the only sensory system that bypasses the thalamus when it is relayed to the cortex, with only a few fibers connecting to the mediodorsal thalamus [41]. The olfactory bulb relays olfactory sensory information directly to the cortex and is very similar to the thalamus in both structure and function [42]. Although the thalamus is initially bypassed, it receives processed olfactory information indirectly from the cortex [43]. A study on patients with thalamic lesions found that olfactory abilities were impaired, suggesting that the thalamus plays a significant role in olfaction [44]. In addition, there are many case studies of patients with lesions in various thalamic nuclei that experienced alterations in olfactory perception [45,46]. The effects of thalamic lesions on olfactory perception provide further evidence of the thalamus's role in consciousness because the thalamus only receives olfactory sensory information after cortical processing. These studies give us insights into the mechanisms that underlie consciousness but further research is needed to elucidate the role of the thalamus in consciousness.

Some researchers have proposed that the small size of thalamic nuclei and the small amount of brain energy utilized by the thalamus make the thalamus unsuitable as a central hub for consciousness. However, thalamic nuclei contain millions of neurons and each thalamic reticular nucleus contains a million neurons with a mean density of $15,093 \pm 73$ neurons/mm³ [47]. In addition, the majority of unconscious processing is done by the cortex and corticothalamic feedback loops. It is only when this information is integrated by the thalamus and

filled-in within the 3D sensory memory space that this information rises to conscious awareness. So the amount of energy utilized by the thalamus is not necessarily indicative of the vital role of the thalamus in consciousness. For example, thalamo-cortical relay neurons are the most energy efficient spiking cells, consuming only 7–18 nJ/cm² [48]. This can be compared to the lower energy efficiency of fast spiking somatosensory neurons which require 38 nJ/cm² per spike [48]. In addition, cortical local energy use only goes up by 6% during conscious perception of visual stimuli [49]. There are much higher firing rates for unconscious processing than for perception or conscious processing, suggesting that the energy expenditure for unconscious processing utilizes more energy than conscious perception [49].

It should also be considered that glutamate is thought to trigger the release of vasodilators which underlie the changes in blood flow that make up BOLD signals. Therefore, when there are both increases and decrease in the firing of various individual neurons within an area of the brain this may lead to a decrease in the total glutamate released and may not be detected as a positive BOLD fMRI signal, even though that area of the brain is “activated” [49]. This may indicate that fMRI studies that compare differences in brain activation, between situations that differ only in perception of a stimulus, may miss neural activations involved in stimulus perception [49]. It should also be noted that changes in blood flow due to sustained neuronal activity are four times greater than the actual increases in ATP consumption by those neurons [50]. So our current understanding of activations and changes in blood flow may not even give an accurate depiction of the energy use of specific areas of the brain involved in perception. In our model, DMN and other resting state networks create the framework and neural space that is filled in by the thalamus. Therefore the energy utilized for intrinsic and default mode activity, which is estimated to be 90% of the energy utilized by the brain, creates the oscillatory space in which consciousness arises. It is likely that the majority of the energy that goes towards consciousness processes is actually utilized by baseline activity of the brain in order to create the neural sensory memory space.

Insights from REM sleep and neurological disorders

Examining visual processing during sleep and visual processing defects that occur in some neurological disorders can give insights into how visual consciousness arises and provide support for our visual processing hypothesis. We will briefly examine the following phenomenon and disorders: (1) dreaming, (2) rapid eye movement sleep behavior disorder, (3) contralateral neglect syndrome, (5) phantom limb syndrome, (6) blind spots, (7) afterimages and (8) visual remapping across saccades.

Dreaming is a prime example of a common experience that helps to demonstrate how visual consciousness occurs within the brain. When a person dreams he or she is conscious but disconnected from the environment and experiences hallucinogenic visual and non-visual sensory experiences [51]. The experience of highly visual dreams during sleep, when the eyes are closed and not receiving external visual input, helps to demonstrate how visual consciousness arises within the brain. During waking, external visual input is received and internalized by the eyes but during sleep the visual images arise from

within the brain. It has been proposed that dreaming occurs via top-down processing rather than the bottom-up processing of waking perceptions [52] and a recent paper has used empirical data to strongly support a top-down mechanism [53]. This top-down processing may disrupt the encoding of new memories and underlie the phenomenon of dream amnesia [52]. During REM sleep, when most dreaming occurs, brain activity is very similar to waking brain activity. In addition, a subject's cognitive and neural organization during waking and dreaming are very consistent. For example, patients with lesions in regions of the brain involved in color perception experience deficits in color perception during waking and dreaming [54] and patients that experience facial blindness while awake experience this during dreams as well [54]. Studies on patients with rapid eye movement sleep behavior disorder have found that the patients' goal-oriented motor behaviors matched their eye movements, suggesting that rapid eye movements are consistent with the scanning of a dream scene [55]. Dreams occur within the mind at a time when no visual information is being detected by the eyes, suggesting that a visual representation is created and perceived within the mind. This visual processing may be similar to the visual processing that occurs during waking states. Further research is needed to elucidate the underlying mechanism of dreaming, but whether it occurs via bottom-up or top-down processing this phenomenon helps to illustrate how visual representations are created within the mind.

