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What makes your body ‘yours’?

The neurodevelopmental mechanisms of body ownership sensation and the mismatch in Body Integrity Identity Disorder

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Abstract:
A correct representation of the body in the brain is necessary for the feeling of body ownership. This sensation seems to arise from the detection of congruency of information coming in through different sensory systems, particularly the visual, tactile and proprioceptive pathway. The congruency is detected by multisensory neurons that integrate input from these systems. This integrative function develops after birth, along with the fine-tuning of the separate sensory systems; both require stimulation experience to reach an optimal state.
In Body Integrity Identity Disorder (BIID), a mismatch exists between the body representation in the brain and the real situation, with an onset of this feeling in childhood or early puberty. The feeling of ownership for one of the limbs is missing, and the patient desires an amputation or paralysis of this limb. Activity in the premotor cortex is decreased when the non-belonging limb is stimulated, suggesting a malfunctioning of multisensory integration. The onset of BIID later in life indicates a disturbance during the development of the multisensory integration system.
Currently there are no effective treatment options for BIID, only amputation of the limb resolves the mismatch completely. Deep brain stimulation could be effective, but due to its invasiveness transcranial magnetic stimulation or transcranial direct-current stimulation might be better options. Furthermore, research should be done to examine the plasticity of multisensory neurons in the adult premotor cortex, and a possible genetic origin of BIID could give more insight into the developmental mechanism and potential drug targets.

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Introduction

Most individuals have no difficulty in distinguishing their own body from the environment or from other bodies; they experience a feeling of ownership for every part of their own body. This sensation of body ownership is important, every body part should feel like it belongs to oneself to optimize the functioning of the whole body in the environment. The feeling of body ownership is a result of the presence of a representation of the body in the brain, formed by the integration of incoming information from different sensory systems [1].

It is essential that the body representation corresponds with the real appearance of the body, and to assure this, the representation needs to be updated constantly. In some situations however, a mismatch can arise between the brain's version of the body and the body itself. There are many different disorders in which such a mismatch seems to exist, like gender disorder, body dysmorphic disorder and eating disorders; in all of them there is a disturbance of a certain part of the body representation [2]. One specific case is the rare disorder called 'Body Integrity Identity Disorder' (BIID), sometimes also called xenomelia. People who suffer from BIID miss the feeling of body ownership for one, or sometimes even more of their limbs, while these limbs are healthy and function perfectly. Patients feel overcomplete with this limb and they desire an amputation or paralysis of the concerned body part to resolve their experienced mismatch [3]. The symptoms of BIID are not present from birth on, the disorder has its onset later in life, usually during childhood or early puberty [3]. This means that the mismatch develops at a certain moment, while there is no evident presence of brain damage [4]. To find out how the mismatch in BIID develops, it has to be clear how the body representation is formed in a non-pathological situation. Besides that, the normal development of the involved sensory systems and the integration of their information in the brain should be understood. After presentation of the non-pathological pathways that lead to a correct body ownership sensation, the anomalities that are present in BIID will be described, along with the possible mechanisms of mismatch development. At last the treatment options for BIID that are currently used will be discussed and new possibilities that might be successful in the improvement of a mismatch will be reviewed. The main focus of this essay is thus, what are the neurodevelopmental mechanisms of body ownership sensation and how can a mismatch between the body and this representation, as seen in Body Integrity Identity Disorder, be explained?

1. Normal self-perception and body ownership

There are three main pathways that mostly contribute to the formation process of the body representation in the brain: the visual pathway, the somatic sensation of touch and the proprioceptive pathway [1]. The essentials of these separate pathways will first be explained in this section, after which the integration of information from all of them to form a complete body representation will be discussed.

1.1 Visual pathway

From the eye to the brain

The visual pathway has a share in the body representation formation by processing visual information about the body. Vision starts with light falling into the eyes, which is translated into a mental image in several steps [5]. The main pathway through which vision takes place is schematically illustrated in figure 1.

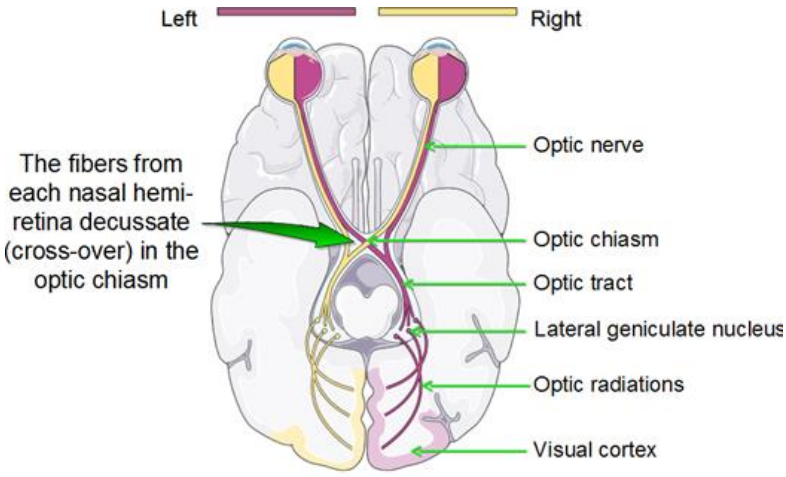

Figure 1: the main visual pathway [6].

