The temporal pole: From anatomy to function-A literature appraisal

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Abstract

Historically, the anterior part of the temporal lobe was labelled as a unique structure named Brain Area 38 by Brodmann or Temporopolar Area TG by Von Economo, but its functions were unknown at that time. Later on, a few studies proposed to divide the temporal pole in several different subparts, based on distinct cytoarchitectural structure or connectivity patterns, while a still growing number of studies have associated the temporal pole with many cognitive functions. In this review, we provide an overview of the temporal pole anatomical and histological structure and its various functions. We performed a literature review of articles published prior to September 30, 2020 that included 112 articles. The temporal pole has thereby been associated with several high-level cognitive processes: visual processing for complex objects and face recognition, autobiographic memory, naming and word-object labelling, semantic processing in all modalities, and socio-emotional processing, as demonstrated in healthy subjects and in patients with neurological or psychiatric diseases, especially in the field of neurodegenerative disorders. A good knowledge of those functions and the symptoms associated with temporal pole lesions or dysfunctions is helpful to identify these diseases, whose diagnosis may otherwise be difficult.

Keywords: Temporal pole, visual processing, autobiographic memory, semantic memory, social cognition, neurodegenerative disorders

1. Introduction

The temporal pole, which constitutes the most rostral part of the temporal lobe, is a complex structure from a cytoarchitectural and functional perspective, which has been associated with various psychiatric and neurological diseases, such as Alzheimer's disease, frontotemporal lobar degeneration, temporal lobe epilepsy, schizophrenia, and many others. It is recent on the phylogenetic level: other mammalian species have a temporal lobe, but a cytoarchitecturally distinct temporopolar area is indeed unique to primates (Gloor et al, 1997, Insausti et al, 1987), which already suggests it is compatible with high-level cognitive functions. When it was first described in the early 20th century, the temporal pole was considered as a functional and anatomical homogenous region (Brodmann, 1909 ; Von Economo and Koskinas, 1929). However, more recent studies revealed its heterogeneity in many high-order brain functions, such as multimodal sensory integration (Roland et al, 1990 ; Sergent et al, 1992 ; Vandenberghe et al, 1995), autobiographic memory (Kapur et al, 1992, Maguire et al, 1999b ; Tomadesso et al, 2015), emotion and social cognition (Dolan et al, 2000 ; Lane et al, 1997, Reiman et al, 1997), or semantic memory (Marinkovic et al, 2003 ; Mesulam et al, 2014 ; Mummery et al, 2000). Moreover, recent anatomical studies of cytoarchitectonic parcellation in non-human primates (Morán et al, 1987 ; Kondo et al, 2003) and in human (Ding et al, 2009 ; Blaizot et al, 2010), as well as studies of connectivity pattern using diffusion tensor imaging (Fan et al, 2014) or functional imaging (Pascual et al, 2015) have suggested the existence of different subregions within the temporal pole, which could account for its different functions. The temporal pole is involved in a growing number of cognitive processes, which makes it hard to determine its precise functions. Thus, there is a lack of a global point of view on this issue. We therefore aimed to perform a literature review focused on studies of structural, cytoarchitectonic and functional anatomy of the temporal pole and its diverse functions, to better understand the overall functioning of this structure.

The literature review was performed according to the recommendations of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement by Moher et al, in 2009. A systematic literature search was conducted using MEDLINE to identify all studies published up to September 2020, based on a keyword search with the terms: temporal+pole AND anatomy OR temporal+pole AND function. The reference lists of retrieved studies were reviewed to search for additional reports of relevant studies. We considered only articles in the English language and excluded abstracts, oral communications, and conference proceedings. 1180 articles were identified

through database searching. After removal of duplicates, irrelevant studies and articles with insufficient or redundant data, 112 relevant articles were included.

2. Classical neuroanatomy of the temporal pole

In humans, the temporal pole is located under the lateral sulcus, at the rostral tip of the temporal lobe, inside the most rostral part of the middle cranial fossa **(Figure 1)**. Its rostral limit is the temporal lobe apex, rearward from the sphenoid greater wing. Its caudal limit, however, is not clearly delimited as there is no anatomical separation between the temporal pole and the other rostrally located areas of the temporal lobes (Chabardès et al, 2002). Its rostral boundary is thus anatomically defined as a virtual line continuous with the limen insulae (Brodmann, 1909 ; Von Economo and Koskinas, 1929). Dorsally, the temporal pole may present one or two temporopolar sulci (Insausti et al, 1998, Insausti et al, 2013), and the boundary between the temporal pole and the superior temporal gyrus is located at the lateral bank of the temporopolar sulcus (the most lateral one when several are present). Ventrally, the temporopolar cortex extends to the inferior temporal sulcus.

In classic cortical maps, the temporopolar cortex was labelled as a unique structure, classified as Brain Area 38 by Brodmann in 1909 and as Temporopolar Area TG by Von Economo and Koskinas in 1929 **(Figure 1)**. At that time, the exact function of the temporal pole was unknown but in 1937, Heinrich Kluver and Paul Bucy described a dramatic behavioral syndrome in monkeys after bilateral temporal lobectomy (Bucy and Klüver, 1955). Human cases were recognized in the 1950s, as surgeons employed bilateral temporal lobectomies to treat seizures. Although these lesions extended beyond the temporal pole, they nevertheless highlighted the putative importance of this region in high-order cognitive processes.

3. Recent advances in histological, connectivity and functional neuroanatomy

Subsequently, several authors proposed to subdivide the temporal pole in different areas, based on different cytoarchitectonic structure or connectivity patterns, summarized in **Table 1**.

3.1 Histological subdivisions

The first subdivision of the temporal pole cortex in Rhesus monkeys was based on histologic and cytoarchitectonic features. This study was done by Moran et al in 1987, who distinguished three subregions from the medial to the lateral part of the TP including: an agranular-periallocortical sector, a dysgranular sector and a granular sector, with specific afferences for each sector (see **table 1**).