Contralateral neglect (CN) syndrome is a condition in which parietal lobe damage causes visual and bodily hemispheric neglect. CN generally manifests as neglect of the left visual field and left side of the body, resulting from damage to the right parietal lobe [56] but it can also result from damage to the right thalamus as well [57]. In our previous paper, we proposed that sensory information from the left side cannot be spatially located in the damaged right parietal lobe of CN patients and in turn does not rise to conscious awareness when it is sent back to the thalamus [16]. Symptoms of CN give us insights into both visual and non-visual consciousness and suggest a dynamic space in which visual and other sensory information is integrated and reimaged in a 3D default space within the mind [16]. For a detailed review of insights from contralateral neglect syndrome on visual consciousness see Jerath et al. 2014 [16].

The processing of visual information and creation of an internal image within the mind can result in inconsistencies between external reality and conscious perception. This may underlie the phenomenon of visual illusions and may contribute to the phenomenon of phantom limb syndrome and the success of mirror therapy used to treat it. Mirror therapy consists of using a mirror to reflect the patient's intact limb so that it appears where the amputated limb once was and having the patient "move" and "relax" the intact limb so that it appears that the amputated limb is intact and moving [58]. This treatment leads to a reversal in the dysfunctional reorganization that occurs within the somatosensory cortex of patients with phantom limb pain [58]. We propose that visual consciousness processes and the recreation of visual and non-visual body space within the 3D default space likely underlie the experience of phantom limb and the success of mirror treatment.

In the presence of accommodative esotropia, eye crossing due to the focusing efforts of the eyes, unconscious suppression of the retinal image from either eye can eliminate double

vision [59]. However, suppression of one of these images can also result in scotomas or blind spots. These suppression scotomas only occur during binocular vision and disappear when one eye is covered [59]. These suppression scotomas are a prime example of visual information that is seen by the eyes but, due to visual processing mechanisms, is never perceived. In addition, the filling-in of visual information into artificially induced scotomas suggests that the "filling-in" process occurs during the creation of a neural representation [60]. This "filling-in" of missing visual information occurs in normal vision due to the physiologic blind spot on the retina where the optic nerve leaves the eye [61]. This phenomenon further supports our model in which an internal visual representation of external space is created within the mind and seems to challenge direct perception models. Afterimages may also involve this filling-in phenomenon.

Afterimages are a type of optical illusion in which an image continues to appear after exposure to the image has ended. This phenomenon is thought to be due to overstimulation and desensitization of photoreceptors [62]. However, some studies have shown that there is also a cortical basis for negative [63] and positive afterimages [64,65]. In addition, positive afterimages are likely representations that are filled-in by cortical activity [64]. We propose that the involvement of higher cortical areas in the creation of afterimages [63–65] suggests that afterimages are the remnants of visual representations within the visual consciousness aspect of the 3D default space.

The location of a projected object on the retina can change drastically during saccades but the resulting perceived surrounding visual scene and object are stable. In addition to the previously mentioned mechanism involving suppression, enhancement, and time compression there are quite a few other hypotheses that have been proposed that may underlie visual stability in the presence of saccades. It has also been proposed that this stability may be due to constant spatiotopic coordinates in the presence of saccades or object-based remapping [66]. This study found that object-based remapping, in which active updates are made regarding object location and object features, likely underlies visual stability [66]. In addition, neurons in areas of the brain associated with planning of eye movements have been shown to change receptive fields around the time of saccades [67]. One way that the brain keeps track of saccadic eye movements is via corollary discharges. These are copies of motor commands that inform other areas of the brain about motor movements but do not result in movements themselves. One study found that visual processing is impaired when corollary discharges from the thalamus are blocked [67]. These studies may support our model in which a dynamic visual representation is created within the neural component of 3D default space. This visual space remains stable and does not move in the presence of saccadic or voluntary eye movements. However, some researchers propose that spatial remapping has little impact on the perceived stability of vision and is more involved in motor control, spatial memory, and sensorimotor adaptation [68]. Also, it has been shown that significant changes made to a scene during a saccade can go unnoticed, including moved, changed, or erased objects [69]. However, in the real world, as opposed to lab tests, the visual system is actually very good at detecting these types of changes due to motion cues that engage selective attention, rather than relying on memory alone [70]. Selective attention within the 3D default space likely plays a role in conscious awareness.