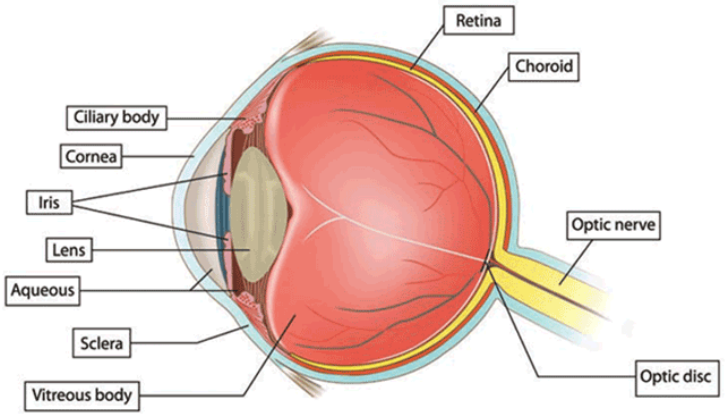

Figure 2: Anatomy of the eye [7].

Light that comes into the eye is focused on the retina by the cornea and the lens (figure 2). The light energy is converted into electrical pulses in photoreceptors in the retina, both rods and cones. The membrane potentials that are formed travel through bipolar cells and ganglion cells, which are other cell types that are present in the retina. The axons of ganglion cells exit the retina in the optic disk, together forming the optic nerve. The optic nerves from both eyes enter the brain in the optic chiasm, where they combine. In the optic chiasm, the fibers coming from the nasal side of both eyes

cross to the other side. Now the nerves that carry information from the left visual field of each eye project to the right hemisphere, and nerves from the right visual field of both eyes send information to the left hemisphere. The axons that leave the optic chiasm are called the optic tracts, which do not continue their route in the unity they formed until now; the optic tracts project to different brain regions [5, 8, 9]. Two small parts of axons go to the hypothalamus and midbrain respectively, but the largest part leads to the lateral geniculate nucleus (LGN), an area of the thalamus in both hemispheres.

Regulation in the LGN

The largest part of the visual pathway thus enters the brain in the lateral geniculate nucleus. The LGN has long been thought to just function as a relay for the signals travelling from the eye to the the visual cortex, but later studies have brought evidence of a regulatory function of the LGN in the information transmission [10].

The input that the LGN receives comes from many different sources, only about 10% is information from the optic tracts. The other 90% is filled by feedback projections from the visual cortex, inhibitory input from the TRN (another thalamic area), and cholinergic projections from the brainstem. Each of these three pathways has an equal share of about 30% of the total input [10].

The activity of LGN neurons is altered by selective attention and visual awareness [10], which is thought to be mediated by information coming in through the different input pathways [9]. Based on the caused alterations in neural signalling, the LGN probably serves as a first regulator of information processing, by modulating the transmission to the cortex according to the behavioural context at that moment [10]. The LGN is thus not merely a passive relay, but seems to function as first filter of visual information.

From LGN to visual cortex: information processing

The output of the LGN, called optic radiations, leads to the primary visual cortex, located in the occipital lobe. The primary visual cortex is the first part of the cortex to receive incoming visual information, from here signals are sent to other cortical areas [9].

In both the LGN and the primary visual cortex, information is stored in a topographical organization, called retinotopy, corresponding to the organization of the retina. Information from different parts of the visual field is processed in the different layers of which both the LGN and the primary visual cortex consist. In this way, an accurate representation of the visual field is present in the brain [9]. The layers that can be distinguished contain different types of neurons, each specialised for the processing of different aspects of stimuli [9]. The specialisation facilitates a parallel processing of all different attributes of the incoming information, like object shape, motion and color.

Signals coming from each eye remain segregated until they reach the primary visual cortex, where neurons are present with binocular receptive fields. These neurons receive information from congruent locations of both eyes and combine this to a single image [5, 9].

Primary visual cortex output: further specialisation

Leaving the primary visual cortex are pathways to many different cortical areas within the visual system. Projections lead to further specialised areas in the secondary visual cortex and to other cortical regions localised in the temporal and parietal lobes. There are also pathways projecting to other brain structures, for example the feedback route to the LGN [9].