More recently, Ding et al (2009) performed a wide histological analysis of the temporal pole in humans, using cellular, neurochemical and pathological markers. They divided the temporal pole in 7 areas from the ventral part of the temporal pole to its inferior part (**Figure 2** and **Table 1**).

3.2 Sub-divisions in humans based on connectivity data

In 2015, Pascual et al used functional MRI to analyse resting-state functional connectivity of the human left temporal pole in 172 healthy subjects. Based on distinct connectivity patterns, he subdivided the temporal pole in 5 different areas with a good agreement with Ding's cytoarchitectural subdivision **(Figure 2)**: the dorsal, ventromedial, medial, anterolateral and rostral regions of the temporal pole.

On the other hand, Fan et al in 2014 studied connectivity of the temporal pole using diffusion tensor imaging, and parcelled it in 3 distinct regions: a dorsal, lateral and medial area.

3.3 Functional neuroanatomy

Temporal pole is thus a complex anatomical region, with several distinct areas, each one having specific cytoarchitectural organization and connectivity patterns. In keeping with this, the temporal pole has been associated with many different functions (Dupont, 2002), namely visual, mnesic, language, semantic and socio-emotional functions, as demonstrated by lesion studies and functional imaging studies. We may hypothesize that different areas within the temporal pole are dedicated to information processing in different modalities, while the temporal pole apex, which is linked with all the other parts of the temporal pole (Pascual et al, 2015), may thereby be a hub for information convergence.

3.3.1 Visual cognition function

Many studies suggest that the temporal pole is a high-level visual cortical area involved in visual cognition, with a specific or preferential function in complex visual scene analysis, face recognition and visual memory. Early studies were done in non-human primates, and selective bilateral ablation of both temporal poles in Rhesus monkeys induced:

- Visual discrimination deficiency, such as loss of discrimination between different food types (Pinto Hamuy et al, 1957) and deficiency in visual complex scene discrimination (Gaffan, 1994)

- Short-term visual memory impairment, similar to those observed in infero-temporal cortex lesions (Delacour, 1977)
- Long-term visual memory impairment for complex two-dimensional objects, but not for simple objects (Gaffan, 1994).

The same deficits were caused by a cold inactivation of both temporal poles using cryodes in Rhesus monkeys (Horel et al, 1982 ; Horel et al, 1984a ; Horel, 1984b), while a later study also identified a face discrimination impairment (Horel et al, 1987). Unilateral cooling of the temporal pole also produced significant face discrimination deficiency, whatever the side, while bilateral temporal pole cooling only increased the severity of the deficit.

It studies that recorded single-unit potentials in the temporal pole of non-human primates, it was shown that temporopolar visual-responsive neurons potentials were maximal when elicited by complex visual stimuli, and much lower for simple visual stimuli (Nakamura et al, 1994).

A few human functional imaging studies, measuring the cerebral blood flow using $H_2{}^{15}O$-PET with variable stimuli in healthy volunteers confirmed that the temporal pole is a high-level visual cognitive area in humans:

- Temporal poles were activated during learning of visual geometrical patterns and mnesic association, but not during recall and recognition (Roland et al, 1990).
- Both temporal poles were activated during a famous face recognition task, but not during object recognition task (Sergent et al, 1992)
- During a two-dimensional abstract figure recognition task, using familiar or unfamiliar stimuli, the left temporal pole activation was inversely correlated to stimulus familiarity (Vandenberghe et al, 1995), with a maximal activation for novel stimuli.

Links with neurodegenerative disorders

MRI studies in patient suffering from neurodegenerative disorders also found visual recognition deficiency correlated with temporal pole lesions:

- Right temporal pole variant of frontotemporal lobar degeneration (FTLD) (Busigny et al, 2009) was associated with a clinical picture of prosopagnosia

- Right temporal pole atrophy was correlated with prosopagnosia in patients with semantic variant Primary Progressive Aphasia (svPPA) (Josephs et al, 2018) and with complex visual object recognition deficiency in patients with progressive primary aphasia (PPA) (Nilakantan et al, 2017)

In conclusion, numerous studies summarized in **Table 2 and Figure 3** showed that the temporal pole is a high-order visual area activated in visual complex tasks, with a preferential activation in complex figure analysis and face recognition. In humans, the temporal pole seems to show a right predominance for visual recognition.

3.3.2 Autobiographic memory function

An anatomo-clinical correlation report first pointed out the role of the temporal pole in autobiographic memory: Kapur et al in 1992 reported the case of a woman who suffered from post-traumatic bilateral lesions of the temporal pole, without any lesions of the hippocampus or medial temporal area. She presented with complete retrograde autobiographical amnesia, extending back to her childhood, and amnesia for public events prior to the injury. On the other hand, her anterograde memory and encoding capabilities were normal, as well as her autobiographical memory for events that happened after the injury. The authors concluded that the temporal pole played a critical role in memory for past events, predominantly for autobiographic memories.

Studies in healthy subjects have also demonstrated the role played by the temporal pole in autobiographical memory: $H_2{}^{15}O$-PET imaging during various memory tasks (autobiographic events, public events, autobiographic facts, general knowledge) revealed that the left temporal pole was only activated during recall of autobiographic events (Maguire et al, 1999b). FDG-PET uptake in both temporal pole was associated with baseline global cognition in cognitively stable healthy subjects aged 80 and above (Arenaza-Urquijo et al, 2019). The emergence of false memories was also correlated with temporal pole activation (Chadwick et al, 2016)

Links with neurodegenerative disorders

Temporal pole is involved in many neurodegenerative disorders, and may account for some of the autobiographic memory deficiencies found in those diseases. Its involvement has been described in early stages of neurodegenerative disorders:

- A neuro-imaging analysis of patients with an amnestic mild cognitive impairment (Tomadesso et al, 2015) showed that performances for autobiographic remote memory inversely correlated with the temporal pole gray matter volume, while performance for autobiographic recent memory inversely correlated with hippocampal volume.