Simple tests to examine the internal visual space within the mind

In order to better understand our hypothesis the reader must familiarize themselves with this visual space within the mind. Our external experience of internal visual representations likely optimizes our interactions with our environment and allows for quicker responses. For example, researchers propose that the primary purpose of perception is to guide actions [71]. Therefore, we propose that the experience of the internal representations of the external world (i.e., vision) within the eyes likely allows for optimal interactions with the external world. If we were more aware of the internal origin of the highly processed visual images that we perceive, this might slow reaction times to external stimuli. We propose that external vision is represented and perceived within the mind but is experienced at the eyes as having an external source, allowing for optimal interactions with the environment. This can also be applied to the other sensory systems as well. For example, a sound is perceived within the mind after processing by corticothalamic feedback loops but experienced at the ear, allowing for optimal perception of the external source of these stimuli. This phenomenon contributes to why we discuss intrapersonal space or 3D default space rather than just the brain because although most processing occurs within the brain, sensory information comes from throughout the body and is experienced at the sensory organs. Recent research has even shown that some processing occurs within non-neural sensory neurons, for example first-order tactile neurons can process data about objects touching the skin [72]. In order to examine the internal visual space, which tends to evade perception by the viewer, we have proposed a few simple tests: (1) Bright light source test, (2) Afterimage test, and (3) Body rotation test.

Bright light source test

In the bright light source test a subject looks at a bright light source at a distance, such as the sun at sunrise (the afternoon sun is too bright for the eyes). When we close our eyes, we see a bright red oval glow. When we place our hand in front of one of our closed eyes the red glow is halved and it resembles the shape of a single visual field. When we move our hand away it again assumes the shape of a binocular visual field. Part of this red-glow effect can be attributed to light shining through the eyelid but it also helps in visualizing the otherwise invisible visual fields. This simple test helps to visualize the internal visual space in which the internal visual representations of external space are perceived.

Afterimage test

When we look at a distant sun rise at a beach and then close our eyes we can see a positive afterimage of the sun, likely followed by a negative afterimage. This afterimage occurs in the original location of the sun and if we slowly move our head sideways, the afterimage that we see follows the same path (Fig. 5).

This afterimage and the subsequent movement of the afterimage with the path of our head and eyes is likely due, in part, to overstimulation and desensitization of photoreceptors [62]. However, as previously discussed, recent studies implicating higher cortical involvement in afterimages [63–65] suggest that the internal visual representation of the sun and horizon may also contribute to this afterimage. This simple test illustrates how we have a hard-wired and dynamically active visuospatial