The cortical projections leaving the visual cortex can be divided into two main pathways: the dorsal stream, leading to the parietal lobe, and the ventral stream that projects to the temporal lobe (figure 3). The dorsal stream is specialised in the processing of object motion and the visual control of action, while the ventral stream is involved in object recognition [9]. The parallel processing of information in the dorsal and ventral pathways – and in the other parts of the whole visual system – leads to the integration of all stimulus features in one perceived mental image.

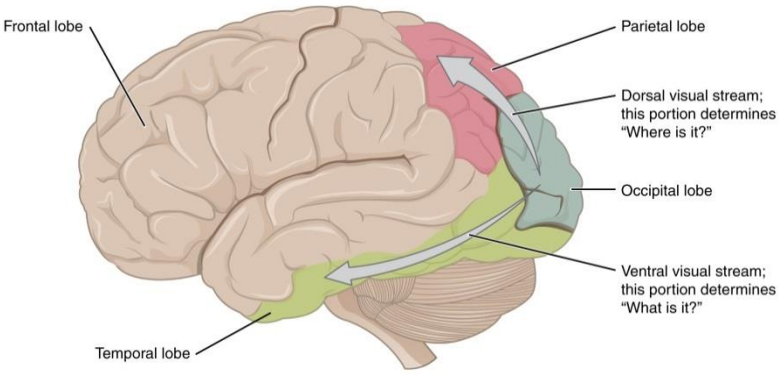

Figure 3: The dorsal and ventral pathway projected from the primary visual cortex [11].

Vision summary

The main pathway of vision thus begins at the eyes. When entering the brain the optic tracts reach the LGN, the first information filter. The LGN projects pathways to the primary visual cortex, where specialised information processing takes places. From the primary visual cortex, projections lead to the secondary visual cortex and areas in the temporal and parietal lobes where areas are located with an even further specialisation. Parallel processing enables integration of all stimulus features to one perceived mental image.

1.2 Sensory pathway

Touch detection

The somatic sensation of touch is a second important contributor to the mental body representation. This somatosensory system has its own pathway leading into the brain. The start of touch sensation is usually at the skin, where it can be detected by various mechanoreceptors, each with a highest sensitivity for a different type of stimulus. Stimuli that are applied to the skin consist of mechanical energy, which is transduced into electrical signals, or receptor potentials, in the receptors [9]. Every receptor, or primary sensory neuron, has its own receptive field and is activated by stimuli that are applied within this area. When different receptive fields overlap, their primary neurons all synapse on one secondary sensory neuron. In this way they combine into one secondary receptive field of which the information can be send to the brain. When more primary neurons converge on one secondary neuron, the secondary receptive field gets larger and the sensitivity to stimulus location detection lowers. The size of receptive fields differs at different locations of the body [5, 9].

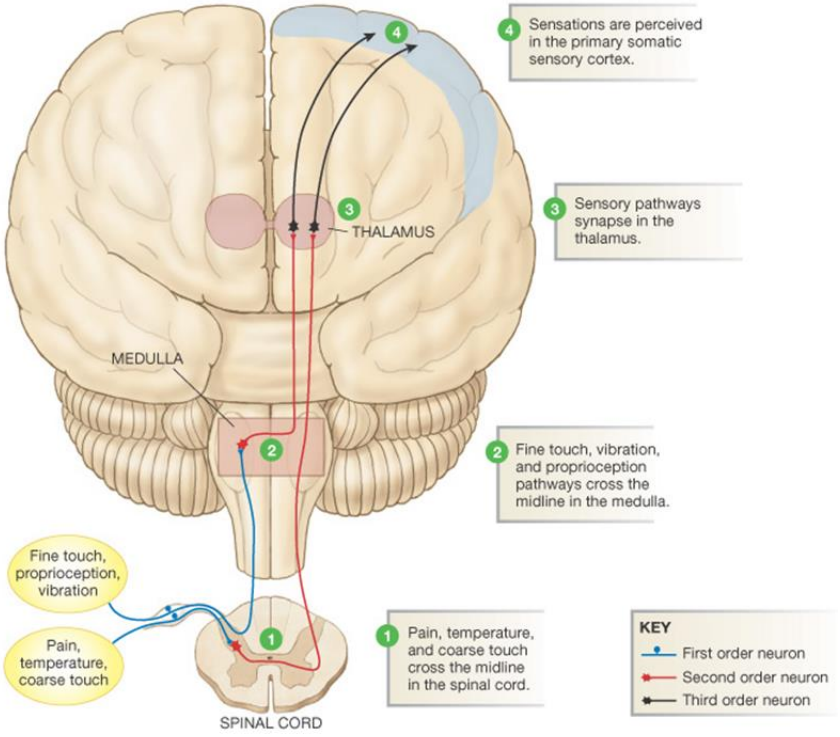

Figure 4: the dorsal column – medial lemniscal pathway [12].