- Histopathological study of TDP-43 pathology in aging and Alzheimer's disease subjects (Nag et al, 2018) showed that the temporal pole is involved since the early stages of TDP-43 pathology, and may represent an intermediate stage between mesial temporal lobe involvement and the last stage with involvement of other neocortical areas.

- Temporal pole atrophy was also found in the early stage of Alzheimer's disease (Ramos Bernardes da Silva Filho et al, 2017),

It was also described in later stages of neurodegenerative disorders:

- Temporal pole cortical thickness was found to correlate with the severity of tau pathology identified with AV-1451-PET (LaPoint et al, 2017).

- Temporal pole atrophy was associated with autobiographic episodic memory dysfunction, both in Alzheimer's disease and FTLD (Irish et al, 2014).

- In patients with svPPA, left temporal pole atrophy correlated with semantic deficiency, but also with episodic future thinking (Irish et al, 2012).

In conclusion, those studies suggest that the mnesic function of the temporal pole is mainly the autobiographic memory, with a predominant activation during recall of autobiographic remote memory (see **Figure 3**).

3.3.3 Language function

The function of temporal pole in language and semantic processing has been more recently discovered, thanks to functional imaging studies in healthy subjects and reports of patients suffering from neurodegenerative diseases.

Activation of both temporal poles in linguistic tasks (story recall, recall of words list, story reading task, comprehensiveness tasks) has been found in several $H_2{}^{15}O$-PET studies performed in healthy

volunteers, with a leftward dominance for language (Andreasen et al, 1995, Tzourio et al, 1998, Maguire et al, 1999a).

Studies in healthy volunteers also confirmed that the temporal pole was a key area for semantic processing:

- Using a combination of diffusion tensor imaging and functional MRI, both anterior temporal poles were found to be a key component of a semantic system, shared by vision and language (Jouen et al, 2015 ; Jouen et al, 2018)
- A follow-up of 306 elderly subjects without dementia showed that a semantic decline was specifically related to temporal pole atrophy (Pelletier et al, 2017).
- A few studies using inhibitory repetitive transcranial magnetic stimulation (Pobric et al, 2007, Pobric et a 2009, Pobric et al, 2010) showed that inhibition of either left or right temporal pole induced a selective semantic memory impairment

Links with neurodegenerative disorders

In the field of neurodegenerative disorders, many studies confirmed the role of the temporal pole in language function, with specifically:

- A role in lexical representation, as demonstrated by the case of a patient with isolated left temporal pole atrophy suffering from severe proper name anomia, with a respect of other cognitive functions (Papagno et al, 1997)
- A role in the selection of verbal labels and representations for objects: in patients with progressive primary aphasia (PPA) with a cortical atrophy located predominantly or exclusively within the left temporal pole, the most consistent and severe deficiency was a failure to name objects, without deficiency in word understanding (Mesulam et al, 2013)
- A role in face naming: in patients with PPA, famous face naming impairment correlated with left temporal pole atrophy, while famous face recognition impairment correlated with bilateral temporal pole atrophy, suggesting that face naming and the face recognition are two functions of the temporal pole, with a left-sided lateralization for naming, and a bilateral or right-sided lateralization for face recognition (Gefen et al, 2013)

Beyond the naming function, studies of patients suffering from neurodegenerative disorders also confirmed that the temporal pole is a key component of the semantic network. The semantic variant Primary Progressive Aphasia (svPPA), clinically defined by a progressive semantic memory deficiency, is a variant of FTLD in which lesions predominate at the left temporal pole (Bruun et al, 2019). Various imaging studies demonstrated that the most significantly and consistently affected region in svPPA was the left temporal pole, with a good correlation between the extent of atrophy of the left temporal pole and the degree of semantic memory impairment (Mummery et al, 2000, Collins et al, 2017, Rohrer et al, 2009, Irish et al, 2012). Neuropathology studies also found ubiquitin-positive inclusions within the left temporal pole in the very early stages of svPPA (Yamamoto et al, 2009). Finally, in patients with Alzheimer's disease, impaired semantic performance was associated with reduced gray matter volume in the temporal pole (Joubert et al, 2016)

Links with other neurological disorders

In stroke patients, damage to the left anterior temporal cortex predicted impairment of complex syntactic processing (Magnusdottir et al, 2013) and semantic processing (Bonilha et al, 2017). A semantic memory impairment was also found in patients with left epileptogenic temporal pole lesions (Campo et al, 2016). Globally, patients with left temporal pole lesions due to various disorders (stroke, herpes simplex encephalitis, focal intracerebral haemorrhage, or surgical resection) were found to have a naming deficiency for unique entities (Mehta et al, 2016).

In conclusion, these different studies, summarized in **Table 3 and Figure 3**, showed that the temporal pole, with a left-sided preference, plays a specific role within the language network in verbal labels and lexical representations, as well as verbal semantic memory.

3.3.4 Socio-emotional function

In 1930, Klüver and Bucy described a clinical syndrome caused by bilateral ablation of temporal lobes in non-human primates, whose main symptoms are hyperorality, hyperphagia, visual agnosia, amnesia, and socio-behavioural changes. In the following years, studies showed that part of socio-behavioural changes were due to temporal pole ablation. Bilateral temporal pole ablation in Rhesus monkeys led to decreased social interaction (such as allogrooming or sexual behaviour) and

decreased facial expressions and vocalizations, with a loss of maternal behaviour (Franzen and Myers 1973), and severe impairment of social behaviour and a decreased emotionality (Horel et al, 1975).
In healthy subjects, many functional imaging studies found a preferential activation of the right temporal pole in emotional (positive or negative) or affective circumstances, such as recalling emotionally intense autobiographical memories (Reiman et, al 1997 ; Dolan et al, 2000) or watching an emotion-inducing movie (Reiman et al, 1997 ; Lane et al, 1997). Emotion recognition deficiency, either with a facial or musical emotion recognition task, was negatively correlated with the right temporal pole volume in healthy subjects (Hsieh et al, 2012).
The temporal pole was also involved in higher-level social cognition functions: it was activated during theory of mind and empathy tasks, more strongly for theory of mind than for empathy (Reniers 2014), and temporal pole gray matter volume correlated positively with modesty score in healthy subjects (Zheng et al, 2017) and negatively with aggressiveness score in martial artists (Breitschuh et al, 2018).