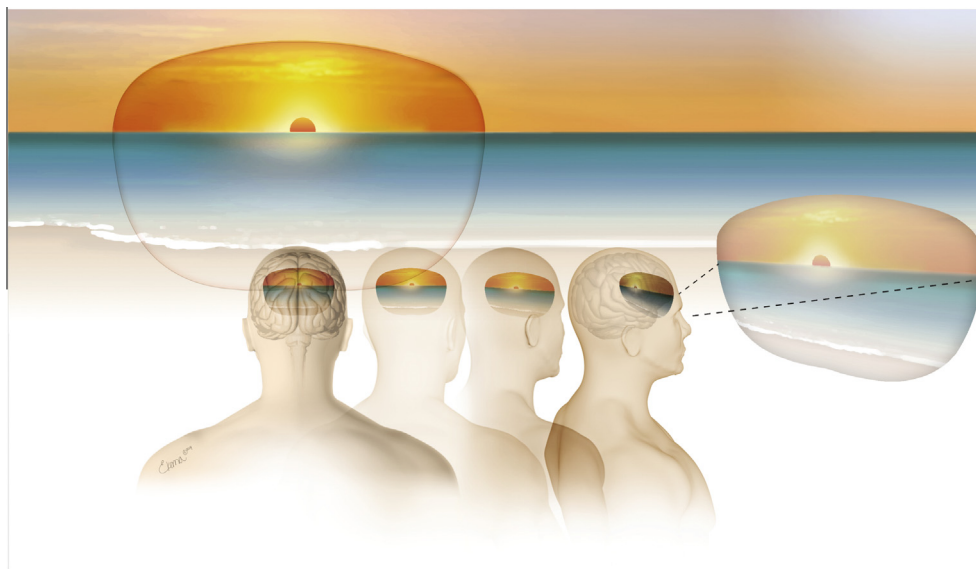


Fig. 5 Afterimage test. This figure illustrates an example of the afterimage test. When you stare out at a sunrise or sunset and close your eyes you may see an afterimage of the scene with your eyes closed. Furthermore, if you slowly rotate your head to either side, with your eyes closed, this image will move with you because it is an afterimage of the image created within your mind. Although some might attribute this to phenomenon to retinal discharges alone, studies have shown that higher processing is involved. Afterimages are likely created by filling in from higher cortical areas, suggesting that positive afterimages are the remnants of external visual space that is reimaged within the 3D default space.

space in our mind that serves as a framework where external visual information is represented and perceived.

Body rotation test

The body rotation test is similar to the effects of being on a merry-go-round. Here we stand in the middle of a room and rotate in a circle 10 times in 20 s, keeping our eyes open. When we stop, we will feel dizzy and the walls of the room will appear to still be moving. Now if we turn at a slower speed, such as 10 times in 60 s, or spin with our eyes closed, then there is minimal dizziness. Normally the visual and non-visual components of the 3D default space are constantly adjusting according to changing stimuli, resulting in the perception of a stable and constant external space. However, when we spin quickly, the room still appears to rotate after we have stopped because the incoming visual information that the surrounding walls of the room are now stable is combined with the conflicting sensory information from the continued movement of fluid within the inner ear. Visual information is integrated with other sensory information within the brain [73,74]. Therefore, we propose that sensory information, such as information from the inner ear, is integrated within the 3D default space. The integration of conflicting information from different sensory systems via the thalamus and corticothalamic feedback loops may contribute to the subsequent physiologic dizziness after rapid spinning is stopped. The integration of conflicting sensory information within the 3D default space may also help explain symptoms of motion sickness and vertigo.

Conclusion

Visuospatial consciousness is perceived by the visual system at our eyes, which function as the end organ for visual consciousness. The eyes, thalamus, and corticothalamic feedback loops act as one cohesive unit in which extensive visual processing occurs but the perception of the final processed visual image occurs at the eyes. Although two separate visual images enter each eye, they are processed and integrated into one 3D image by corticothalamic feedback loops and the thalamus. The thalamus processes and integrates the external visual world within the mind via its feed-forward and feedback interactions with the cortex. The unique central position of the thalamus allows it to process and relay information from our retina to the visual cortex and other cortices, integrate the processed visual information, creating a seamless binocular internal image of external vision within this 3D space that is experienced at the eyes. Fast parallel processing enables us to seamlessly and imperceptibly form a visual and non-visual reproduction of the external world within our minds, which allows us to perceive and interact with our external world. If proven correct, this hypothesis will be a key element in illuminating how the brain functions as the mind and may help us to further understand related memory, awareness, and cognitive processing, as well as countless disorders.

Overview box

First Question: What do we already know about the subject?

Consciousness and how the brain functions as the mind are processes that still evade explanation by neuroscience. The mechanisms underlying consciousness and visual consciousness processes remain largely unknown but most researchers agree on the important role of corticothalamic feedback loops. Vision is the most salient sensory component of consciousness processing and can provide insights into consciousness and how visual representations are recreated within the mind.

Second Question: What does your proposed theory add to the current knowledge available, and what benefits does it have?

There are various schools of thought regarding visual consciousness processing; some researchers propose that visual sensory information is of poor quality and must be interpreted using previously acquired knowledge while others propose that we gain direct awareness of our environment from vision and no interpretation is necessary. Our model incorporates aspects from these and other previously proposed vision and consciousness models to create a new visual consciousness model. We propose that the thalamus integrates processed information from corticothalamic feedback loops and fills-in the neural component of 3D default space with an internal visual representation of external space, leading to the experience of visual consciousness. Understanding consciousness would provide insights into the inner workings of the mind and brain and may help us to better understand and treat countless neurological disorders.

Third question: Among numerous available studies, what special further study is proposed for testing the idea?

In order to study this visual consciousness model we must continue to study the neural correlates of consciousness and further examine processing times involved in conscious awareness. Further studies on the thalamus and various thalamic nuclei must also be done to explicate their role in consciousness. The subjective nature of conscious experience remains an obstacle in consciousness studies but examining the visual system can provide much needed insights.

Conflict of interest

The authors declare that there are no conflicts of interest.

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