From the skin to the brain

When a stimulus is above a certain threshold, the receptor potential that is formed in a primary neuron initiates the process of information transfer to the central nervous system. This takes place through the so-called 'dorsal column – medial lemniscal' pathway, illustrated in figure 4 [9]. In this figure can be seen that the axon of a primary neuron enters the spinal cord in the dorsal root and continues its way toward the brain in the white matter of the ipsilateral dorsal column. The place where the spinal cord ends and the medulla begins is the location where the primary sensory neurons synapse onto the secondary sensory neurons. At this point, the neurons that came from the left and right side of the body cross to the opposite side and continue their path into the brain contralaterally. After crossing to the other side, the axons follow a route within the medial lemniscus – a white matter tract – through the medulla, pons and midbrain, until they reach the thalamus where they synapse onto tertiary sensory neurons. These neurons lead to the somatosensory cortex, which is mainly located in the parietal lobe [5, 9].

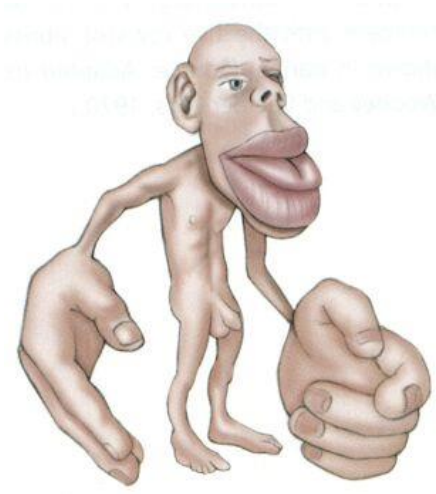

Figure 5: The homunculus as an image of the somatopic map [13].

Information processing in the somatosensory cortex

As in the visual system, incoming information in the somatosensory cortex is organised topographically – in this case called somatotopy – and processed in different layers. The somatotopic map that is formed is often referred to as the 'homunculus' (figure 5), illustrated as a little man with a distorted scaling of body parts. The size of each body part depends on the sensitivity of this body part to stimuli, and thus the amount and importance of the information that the brain receives from it [5, 9]. The somatotopic map is not fixed, it can be changed continuously based on the input it receives. A high amount of input from a certain body part has been shown to increase its representation in the corresponding cortical area. An absence of input however, as occurs after an amputation, results in an altered version of the somatotopic map; the cortical area formerly devoted to the representation of the missing body part starts to respond to stimuli applied to the body regions that are represented by neighbouring cortical areas [9]. The somatotopic map is thus very dynamic and changes along with body alterations, so that no space is wasted. A reorganisation can however lead to misinterpretations of sensation in an amputated body part, which can occur when one of the body parts that the area now represents is stimulated. This phenomenon demonstrates that while the cortical area has switched to responding to other input, there are still existing pathways associating this area with its original input source [9].

Somatosensory cortex output

The primary somatosensory cortex, also named area 3b, is the first region of the cortex that receives input from the sensory pathway. From here output pathways project to the secondary cortex regions, area 1 and 2, specialised in the processing of texture information and size and shape characteristics respectively [9]. The somatotopical organisation exists in all areas of the sensory

cortex, so that features that are processed in different pathways can be attributed to the same stimulus corresponding to its correct location [14].

Sensory pathway summary

The detection of touch starts at the skin, from where the signals travel through neurons in the dorsal column–medial lemniscal pathway, finally reaching the thalamus. Neurons coming from the thalamus lead to the somatosensory cortex, where information is processed in a 'homunculus organisation'. Pathways from the primary cortex project to more specialised secondary cortex regions. Due to the somatotopical organisation, features processed in different pathways can be attributed to the same stimulus.

1.3 Proprioceptive pathway

The third pathway that plays a role in the creation of the body representation is the proprioceptive pathway, which is a part of the general somatosensory system. Proprioception is defined as the perception of the position of the own body in space, the relative location of body parts compared to each other, and movements that are made [5, 15]. Proprioceptive information is mostly retrieved from muscle spindles, for a smaller part from Golgi tendon organs and for a minor part from mechanoreceptors in joints [8, 9, 15]. These receptors together, collectively called proprioceptors, provide the brain with accurate information about the body.