Links with neurodegenerative disorders

Temporal pole atrophy was correlated with various aspects of social cognition in patients with neurodegenerative disorders, such as deficiency in moral judgement task in FTLD patients (Baez et al, 2016) and theory of mind impairment in behavioral variant of frontotemporal dementia (Baez et al, 2019).
More specifically, studies in neurodegenerative patients pointed out a rightward predominance of temporal pole involvement in social cognition:

- The degree of atrophy of the right temporal pole was correlated to emotion recognition deficiency in both Alzheimer's disease and svPPA patients (Hsieh et al, 2012) and to altered negative emotion and sarcasm recognition in behavioural variant of FTLD (Kipps et al, 2009).
- Hypometabolism of the right temporal pole was correlated to social conceptual impairments in patients with bvFTLD (Zahn et al, 2009)
- Right temporal pole volume was correlated with impaired empathy in various neurodegenerative disorders (frontotemporal lobe degeneration, Alzheimer's disease, corticobasal degeneration and supranuclear progressive palsy) (Rankin et al, 2006)

One of the most striking examples is the right temporal variant of FTLD, which causes a predominant and progressive right temporal pole atrophy, mirroring with the svPPA. Its main clinical features are

social and behavioural impairment, and studies revealed that patients with right temporal variant of FTLD had the following symptoms:

- Social awkwardness, loss of insight, and difficulty in identifying people (Thompson et al, 2003),
- Prosopagnosia, spatial orientation deficiency, and behavioural symptoms (including loss of insight, loss of empathy, aggressive behaviour…) (Chan et al, 2009)
- Emotion recognition deficiency (Kumfor et al, 2016)
- Altered behaviour and problems with interpersonal relationships (Okada et al, 2018)
- Personality changes and behavioural symptoms (hyper-religiosity, hypergraphia, and poor emotional regulation such as irritability, impulsivity, disinhibition, or egocentric behavior) (Veronelli et al, 2017)

Nevertheless, the left temporal pole is also associated with social cognition, although to a lesser extent: a left temporal pole hypometabolism was thus associated with anosognosia for social behavioural disability in patients with FTLD (Ruby et al, 2007).

Links with other neurological and psychiatric disorders

Impaired affective empathy was described after ischemic stroke involving the right temporal pole (Leigh et al, 2013), whereas impairment of a social problem-solving task correlated with a lower cortical thickness of the temporal pole in patients with traumatic brain injury (Hanten et al, 2011). Interestingly, temporal pole involvement was also described in psychiatric disorders, particularly in schizophrenia. In a large meta-analysis of 4474 individuals with schizophrenia (Van Erp et al, 2018), a lower bilateral temporal pole thickness was found to be strongly associated with individuals with schizophrenia compared with healthy subjects. There was a significant negative correlation between temporal pole thickness and normalized medication dose, symptom severity, and duration of illness, and a positive correlation with age at onset, confirming previous studies suggesting a smaller cortical surface of the temporal pole in subjects with schizophrenia (Rais et al, 2012 ; Horn et al, 2010 ; Tomelleri et al, 2009 ; Crespo-Facorro et al, 2004 ; Kasai et al, 2003 ; Xu et al, 2015 ; Lee et al, 2016). Reduced temporal pole volume was also found in several other psychiatric disease : obsessive-compulsive syndrome (with a correlation between obsessing symptoms and right temporal pole

volume, Suñol et al, 2018), panic disorders (Kang et al, 2017), post-traumatic stress disorder (Kuhn and Galliant, 2013), social anxiety disorder (Talati et al, 2013), bipolar disorder type I (Neves et al, 2015), mild depressive symptoms (Webb et al, 2014), major depressive disorder (Peng et al, 2011) and ADHD (Fernández-Jaén et al, 2014).

Some patients with personality disorder, mostly patients with social cognition deficiency, also had reduced temporal pole volume, such as cocaine-dependent patients with personality disorders (Albein-Urios et al, 2013) or offending pedophiles (Schiffer et al, 2017)

Some patients at the border between neurological and psychiatric disease also demonstrated the involvement of temporal pole in emotional processes and psychiatric symptoms: depression and anxiety symptoms in Alzheimer's disease patient were associated with temporal pole atrophy (Hayata et al, 2015), and lesions of the temporal pole white matter in patient with glioma was associated with schizotypal traits (Lemaitre et al, 2018)

In conclusion, those studies, summarized in **Table 4 and Figure 3**, showed that the temporal pole, with a right-sided dominance, is involved in various functions of the social cognition network, mainly emotional processing, empathy and insight.

3.3.5 The semantic hub hypothesis

As seen in previous paragraphs, the temporal pole has complex and high-level functions in visual recognition, language processing and verbal semantic memory. Some authors (Mesulam et al, 2014) suggested that those different functions observed could in fact derive from a single function: temporal pole could be an amodal hub for semantic knowledge, and a key region for binding an item's names and representations in all modalities.

In order to test this hypothesis, several studies tested semantic knowledge and recognition in non-verbal modalities in patients with temporal pole lesions. Left temporal pole lesions were thus associated with:

- A deficiency in music naming, without deficiency in music recognition (Belfi et al, 2014).
- A defective naming of famous voices, but no deficiency in the ability to recognize the voices (Waldron et al, 2014).

- A selective naming deficiency using a famous face and landscape recognition tasks (Waldron et al, 2014).