Muscle spindles

Muscle spindles are stretch receptors that provide information about muscle length and changes that occur in muscle length, by giving impulses in response to the degree and rate of stretch [5, 8]. A muscle spindle is surrounded by a capsule. Fibers within the capsule are named as intrafusal, and the fibers outside the spindle are extrafusal fibers.

Information about muscle length is sent to the central nervous system by afferent sensory axons that are wound around the intrafusal muscle fibers. When the muscle stretches, the intrafusal fibers also stretch, which stimulates the receptor endings of the sensory neurons and increases firing rate. Besides the sensory neurons, gamma motor neurons are connected to muscle spindles. Gamma motor neurons are an efferent class of neurons that innervate muscle spindles to adjust and maintain their sensitivity when muscle length changes [8].

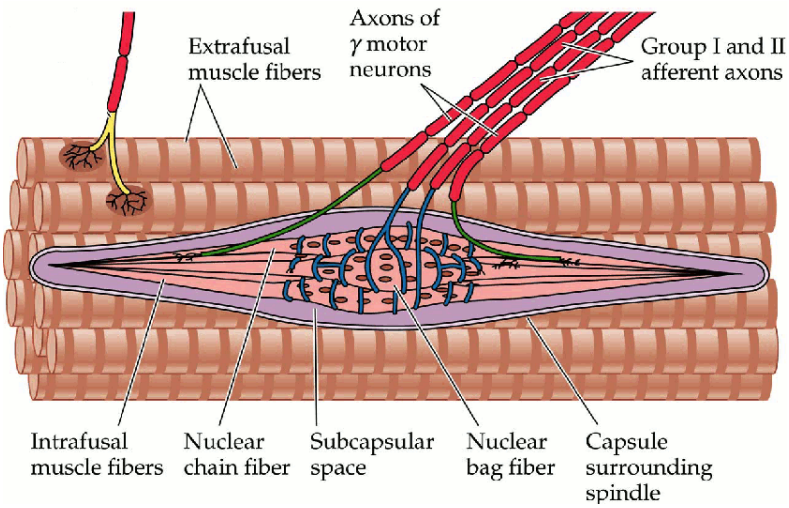

Figure 6: muscle spindle in the muscle [16].

Golgi tendon organs

Golgi tendon organs form another type of sensors in skeletal muscles, located at the junction of a muscle and its tendon. They do not receive information about muscle length, but respond instead to changes in muscle tension [8, 9, 17].

Joint mechanoreceptors
Another part of the proprioceptive perception that reaches the brain originates from mechanoreceptors in joint capsules and ligaments. These receptors are sensitive to mechanical changes that occur when the relative position of bones alters. Signals about angle, direction and speed of a joint movement are sent primarily to the cerebellum [5, 9].

Proprioceptive pathway to the brain
Axons of the sensory neurons of all proprioceptors enter the spinal cord in the dorsal root, from where they follow the same pathway as the sensory neurons responding to touch: they travel through the ipsilateral dorsal column, then synapse and cross in the medulla, the thalamus is passed and finally the sensory cortex is reached [17] (figure 4). Besides the projection to the thalamus, proprioceptive sensory neurons also send signals to the cerebellum, the center of motor coordination.

Information processing in the brain
In the sensory cortex, proprioceptive information is processed along with the information of touch sensation, and it is integrated in the somatotopic map. The primary sensory cortex projects output to different areas in the parietal cortex, which in turn is strongly connected to the frontal lobe. The prefrontal cortex is involved in decision making and consideration of action consequences. Both the parietal and the prefrontal cortex send input to the motor cortex, where the execution of movements begins [9].
The cerebellum receives input from the sensory neurons as well as from cortical areas of the cerebrum. Here an integration of these signals takes place which results in a correct coordination of movements [5].

Proprioceptive pathway summary
Proprioception is based on information from muscle spindles about muscles length, Golgi tendon organs about muscle tension, and joint mechanoreceptors about the position of bones. This information travels through the same pathway as the neurons involved in touch sensation, and it is finally integrated in the homunculus organisation in the sensory cortex. The cerebellum also receives proprioceptive information which is used for movement coordination.

1.4 Multisensory integration
We define body ownership sensation as the feeling of awareness that arises from a correspondence of information detected by multiple sensory systems in the phase of sensory integration (1, 18). The contribution of several sensory systems to one correct body representation in the brain suggests an integration of the information coming from these separate sources, that have been described in the previous section: the visual, tactile and proprioceptive system. The core question to be answered when following this definition is: how is this correspondence perceived and processed by the brain?