Right temporal pole lesions also were associated with non-verbal semantic deficiency:

- A selective associative phonagnosia (selective impairment in famous voice recognition in the absence of alteration of voice perception, face perception and famous face recognition) was described after right temporal pole stroke (Luzzi et al, 2018)
- A deficiency in recognition of famous tunes correlated with the degree of right temporal pole atrophy in semantic dementia and Alzheimer's disease patients (Hsieh et al, 2011)

In healthy subjects, fMRI studies showed that recognition of famous and personally familiar names strongly involved temporal pole bilaterally (Sugiura et al, 2006), and that right temporal pole was activated during familiar voices recognition (Nakamura et al, 2001). Moreover, Marinkovic et al, in 2003, using MEG, showed that subjects who were asked a semantic judgement about an object presented on visual or verbal material quickly activated the left temporal pole, immediately after the primary (auditory or visual) cortices activation, suggesting that the temporal pole is involved whatever the modality and has a supramodal semantic function.

In conclusion, those studies demonstrated that the temporal pole is an amodal hub, critical for all domains of semantic representations, with a differentiated asymmetric organization: the left temporal pole is critically important for verbal association, while the right temporal pole has a predominant function for visual association (**Figure 3**).

3.4 Synthesis and discussion

The temporal pole has been associated with several functions, which all are complex cognitive functions underpinned by wide cortical networks. Thereby, in functional imaging studies, the temporal pole is not activated alone but rather co-activated with many other cortical areas, depending on the network requested by the task, which makes it hard to individualize the exact role of the temporal pole in those functions. Moreover, the temporal pole is heavily connected with the other rostrally adjacent temporal areas, which constitute inputs of the temporal pole and are often co-activated in functional imaging studies: this further increases the difficulty to isolate the temporal pole activations, as the

anatomical borders between those areas is not always clearly defined on MRI and may require histological analysis, which is of course not possible in functional imaging studies. Studies in patients can be very instructive, but they have their own caveats: focal lesions of the temporal pole, such as stroke or traumatic injuries, are rarely strictly restricted to the temporal pole, and histological lesions in patients with neurodegenerative disorders extend far beyond the temporal pole even when they seem focal on morphological MRI.

However, despite those difficulties, recent studies presented in this review made it possible to associate the temporal pole with a few specific roles. Its most studied and strongly associated role is in language, and more specifically in verbal semantic processing, as assessed by many studies in svAPP and replicated in healthy subjects and in patients with various neurological diseases (paragraph 3.3.3). More recent studies have found its implication in semantic memory beyond its verbal aspect, and some author, such as Mesulam et al, concluded that the temporal pole is, among other things, a structure devoted to semantic processing whatever the modality (paragraph 3.3.5). We may hypothesize that the temporal pole activation in visual tasks (paragraph 3.3.1) might result from this function, and could account for a semantic processing of visual complex objects.

Another function with which the temporal pole has been strongly associated is socio-emotional processing, and many studies over the past few years demonstrated that the temporal pole belongs to the brain social network (paragraph 3.3.4). Moreover, temporal pole dysfunctions were found in various neurological and psychiatric diseases, and correlated with social cognition deficiencies. Its exact role inside this network is still debatable, and will require further researches to specify it. On the other side, early studies associated the temporal with autobiographic memories (paragraph 3.3.2), but this role seems rather minor. Given its role in social cognition, it is possible that temporal pole activation during autobiographic tasks results from social or emotional processing of memories.

4. Conclusion

The temporal pole is a complex structure, with different anatomical and functional subregions as shown by several histological studies and connectivity analysis, in non-human primates and in humans. This structure is responsible for several distinct functions such as language and semantic processing, socio-emotional processing, autobiographic memory, facial recognition and complex objects analysis and recognition.

The anatomical and structural complexity of the temporal pole and its wide connections with many other cortical areas enable the temporal pole to receive and process information from different sensory modalities. It thereby acts as a hub, binding different high-order information and being able to process many high-level cognitive treatments in different modalities, which explains its varied complex functions. Those functions also account for the diverse diseases in which the temporal pole is involved, primarily the neurodegenerative disorders. Temporal pole atrophy is indeed the landmark of two neurodegenerative syndromes: the semantic variant Primary Progressive Aphasia, with a predominant left temporal pole atrophy, and the right temporal variant of FTLD, with a predominant right temporal pole atrophy. The former has been quite well studied and described, while there are still many unanswered questions regarding the latter, for which the number of studies remains low, among other things because of the difficulties in identifying the symptoms and establishing the diagnosis. The involvement of the temporal pole in psychiatric diseases, especially schizophrenia, is also well defined now, but its exact role in the pathophysiology of the diseases remains to be determined. An improved knowledge of temporal pole anatomy and functions will therefore be helpful for clinicians, in order to achieve earlier and more precise diagnoses, to better understand those diseases and to guide future researches.

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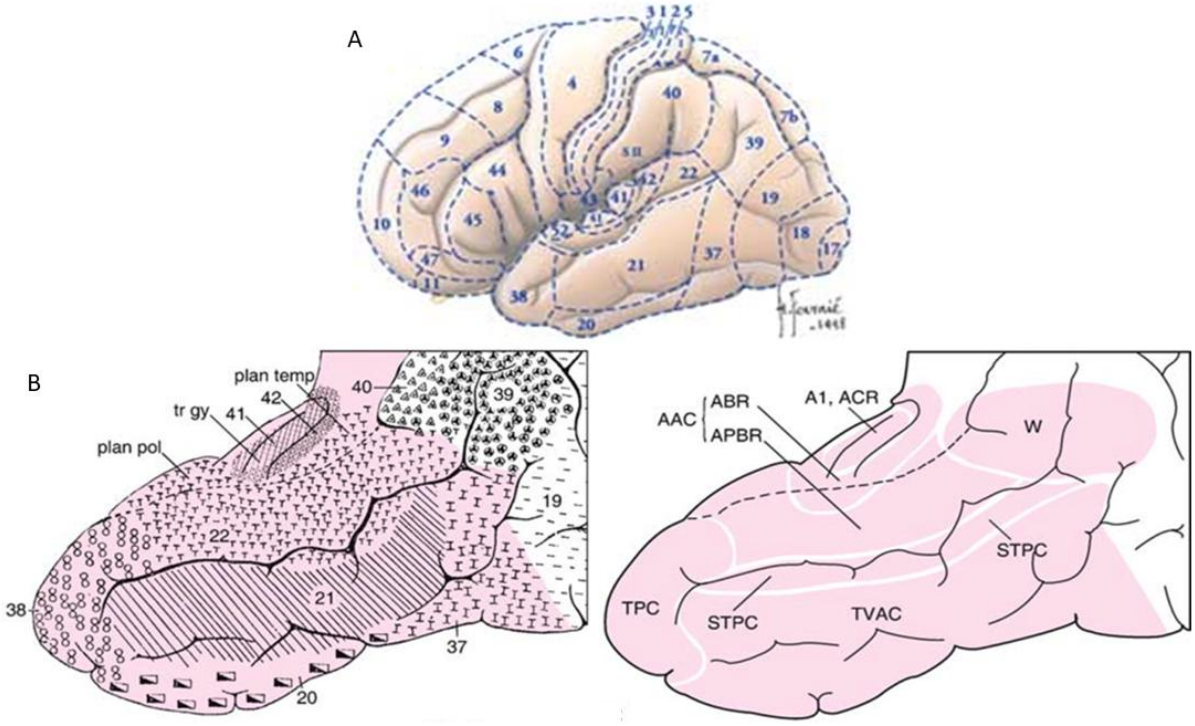
Figure 1. Classical anatomy of the temporal pole

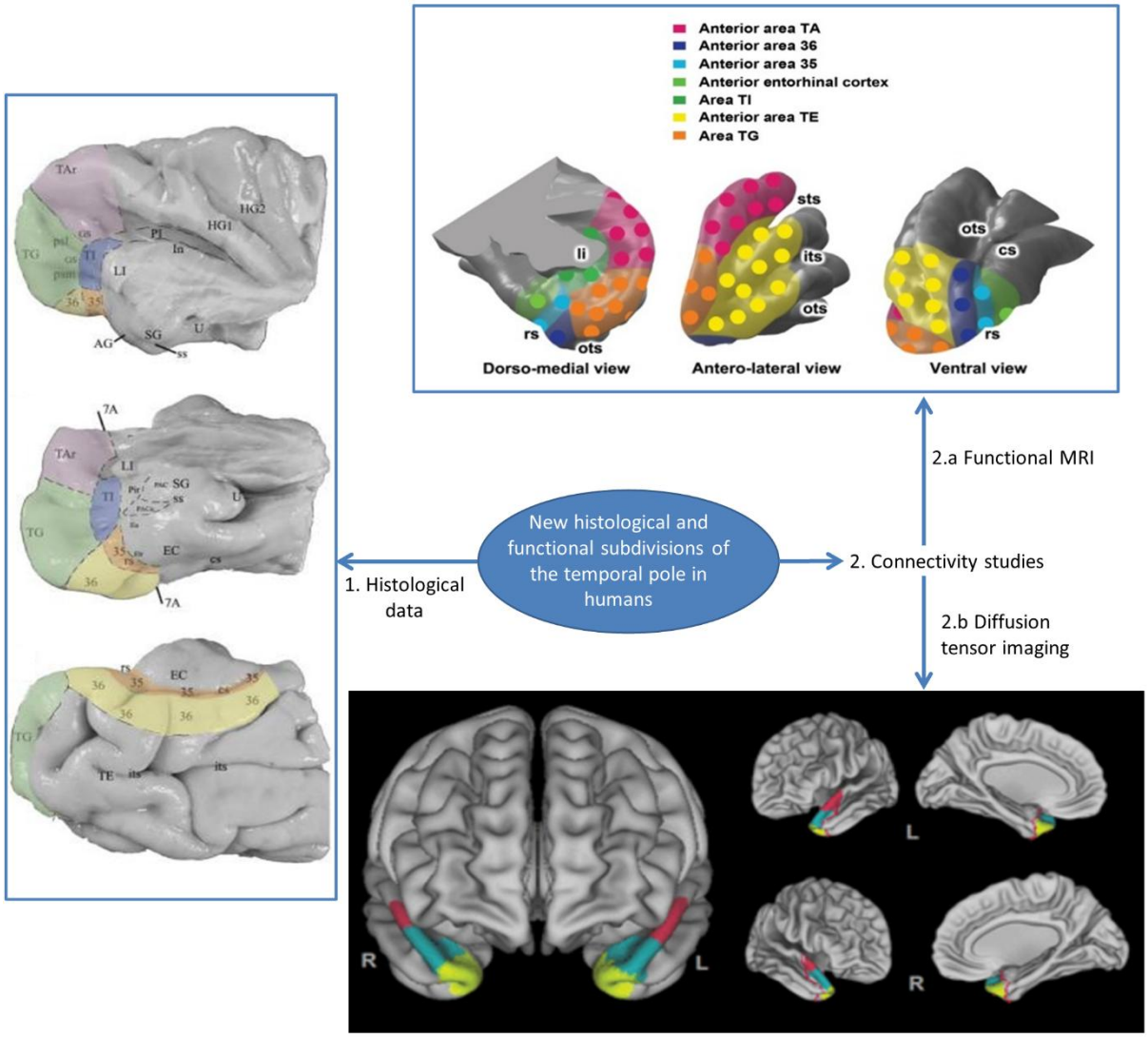


A. Brodmann areas of the human cerebral cortex

B. B. Structural anatomy and Brodmann areas of the lateral temporal cortex. A1, primary auditory cortex; AAC, auditory association cortex; ABR, auditory belt region; ACR, auditory core region; APBR, auditory parabelt region; plan pol, planum polare; plan temp, planum temporale, STPC, superior temporal polymodal cortex; TPC, temporopolar cortex; TVAC, temporal visual association cortex; tr gy, transverse gyrus of Heschl; W, Wernicke's region