The rubber hand illusion
An example of cerebral multisensory integration is the rubber hand illusion. The neurological basis of body ownership sensation has been investigated using this rubber hand illusion. In this experiment, a subject sees a rubber hand instead of its own hand, while both real and fake hand are stroked simultaneously. In this way a strong feeling of ownership for the rubber hand can be induced [19, 20]. Brain activity can be monitored during this experiment with fMRI or PET. When the rubber hand illusion is experienced, an activation of different areas is observed compared to a control situation; especially the ventral premotor cortex (vPMC) in the frontal lobe and the intraparietal sulcus (IPS) area become activated during the illusion [1, 21]. These findings suggest a multisensory integration of stimuli in these areas.

Multisensory integration and body ownership sensation

The idea of multisensory integration in the vPMC and IPS area is further reinforced by the presence of neurons that respond to different sensory stimuli, located in corresponding brain regions in non-human primates [22, 23]. The multisensory response suggests that these neurons integrate information coming from the different sensory systems. The multisensory neurons receive input that originates from the separate systems, which is facilitated by the extensive connections of the PMC and IPS with visual and somatosensory cortical areas. The multisensory neurons thus have a combined sensitivity for different sensory types of input, coming from a specific part of the body [21]. Besides the ventral premotor cortex and the intraparietal sulcus area, another region that contains many multisensory neurons is the superior colliculus, a structure in the midbrain [9].

Following our definition of body ownership, we propose that the activation of multisensory neurons – integrating visual, tactile and proprioceptive information – might be responsible for the feeling of ownership of that specific body part.

2. Development of body ownership sensation

2.1 Development of the sensory systems

A large part of the development of the sensory systems takes place in utero; the sense organs develop and the pathways that connect the brain with these organs are formed [24]. This facilitates the basic functioning of the senses at birth, but the development is not yet completed. The connections that now exist are highly non-specific; the neurons of the visual system for example still respond to stimuli coming from both eyes. For the sensory systems to become sensitive and accurate, the connections with the brain must be fine-tuned, which happens with the reception of sensory input [24]. The unfinished development facilitates a certain degree of plasticity, which allows an optimal adaptation to the environment. At the same time, this incompleteness makes sensory stimulation necessary to reach the best development; a deprivation of input has been shown to impair functionality of a system [25]. A competition of incoming stimuli takes place, resulting in the existing connections to become either stronger or weaker. Weakened connections will eventually disappear, while the stronger connections remain. The alterations of connection strength lead to organisational changes in the projected brain areas, so that specific functional regions are formed [24]. In this way, the sensory systems become highly specialised.

This post-natal developmental process occurs for all sensory pathways, the degree of plasticity and the time until full maturation may however differ. For all systems, there is a critical period in which the neuronal connections are susceptible to modifications. When this period has ended, the connections are relatively fixed and insensitive to alterations caused by sensory input [26].

2.2 Development of multisensory integration and body ownership sensation

Multisensory integration development

Although multisensory neurons are already present at birth, they do not yet have the capability to integrate input from the different sensory systems. In order to develop their integrative function, experience with multisensory stimuli is required, whereby the spatial and temporal synchrony of the stimuli are important [27]. The critical period for multisensory development seems to be in the first few months after birth, and when input from one of the sensory systems is absent or disturbed during this period, integration of information including this system will not develop to its optimal form [27].

Body ownership sensation development

Since a multisensory integration seems to be non-existent at birth, one can state that newborns do not have a real feeling of body ownership yet, but that this develops along with the functioning of multisensory neurons. The exact development of body ownership sensation is hard to investigate, since infants are unable to communicate about it. What has been shown however, is that infants

gradually learn to differentiate their own body from the environment, which seems to happen by detecting congruencies between incoming information from different sensory systems [28]. This detection of correspondence matches the definition of the feeling of body ownership, thus indicating a correlation between multisensory integration development and the development of the actual body ownership sensation.

3. Body Integrity Identity Disorder (BIID): an example of a mismatch between the body and the representation in the brain

3.1 BIID: description of the disorder

As described in the introduction part of this review, BIID is a disorder in which the feeling of body ownership for a specific healthy body part is missing, in most cases the left leg. The disorder seems to be more prevalent in men than in women [29, 30]. Patients feel overcomplete with the concerned body part and they desire an amputation or paralysis of this limb. While resolving the experienced mismatch is the main reason for amputation, a second motive that is sometimes stated is the feeling of sexual arousal that patients get when they imagine themselves as disabled or when they see someone who has the disability they desire [3].

BIID has a great impact on normal life, due to the presence of severe obsessions with the concerned body parts. Besides that, overall feelings of distress and disability are frequently present, and there is a higher prevalence of feelings of depression and anxiety among BIID patients compared to the general population [3].

3.2 Possible causes and changes in the brain

The symptoms of BIID are not present at birth; patients report an onset of the feeling of a mismatch and the desire for amputation or paralysis during childhood or early puberty [3, 30]. This indicates that the mismatch develops at a certain moment, without occurrence of a specific causal incident and without evident presence of brain damage [4].

Following the definition as stated before, the feeling of body ownership relies upon a correct body representation in the brain, which in turn is formed by the integration of input from different sensory systems. We propose that the missing feeling of ownership for a limb in BIID is caused by an incorrect body representation, based on a disturbance in either one of the distinct sensory pathways, or a malfunctioning of the multisensory integration.

Neuroimaging in BIID

To get more insight into which brain areas, and therefore which sensory systems, could be involved in BIID, imaging techniques have been used to measure brain activity in BIID patients compared to healthy controls during stimulation of the limbs [4, 21]. fMRI results showed a lower activity in the ventral and dorsal premotor cortex when tactile stimuli were applied to the leg with a missing ownership sensation, compared to stimulation of the own other leg and the results of healthy control subjects [4, 21]. Although it cannot be interpreted as a causal relationship, these results suggest that the premotor cortex is affected in BIID. As previously described, the premotor cortex seemed to be involved in multisensory integration; a decreased activity in this area might therefore indicate a disturbance of this integration. Imaging the feeling of ownership in the rubber hand illusion and in actual BIID patients thus show corresponding results for the premotor cortex; an arising feeling of ownership correlates with increasing activation of this area, while missing ownership sensation comes with a lowered activity in the premotor cortex.

Altered activity in the IPS area, as was measured in the rubber hand illusion, is not seen in BIID patients [4, 21] The IPS area can still be involved in the formation of a correct body representation, but it does not seem to be associated with the mismatch that is seen in BIID.

BIID causation theory
The later onset of BIID symptoms might suggest that the prenatal development is not yet disturbed, but that the mismatch arises during postnatal development. The neuroimaging results that show alterations of activity in one of the multisensory integration areas lead to the hypothesis that disturbances of this integration system during postnatal development might be involved in causing the ownership sensation mismatch in BIID.

4. Body Integrity Identity Disorder treatment

4.1 Currently used treatments

Symptom relief
Up until now there is no known treatment that resolves the mismatch of limb ownership in BIID patients. Several methods have been used, most of them as attempts of curing different symptoms that are often seen in BIID patients, like anxiety, depression and obsessive thinking. Based on the idea that curation of the symptoms might resolve the overall feeling of disownership, patients have been treated with antidepressants, antipsychotics and psychotherapy like cognitive behavioural therapy. While these types of treatment sometimes resolve the aimed symptoms, the actual feeling of disownership remains unchanged [3, 31]. This has led to the understanding that feelings of anxiety and depression are merely secondary symptoms that BIID patients experience. While it is useful to treat these symptoms to improve the patients quality of life, the methods can only be specified as effective treatment options for these targeted problems and not for BIID itself.

Amputation
The only known intervention that does completely solve the mismatch between the body and its representation, is an amputation of the concerned limb. Despite of acquiring a physical disability, BIID patients who have undergone an amputation report feeling less disabled than before, they are happier and say that their body is finally how it is supposed to be [3]. So far, amputation of the mismatched limb seems to be the only effective 'treatment' option for BIID [4]. Although it improves the patients quality of life, it is not an optimal method to treat the disorder; that would be resolving the mismatch without having to remove a well-functioning body part.

4.2 New possible treatment options

Instead of focusing on curing various symptoms, a treatment of BIID should be investigated from a causal perspective. Following the multisensory integration definition of body ownership sensation, the cause of the problem is located in the brain, not in the affected body part. Therefore, treatment options should focus on neurological targets to change the feeling of disownership.

Multisensory integration as target
Possibilities to alter activity in the multisensory integration system could be investigated first, based on the theory that suggests a malfunctioning of this system in BIID.
As previously mentioned, there is a critical period for multisensory integration development. A study that has been done in cats however reports a certain degree of plasticity in multisensory neurons in the adult brain. A disturbed integration development during childhood could be partly restored when plenty multisensory experience was available later in life. This experience led to an improvement of the dysfunctioning of multisensory neurons, however it was only tested in neurons in the superior colliculus in cats [32]. Although real comparisons can not be made, based on this cat experiment the enhancement of functioning of the multisensory neurons in the human premotor area could be studied. A possibility to improve the multisensory integration concerning the specific limb, might have an effect on the feeling of ownership. This would require more research to find out whether a certain kind of input can alter the neuronal functioning in this specific brain region.

Brain stimulation

A treatment option that is already used in other disorders and might also have an effect in BIID, is brain stimulation. The mostly used variants are transcranial magnetic stimulation (TMS) and deep brain stimulation (DBS) [31]. Another type of brain stimulation that has been gaining interest in the last few years is transcranial direct current stimulation (tDCS) [33].