From Sorbonne University Department of Anatomy

Figure 2. New histological and functional subdivisions of the temporal pole in humans



Subdivision of the human temporal pole: based on histological data, from Ding et al (left), on functional MRI, from Pascual et al (upper right), and on diffusion tensor imaging, from Fan et al (lower right).
In Ding et al: *CS*, collateral sulcus, *EC*, entorhinal cortex, *Elr*, rostral lateral part of entorhinal cortex, *Eo*, olfactory part of entorhinal cortex, *FI*, frontal insular area, its inferior temporal sulcus, *LI*, limen insulae, mts middle temporal sulcus, *PI*, parainsular cortex, *Pir*, piriform cortex, *psm and psl*, medial and lateral temporopolar sulci, *rs*, rhinal sulcus, *SG*, semilunar gyrus, *ss*, semiannular sulcus, *sts*, superior temporal sulcus, *TA*, temporal area TA based on Von Ecomono (1929), *Tar*, temporal area TAr, the area rostral to area TA, *TAp*, temporal area TAp, the polysensory area in the dorsal bank of the STS, *TE*, temporal area TE based on von Economo (1929), *Ted and TEv*, dorsal and ventral parts

of area TE, *TG*, temporopolar area TG, the area caps the tip of temporal pole, *TI,* temporal insular area

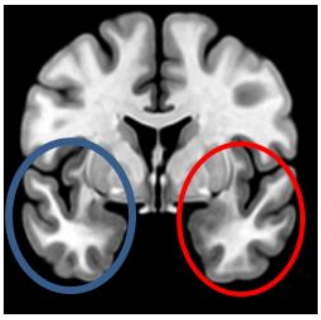
In Pascual et al: *its*, inferior temporal sulcus; *ps*, polar sulcus; *sts*, superior temporal sulcus; *ots*, occipitotemporal sulcus; *rs*, rhinal sulcus; *li*, limen insulae.

In Fan et al: *TGm*, medial temporal pole (yellow); *TGl*, lateral temporal pole (green), *TAr*, dorsal temporal pole (red).

Figure 3: Summarized functions of the temporal pole

2. Autobiographic memory, with a predominant activation during recall of autobiographic remote memory
No side predominance

1. Visual complex tasks, with a preferential activation in complex figure analysis and face recognition with a right predominance for visual recognition



3. Language and semantic processing, verbal labels and lexical representations, verbal semantic memory with a leftward preference

4. Social cognition, mainly emotional processing, empathy and insight with a rightward preference

5. Amodal hub, critical for all domains of semantic representations, with a differentiated asymmetric organization: leftward preference for verbal association, rightward preference for visual association.

Table 1. Recent advances in histological and functional subdivisions of the temporal pole

Study	Moran et al (1987)	Ding et al (2009)	Pascual et al (2015)	Fan et al (2014)
NUMBER OF AREAS	3	7	5	3
TYPE OF AREAS	Primates (Macaca mulatta) Histologic	Human Cytoarchitectonic & chemoarchitectonic	Human Functional MRI connectivity	Human DTI connectivity
NAMES	1. Agranular-periallocortical sector 2. Dysgranular sector 3. Granular sector	1. Anterior area 35 2. Anterior area 36 3. Anterior area TE 4. Temporo-insular area 5. Temporal rostral area 6. Anterior polysensory area 7. Temporopolar dysgranular area TG	1. Dorsal 2. Ventro-medial 3. Medial 4. Ventro-lateral 5. Dysgranular temporal pole	1. Dorsal 2. Medial 3. Lateral
CYTO ARCHITEC	1. Absence of granule cells, 3-layers cortex 2. Increasing differentiation of the cortex (appearance of layer 4, separation of infragranular layer into layer 5 and 6, no layer 2) 3. Neocortical	1. Distinct columnar organization in superficial layers, unique layer of large pyramidal cells named layer IIIu, lack of granular layer IV 2. Dysgranular region, thin layer IV, no clear distinction between layer V & VI	NA	NA

TONY	cortex composed with 6 layers	3. Neocortical granular region with clear & thick layer IV 4. Agranular cortex, lacking layer IV, unique layer I with many olfactory fibers 5. Granular cortical region with thick layer IV 6. Granular cortex, with prominent columnar organization in its layer IV and V 7. Dysgranular cortex, dysgranular thin layer IV, thin layer II and thick layer III and VI, medium-sized pyramidal cells packed in layer III		
AFFERENCES	1. Afferences from limbic and piriform olfactory cortex 2. Afferences from limbic and inferotemporal cortex 3. Afferences from superior temporal (auditory) areas and frontal cortex	1, 2 and 3. Afferences from their rostral counterpart (visual association cortical regions) 4. Afferences from piriform cortex 5. Afferences from auditory cortices 6. Afferences from both auditory and visual cortices 7. Afferences from all other temporopolar areas	1. Afferences from somatosensory cortex, auditory cortex, olfactory cortex, SMA, cingulate gyrus (middle portion), insula 2. Afferences from rostral visual areas of the occipitotemporal pathway, paralimbic regions, limbic subcortical regions 3. Afferences from olfactory cortex, ventral temporal structure, orbitofrontal cortex, amygdala, hypothalamus 4. Afferences from default-semantic network, limbic medial temporal regions, parahippocampal gyrus 5. Afferences from all other temporopolar	1. Afferences from inferior frontal gyrus (orbital part), insular cortex, auditory cortex of the superior temporal gyrus, middle temporal gyrus 2. Afferences from parahippocampal gyrus, inferior temporal gyrus, fusiform gyrus, hippocampus, amygdala 6. Afferences from superior frontal gyrus, olfactory cortex, gyrus rectus, insula