The underlying mechanisms of brain stimulation in general are not completely clear, but it has been shown to modify activity in the brain areas in which it is applied [34]. Therefore brain stimulation could alter the feeling of body ownership when it is applied to the premotor cortex area that seems to be involved. Deep brain stimulation however requires invasive brain surgery and is not without risks, which gives rise to the ethical question whether this would be a better alternative than limb amputation. Transcranial magnetic stimulation is not as invasive, since it does not require insertion of electrodes in the brain but alters brain activity through the skull. For transcranial direct current stimulation no surgery is needed either, and it has the advantage of being cheaper and easier to apply than TMS. In addition, no serious adverse effects have been found in numerous studies that have been done both in healthy subjects and patients with different neuropsychiatric diseases [33]. Due to the advantages that tDCS has over deep brain stimulation and transcranial magnetic stimulation, this type of brain stimulation should be the first to be tried on BIID patients. Since tDCS has already been shown to have positive effects in several disorders, this option could be a promising method for the treatment of BIID [33].

Genetics of BIID

Another possibility that could lead to new insights, would be to determine whether BIID seems to have a genetic origin. Finding a possible genetic source could give a further understanding of the mechanism of development of a mismatch in BIID, which in turn could give rise to the discovery of specific potential drug targets.

Conclusion & Discussion

Body ownership sensation

In this essay, the neurodevelopmental mechanisms of body ownership sensation have been reviewed. We defined this feeling of body ownership as resulting from the detection of congruency of information coming in through different sensory systems, particularly the visual, tactile and proprioceptive pathway. This congruency is detected by multisensory neurons that integrate input from these systems. For a correct body ownership sensation it is necessary that all separate pathways are well-developed, as well as the multisensory system. The integrative function develops after birth, along with the fine-tuning of the separate sensory systems; both require stimulation experience to reach an optimal state.

The mismatch in BIID

The mismatch that is present in BIID is associated with a decreased activity in the premotor cortex when the non-belonging limb is stimulated, suggesting a malfunctioning of multisensory integration. These neuroimaging results can however not be interpreted as a causal relationship between a specific aspect and brain activity, since they do not give any information about the underlying mechanisms. Therefore it remains unclear why in particular the premotor cortex seems to be involved, also taken into account that multisensory neurons are located in more regions. To be able to draw further conclusions about the real underlying causes of BIID, more research should be done to identify the precise pathways associated with the altered brain activity that is seen.

BIID cause and onset

Another point of discussion is the causation of the onset of BIID. The symptoms arise during childhood or early puberty, which is suggested to be due to a disturbance of the postnatal development of the multisensory integration system. However, this development takes place mainly during the critical period in the first months after birth. If a developmental disturbance were to be the cause of BIID, then why is there a difference in timing between symptom onset and the critical period in which the mismatch would arise? This remains unclear, but leads to the hypothesis that the developmental factor is only a one of more involved causes, so that other factors could play a role in the final triggering of BIID onset.

BIID treatment options

Currently there are no effective treatment options for BIID, only amputation of the limb resolves the mismatch completely. Neuroimaging however suggests that the cause of the mismatch in BIID is located in the brain, rather than the disorder being a problem of the affected body part. Following this theory, the limb itself is completely healthy, so amputation is not a proper treatment option for this disorder. In fact, amputation can even be viewed as unethical since it means that a normal and well-functioning body part is cut off while this does not solve the cause of the disorder. Whether or not amputation is thought to be unethical, it should not remain the best solution for BIID patients; ideally, a treatment option will be found that solves the mismatch without inducing a disability. Currently, transcranial direct current stimulation seems to be a promising treatment option. This method has had positive effects in several neuropsychiatric disorders, it is highly non-invasive and relatively easy to apply. Transcranial direct current stimulation is therefore the best option to try in BIID patients on short term.

Completely new treatment options might be discovered when more research is done to examine the plasticity of multisensory neurons in the adult premotor cortex. Besides that, a possible genetic origin of BIID could be sought in order to get more insight into the developmental mechanism and potential drug targets.

Concluding remarks

In conclusion, the feeling of body ownership seems to be relatively well understood, but a lot of uncertainty remains about the mismatch that exists in BIID. Neuroimaging results indicate lowered activity in a premotor cortex area that is thought to be involved in multisensory integration. Optimal treatment options for BIID have not been found until now, but we conclude that new methods should focus on neurological targets instead of limb amputation. Further research and experimentation is needed to discover the most effective neurological treatment option and to find out more about the specific causes and mechanisms of BIID.

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