			areas	

Table 2. Temporal pole visual functions

Study (year)	Type of study	Function
Pinto Hamy (1957)	Primate, lesional study	Visual discrimination (food type)
Delacour (1976)	Primate, lesional study	Short-term visual memory
Gaffan (1994)	Primate, lesional study	Visual complex scene discrimination, long-term visual memory for complex two-dimensional objects
Horel (1982)	Primate, inactivation	Short-term visual memory
Horel (1984a and 1984b)	Primate, inactivation	Visual discrimination for complex scene
Horel (1987)	Primate, inactivation	Face discrimination
Nakamura (2016)	Primate, intracranial recording	Complex visual stimuli
Roland (1990)	Human, PET (healthy subjects)	Visual learning and visual mnesic association
Sergent (1992)	Human, PET (healthy subjects)	Face recognition
Vandenbergue (1995)	Human, PET (healthy subjects)	Abstract and novel two-dimensional figure recognition task
Busigny (2009)	Human, MRI (neurodegenerative disorder)	Face recognition
Josephs (2008)	Human, MRI (neurodegenerative disorder)	Face recognition
Nilakantan (2017)	Human, MRI (neurodegenerative disorder)	Object recognition and memory

Table 3. Temporal pole language and semantic function

Study (year)	Type of study	Function
Andreasen (1995)	Human, PET (healthy subject)	Story recall, words list recall
Tzourio (1998)	Human, PET (healthy subjects)	Story understanding
Maguire (1999)	Human, PET (healthy subjects)	Story understanding
Papagno (1998)	Human, case report (neurodegenerative disorder)	Lexical representation (mainly proper name)
Mesulam (2013)	Human, anatomo-clinical correlation (neurodegenerative disorder)	Verbal representation of objects, selection of verbal labels for objects
Gefen (2013)	Human, gray matter volume measurement (neurodegenerative disorder)	Famous subjects naming
Magnusdottir (2013)	Human, anatomo-clinical correlation (stroke patients)	Complex syntactic processing
Mehta (2016)	Human, anatomo-clinical correlation	Naming deficiency
Mummery (2010)	Human, gray matter volume measurement (neurodegenerative disorder)	Semantic memory
Collins (2017)	Human, gray matter volume measurement (neurodegenerative disorder)	Semantic memory
Rohrer (2009)	Human, gray matter volume measurement (neurodegenerative disorder)	Semantic memory
Bonilha 2017	Human, anatomo-clinical correlation (stroke)	Semantic processing
Campo (2016)	Human, anatomo-clinical correlation (epilepsy)	Semantic processing
Joubert (2016)	Human, gray matter volume measurement (neurodegenerative disorder)	Semantic memory
Hsieh (2011)	Human, gray matter volume measurement (neurodegenerative disorders)	Auditory semantic processing
Pelletier (2017)	Human, gray matter volume measurement (healthy subjects)	Verbal semantic processing
Jouen (2015, 2018)	Human, functional MRI and diffusion tensor imaging (healthy subjects)	Visual and verbal semantic processing
Sugiura 2006	Human, functional MRI (Healthy subjects)	Verbal semantic memory
Pobric (2007, 2009, 2010)	Human, rTMS inactivation (healthy subjects)	Semantic processing

Table 4. Temporal pole socio-emotional function

Study (year)	Type of study	Function
Kluver-Bucy (1930)	Primate, lesional	Socio-behavioural regulation
Franzen (1972)	Primate, lesional	Social interaction, maternal behaviour
Horel (1975)	Primate, lesional	Social behaviour regulation, emotionality
Thompson (2003)	Human, anatomo-clinical correlation (neurodegenerative disorder)	Insight, social behaviour
Chan (2009)	Human, anatomo-clinical correlation (neurodegenerative disorder)	Social behaviour (emotional processing, insight, empathy)
Reiman (1997)	Human, PET (healthy subjects)	Emotional-intense memory recall
Lane (1997)	Human, PET (healthy subjects)	Positive and negative emotion experiment
Dolan (2000)	Human, PET (healthy subjects)	Emotional memory retrival
Zheng (2017)	Human, fMRI (healthy subjects)	Modesty trait score
Reniers (2014)	Human, fMRI (healthy subjects)	Empathy and theory of mind
Kipps (2009)	Human, anatomo-clinical correlation (neurodegenerative disorder)	Negative emotion recognition
Zahn (2009)	Human, anatomo-clinical correlation (neurodegenerative disorder)	Social concepts
Ruby (2007)	Human, anatomo-clinical correlation (neurodegenerative disorder)	Self-perception of social behaviour
Okada (2018)	Human, anatomo-clinical correlation (neurodegenerative disorder)	Interpersonal relationship
Veronelli (2017)	Human, anatomo-clinical correlation (neurodegenerative disorder)	Behaviour, emotional regulation
Kumfor (2016)	Human, anatomo-clinical correlation (neurodegenerative disorder)	Emotion recognition
Breitshuh (2018)	Human, fMRI (healthy subjects)	Agressiveness regulation
Leigh (2013)	Human, anatomo-clinical correlation (stroke)	Emotional empathy
Rankin (2006)	Human, anatomo-clinical correlation (neurodegenerative disorder)	Empathy
Baez (2019)	Human, anatomo-clinical correlation (neurodegenerative disorder)	Theory of mind
Hornberger (2011)	Human, anatomo-clinical correlation (neurodegenerative disorder)	Behavioural inhibition
Baez (2016)	Human, anatomo-clinical correlation (neurodegenerative disorder)	Moral judgment
Hsieh (2012)	Human, anatomo-clinical correlation (neurodegenerative disorder)	Emotion recognition
Hanten (2011)	Human, anatomo-clinical correlation (Traumatic brain	Social problem solving

	injury)	